DECISION MAKING UNDER UNCERTAINTY: ECONOMIC EVALUATION OF STREAMFLOW FORECASTS

FINAL REPORT

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ABSTRACT

The research focuses on the potential economic benefits that could accrue to different classes of water users as a result of improvements in the accuracy of streamflow forecasts. While such potential benefits can be identified for many water use activities, many of the latter could not make use of the former unless the accuracy of the forecasts approach certainty--equivalent levels, This is so because for many uses the physical costs of water, and the costs of assuring its uninterrupted supply by physical means, is low relative to the losses that would be incurred if supplies were to be interrupted.

Furthermore, for regions and river basins in which streamflow depends largely on difficult-to-predict rainfall events the likelihood of achieving a higher forecast accuracy level on a longer term (i.e., seasonal basis) is presently not high.

However, in the water deficient areas of the Western United States a large percentage of annual streamflow is determined by winter snowpack accumulations. Prospects are high that much higher forecast accuracy can be achieved from snow pack monitoring systems. Costs for such improved forecasting systems and methodologies appear to be quite modest. Detailed efforts for the evaluation of the economic benefits from improved streamflow forecast accuracy, therefore, were concentrated on water use activities that depend substantially on snowmelt runoff, since it appears that for these regions pay-offs in terms of additional benefits minus the costs of providing more reliable forecasting system appear to be highest.

The first study qualifies the approximate benefits to a typical western irrigation area from improved seasonal streamflow forecasts through the use of a probabilistic linear programming model.

The decision variable of interest is the change in acreages planted that may take place as the dispersion of forecast error is reduced. Seasonal streamflow forecasts give rise in theory to conditional probability distributions of observing various quantities of seasonal water supply. Hypothetical conditional probabilities are computed using Bayes' formula. Increase in accuracy is measured by using calculations of the conditional entropy of the probability distributions derived from the Bayes formulation.

The probabilistic linear programming model serves to allocate a region's crop acreages, so as to maximize the expected income of planting associated with each forecast. Output includes expected income for each forecast and crop acreages planted based on each forecast.

Results from testing the model indicate gross benefits ranging from a few cents per acre up to as much as $6.00 per acre. As would be expected, the results exhibit diminishing returns to successive increments of increased forecast accuracy.

The second study analyzes the effect that more accurate forecasting would have on the efficiency of multiple purpose water reservoirs. These already are generally operated on the basis of forecasts of future hydrologic events.

The study investigates the causal relationship between errors in streamflow and water supply forecasts and any resulting inefficient reservoir operation. The causality is determined by examining first, the types of forecast errors which may arise, second, the states of nature necessary for the forecast error to result in an improper operating decision, third, the states of nature required for an economic loss to occur. The forecast errors may be positive or negative and each type of error may cause losses from the flood control and irrigation operations.

To estimate the benefit of avoiding these inefficiencies through improvements in streamflow forecasting, a computer simulation model is developed. The model represents a first attempt to combine a hydrologic forecasting routine capable of generating forecasts of varying degrees of accuracy with a reservoir operation model reflecting the objectives of the operator and the constituents of the water service area, and the social and political constraints imposed by the real world. These include a Congressional guideline that minimization of flood losses represents the overriding objective of the operation.

The model allocates joint-use storage space in the reservoir on the basis of a Flood Control Reservation Diagram and daily forecasts of remaining season runoff and daily streamflow over the next thirty day period. To prevent wildly fluctuating release patterns, which are unacceptable on a real river, feedback and smoothing functions are included in the operations package. The operations model is based on the Palisades-Jackson Reservoir complex on the Snake River in Idaho and Wyoming.

The results of the estimating procedure indicate that significant benefits may be derived from improved seasonal water supply forecasts if the economic values in the water service area are significant. Although the tests performed in this study indicate the presence of benefits utilizing the present reservoir operating scheme, it is apparent that additional major benefits of forecasting improvements are likely to arise in situations where the operating procedures of existing reservoirs are revised by reducing flood storage requirements in line with reductions in likely forecast errors. These revisions would be equally beneficial for the design and lay-out of newly planned reservoirs.

LIST OF RECOMMENDATIONS

The study proves that significant economic benefits could be obtained from improvements in streamflow forecasts for many types of water uses. However, because of the present difficulties to predict streamflow in those regions and river basins of the country in which flow is largely a consequence of rainfall events, efforts on improving streamflow forecasting techniques should be concentrated in those basins in which snow melt provides the major source of seasonal run-off.

Irrigated surface run-off-dependent agriculture appears to be one of the major potential beneficiaries of improved forecast accuracy. For this group of beneficiaries the most critical part of the forecast is that provided prior to planting time. A highly reliable forecast at that time would allow irrigators to chose between more or less water-sensitive crops to be planted. If such an improved forecasting system were to be geared to a seasonal water storage system which could regulate the projected total seasonal run-off, water utilization would reach optimal levels.

Multi-purpose reservoir operations could benefit from improved forecasting techniques as well. As forecast accuracy improves better evaluations of potential flood encroachments become possible with the result that on average, reservoir levels at the end of the spring-run-off period will be higher than they otherwise would be. This would increase the average quantity of useable water and, hence, the utility of these reservoirs for all water use categories dependent on reservoir water supply. It would also reduce the need for additional reservoir construction in order to satisfy growing demands.

A major obstacle in the way of economically optimal reservoir operations, given improved forecast accuracy, is the Congressionally determined operating procedure which mandates absolute priority to flood protection as an operational goal for multi-purpose reservoirs. If this institutional restriction could be removed, much higher operating efficiencies (in terms of economic gains from additional supply minus possible losses from flooding) could be achieved.

If serious efforts are to be made to improve forecast accuracies, farmers and other potential beneficiaries should be informed about the potential benefits that they may derive from basing their planting strategies on these forecasts. The model developed in Section II of this report could be used to develop more specific analytical models for each of the irrigation districts in the Western United States, while the simulation reservoir operating model could be adapted to bring about more efficient water management techniques for already existing or newly developed reservoir sites.

LIST OF PUBLICATIONS RESULTING FROM THIS PROJECT UNTIL PUBLICATION TIME

John L. Moore, Methodology for Estimating the Benefits to Irrigated Agriculture from Increased Accuracy in Seasonal Streamflow Forecasts, doctoral dissertation, The University of Michigan, Ann Arbor, Michigan, 1972.

Robert W. Fenton, A Methodology for Estimating Reservoir Operations Efficiency Benefits from Snowmelt Forecasting Improvements, doctoral dissertation, The University of Michigan, Ann Arbor, Michigan, 1972.

John L. Moore, "Estimating Benefits to Improved Seasonal Water Supply Forecasts: A Case Study of Irrigation Benefits", *Proceedings of the International Symposium on Uncertainties in Hydrologic and Water Resource Systems*, Vol. II, University of Arizona, Tucson, Arizona, Dec. 11-14, 1972, pp. 610-628.

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PREFACE

Research on this project was initiated by Professors Ayers Brinser (Principal Investigator) and Charles Cooper of the School of Natural Resources in 1967. Owing to the untimely death of Professor Brinser in September, 1967 the project remained dormant until the Fall of 1969 when Professor Gunter Schramm assumed responsibility for it.

A primary purpose of a research project of this nature is to explore the potentials for more efficient utilization of water resources. Growing demands for their consumptive and non-consumptive use, coupled with the increasing real cost of large-scale structural measures, have increased the feasibility of some alternate methods for securing benefits from existing distributions and timing of water supplies. Alternatives such as legal changes promote more flexible exchange of the rights to use water. Other changes may involve more effective and coordinated management through closer adaptation to natural or existing conditions. Increased accuracy in the forecasts of water supply may serve as one means by which water users can adapt their expanding operations more closely to variable conditions while still maintaining economically viable enterprises.

Research on this project proceeded in three stages. The first one was concerned with the identification of all of those water uses that appear to have the potential for obtaining some net gains from better knowledge of future streamflow conditions in the short, medium or long run. It became apparent that many of them would benefit little, if at all from such improved forecasts unless their accuracy would approach the certainty equivalent. This is so because in many uses the value of water (or the costs of assuring absolute safe supply by physical means) is rather low relative to the value of output that would be lost if water supply should fail. On the other hand, there are other activities, such as reservoir operations, irrigation and power production, that could benefit substantially even from a partial and limited improvement in forecast accuracy as long as the average gains from relying on these forecasts outweight the potential losses that could occur if they turn out to be wrong.

The second stage of the research addressed itself to a review of the present and likely future "state of the art" of streamflow forecast accuracy. While it was found that many promising avenues have been opened up in recent years, ranging from improved snow pack evaluations, partial weather and precipitation control by cloud seeding to world-wide modelling of long-range temperature, weather and precipitation patterns (helped substantially by new techniques of aerial photography, satellite observations, etc.) the major, and most promising, relatively low-cost improvements were found to be related to efforts to improve the accuracy of snow-melt run-off patterns.

Snowmelt provides the major portion of total streamflow of Western river systems. But it is in the West where water availability relative to people and economic activity is lowest, and, hence its relative value is highest given this substantial potential for forecast improvements on the one hand and the need for high efficiency use of existing, limited water supplies on the other, it is clear that the potential for benefiting from forecast improvements is substantially higher in the West than anywhere else in the nation.

It was therefore decided to concentrate all of the more detailed research efforts of this project on the evaluation of the potential benefits from improvements in streamflow forecast accuracy in those river basins that obtain their major supply from seasonal snowmelt. These efforts represent the third and most extensive stage of the overall research.

The overall report has been divided into three sections. The first provides a general overview of the issues involved and discusses in detail the technical problems related to dealing with uncertainty in economic analysis as well as the physical-hydrological characteristics of streamflow behavior. A final chapter in this section provides a conceptual analysis of the potential benefits from forecast improvements for flood protection measures.

The second section develops a detailed linear programming model of the nature and magnitude of the potential economic benefits which could accrue to irrigated agriculture from increased accuracy of streamflow forecasts. As the findings show, these benefits could be substantial.

In the third section a simulation model is being developed that assesses the potential for improved reservoir operating strategies in situations where alternative reservoir uses are competitive with each other (i.e., flood protection, which calls for empty storage space, and irrigation, power production and others, which derive benefits from full reservoirs). As is shown, improvements in forecasts could lead to more economically optimal operating strategies, particularly if some Congressionally prescribed institutional restrictions on operating procedures could be removed.

Section I is based on the contribution of all participating researchers. Mr. David Hughart developed the conceptual flood protection evaluation model in Chapter IV. Section II represents the research efforts of Dr. L. Moore and is based on his doctoral dissertation while Section III was developed by Dr. R. Fenton also as part of his dissertation. Mr. George Moore provided substantial and valuable assistance in the design of the simulation used in this section.

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SECTION I

SCOPE OF PROBLEM AND METHODOLOGY

CHAPTER I

INTRODUCTION AND OVERVIEW: THE PROBLEM SETTING

One of the most common and usually implicit assumptions made in the application of economic theory to practical problems is that of perfect knowledge. This assumption is generally acceptable when there are many events, none of which is large relative to the others, and when the assumed state of perfect knowledge is equivalent to the mean outcome of the sum of these events. In the field of natural resource economics, however, this assumption frequently does considerable violence to reality. The reasons for assuming perfect knowledge are many and include lack of knowledge of the natural relationships that determine the true states of nature; technical change and the dynamic factors that enter when long time spans are involved; effects of price fluctuations due to the inelastic nature of demand and supply; the effect of difficult-to-predict events such as weather; and the general effects politics, laws, and institutions have on the economic aspects of any real world problem. In economic theory, these types of considerations are dealt with under the heading of "decision-making under uncertainty" or simply decision theory.

In the field of surface water management, lack of perfect knowledge of the available supply sometime in the future is one of the fundamental facts of life. This matters little, of course, when supply, even at its lowest possible level, is greater than potential demand at its highest, or when supply, at its highest level, does not cause damages through flooding, excessive erosion or similar consequences. Unfortunately, situations in which these conditions hold are diminishing more and more, owing to the ever increasing demand for water in the face of an essentially static, albeit stochastically variable supply on the one hand and the increasing developmental pressure on floodprone lands on the other.

This clearly is apparent from the data in Table I which show the average low-flow and projected consumptive use in 1980 as a percentage of the mean annual runoff for each of the major U.S. river basins. As can be seen from the table, projected consumptive use is likely to exceed available low-flow runoff in at least five of the 17 basins while in two others it closely approaches the available minimum supply.[1]

TABLE 1

RELATIONSHIPS BETWEEN LOW FLOW AND PROJECTED CONSUMPTIVE USE, 17 U. S. RIVER BASINS

BASIN	LOW FLOW AS A PERCENT OF AVERAGE FLOW	1980 PROJECTED CONSUMPTIVE USE AS A PERCENT OF AVERAGE FLOW	BASINS IN WHICH 1980 CONSUMPTIVE USE WILL EXCEED** OR APPROACH* LOW FLOW	TOTAL AVERAGES FLOW
North Atlantic	68	4	-	163×10^9 gal/day
Great Lakes	67	6	-	63.2
Columbia - N. Pacific	64	6	-	210
South Atlantic - Gulf	59	4	-	197
Tennessee	58	3	-	41.5
Upper Colorado	55	86	**	13.45
Ohio	54	3	-	125
Lower Mississippi	50	3	-	48.4
Missouri	44	36	*	54.1
Upper Mississippi	43	3	-	64.6
Rio Grande	42	92	**	4.9
Great Basin	41	52	**	5.89
California	39	45	**	65.1
Arkansas-White-Red	34	11	-	95.8
Souris-Red-Rainy	30	5	-	6.17
Texas-Gulf	28	25	*	39.1
Lower Colorado	26	87	**	3.19

Source: U.S. Water Resources Council, The Nation's Water Resources, Washington, 1968 Columns (1) and (2) are approximations taken from graphs on pages 1-5 and 1-30, 31. Column (4) is from page 7-3-1. "Average Flow" is mean natural runoff not including runoff from other basins, Canada, or Mexico. "Low Flow" is the flow exceeded 19 years out of 20.

What can also be seen from Table 1 is that the potential threat of water shortages is most pronounced in the western and particularly south western regions of the country. Nevertheless, both short-run and long-run unpredicted variations in streamflow have had serious consequences even in those regions where streamflow relative to consumption appears to be more than adequate. For example, the well known drought of 1961 to 1966 in the normally quite humid Northeast led to significant economic dislocations[2] while flood losses both in dry and humid regions have been increasing steadily, despite the continuing and costly structual flood protection measures undertaken by the Corps of Engineers.

A priori, then, it appears reasonable to assume that in many situations significant improvement in the accuracy of future streamflow conditions could lead to managerial, behavioral or even structural changes that would increase net gains or reduce net losses compared to situations in which such better knowledge is lacking.

Alternatives to Meet Growing Demand

While the precise estimates of growth in the magnitude of demand for water consumption and withdrawals is a subject of professional and political disagreement, the general trend is apparent. Alternatives for meeting these demands also can be specified. Alternatives that presently or potentially are available for securing incremental benefits involve combinations of engineering-structural measures and application of management techniques such as weather modification, legal changes designed to promote transfer of water among uses, implementation of schemes for greater coordination between surface and ground water use, waste water reclamation and improvements in forecasts of weather and seasonal water supply. The two categories of alternatives are discussed below.

Engineering-Structural Measures

Historically, along with the development of ground water resources, federally supported reservoirs and trans-basin diversion projects have been an important means by which benefits to water users have been procured. These structures have served to increase the certainty of adequate water supply for a variety of uses, including power generation, irrigation, municipal and industrial water supply, recreation, and transport of urban and industrial wastes. Structural measures serve to reduce the uncertainty of water availability by giving the user physical control over a portion of his water supply both in terms of location and timing of use. As the better reservoir sites have been developed, however, the incremental costs associated with additional reservoirs have risen relative to the increment of benefits provided. Likewise, the non-market opportunity costs in terms of recreation, aesthetics, and environmental considerations associated with reservoir sites have risen. Without touching the issue of regional subsidies to water development which has resulted from past national water development policy, it is important to explore to what extent improved water management techniques in conjunction with existing structures may provide lower cost alternatives for securing some of the benefits desired by water users.

Management Alternatives

As competing demands for the limited quantities and temporal distributions of water grow, adjustments in utilization patterns which would result in greater efficiency in use will often require shifts away from the lower value water uses particularly those represented by some forms of irrigated agriculture. The economic rationale and pressures for some transfers away from irrigated agriculture, which uses about 90 per cent of all water in western states, are underlined in a number of studies of the arid and semi-arid West[3,4,5] For example, the estimated differences in the value of the marginal product of water among various uses as shown below in Table 2 indicate that continued economic growth is not necessarily dependent on securing new sources of supply but could be achieved by a transfer of water from low value to higher value uses.

While the potential gains from transfer of some water to higher value uses serves to refute the argument that water supply is a binding constraint on continued economic growth particularly in the semi-arid western states, institutional constraints often make implementation of such transfers difficult if not impossible. These institutions evolved with the early settlement of the West as it became apparent that the riparian rights doctrine was inadequate for arid conditions. In order

TABLE 2

PERSONAL INCOME PER ACRE-FOOT OF WATER INTAKE IN ARIZONA, 1958[a]

Sector	Dollars in Personal Income per Acre-foot[b]	Sector Rank
Food and Feed Grains	14	10
Forage Crops	18	9
High Value Intensive Crops[c]	80	8
Livestock and Poultry	1,953	6
Agricultural Processing Industries	15,332	3
Utilities	2,886	5
Mining	3,248	4
Primary Metals	1,685	7
Manufacturing	82,301	1
Trade, Transportation and Services	60,761	2

[a] Source: National Research Council, Committee on Water, Water and Choice in the Colorado Basin: An Example of Alternatives in Water Management (Washington, D. C.: National Academy of Sciences, 1968). Adapted from H. G. Tijoriwala et al., The Structure of the Arizona Economy, Technical Bulletins 180 and 181, Arizona Agricultural Experiment Station, 1967.

[b] Personal income is defined to include wages, salaries, rents, profits, and interest.

[c] Includes cotton, vegetables, citrus, and other fruits.

to assure an adequate supply, it became necessary to establish a right to water based on prior and beneficial use.[6] The doctrine of prior appropriation grew out of these needs and is based on the premise that water rights are determined by priority of use and that beneficial use creates the right.[7] Unfortunately, the doctrine of prior appropriation oftentimes has the effect of protecting low value uses of water in the face of rising and unsatisfied higher value uses. As Hirshleifer et al. state:[8]

> Although suited in principle to permit transfer of rights, the doctrine of appropriation as presently interpreted or adapted is ordinarily associated with a number of limitations that interfere with sale or exchange and thus introduce undesirable rigidity of water use. A few states even prohibit the transfer of water from the land and the use for which it was originally appropriated.

The specific rigidities that result from the present interpretation and application of the doctrine of prior appropriation vary among states and are too detailed to be discussed here. Hirshliefer et al. provide a review of some of these details.[9] Hartman and Seastone also provide a detailed presentation of the issues and alternatives involved in developing more effective institutions for the transfer of water between uses.[10]

In general, development of mechanisms and alteration in the provisions associated with water rights which increase the transferability of water will serve to improve the working of the market mechanism. This in turn would promote greater efficiencies in use. Also there is need in some states to achieve greater coordination in the legal provisions governing situations in which surface and ground water are measurably interdependent. There is considerable evidence to suggest that such changes along with efforts to develop workable institutions for seasonal or longer duration transfer of either the use of water or the water right itself are likely to increase the overall marginal value product of water[11,12,13] and thus help to alleviate problems which presently exist.

Augmenting Supply by Other Means

Weather modification, desalination, reduction of evaporation and transpiration on watershed source areas, schemes to increase the holding of snow in specific areas, and use of ground water for cyclic storage are potential alternatives with varying degrees of feasibility. Each of these may serve to augment usable supplies in a given basin or over broader areas, though the total effect will only involve a redistribution of water from one geographic area or point in time to another. Though potentials exist, most of these alternatives are of an experimental nature or involve unit costs that would likely exceed marginal value in most present uses. Cyclic storage combining artificial or natural recharge of ground water aquifers and pumping is practiced in some areas of the West and may be a feasible alternative to reservoir construction in some cases. Likewise, reduction in transpiration by removal of some phreatophyte growths (plants whose roots extend to the water table) along river bottoms may be another low cost means of augmenting supplies.

Improving Information

In many cases, benefits would be realized through partial adjustments in operations to fit seasonal water supplies rather than achieving almost total dependability of water supplies through measures with very high marginal costs. For example, the ultimate ability to predict long range weather in terms of precipitation amounts and locations would be of great potential value in allowing decision-makers adequate time to adjust their plans so as to reduce losses or capture potential benefits. Such long range forecasts are not yet feasible and may not be for many years, if ever.

On the other hand, in basins where a large portion of water supply comes from melting snow, forecasts of water supply are presently made based on recorded relationships between snow depth, soil moisture, and other factors, and the volume of runoff observed during the warm season (usually May through September). Although the extent to which these forecasts can be improved is difficult to define precisely, application of technologies involving automatic data collecting devices, radio relay of information, satellite coverage, and improved modelling and data assessment capabilities through modern computers hold promises for increases in forecast accuracy. The benefits that would accrue from implementation of these potentials would be of immediate interest.

Thus, better management techniques, among them the utilization of information from improved streamflow forecasting capability, become genuine substitutes for oftentimes costly engineering solutions to problems of water shortages.

Potential Benefits From Improvements in Forecast Accuracy: An Overview

While the focus of this study is directed towards the evaluation of benefits from seasonal, rather than very short-run or multi-year improvements in the accuracy of streamflow forecasts it is useful to look briefly at the whole range of potential benefits that might arise throughout the spectrum of forecasts from the very short run, i.e., hours, days, weeks, to the very long run i.e., multi-seasonal forecasts for several years into the future. The key requisite for capturing any type of benefit from improved forecast accuracy is, of course, that the behavior of the beneficiary group can be sufficiently altered to obtain the potential benefit. For example, the knowledge of higher than average streamflows in the future is of little use to a run-of-the-river hydro-electric powerplant without free available storage capacity or excess generating capacity that could be used to utilize the additional flow.

Table 3 lists some of the major water use categories and their potential for benefiting from improvements in streamflow forecast accuracy in the short, medium (seasonal) and long (multi-seasonal) run.

Domestic, urban and industrial water users are unlikely to benefit from improvements in short-run forecast accuracy, unless their existing storage reservoirs are almost empty, in which case they could relax existing rationing measures. They also are not likely to gain much if the seasonal or multi-seasonal outlook is for a higher than average supply. On the other hand, if the longer-term outlook is for a lower than average supply, appropriate measures taken to reduce low-value demand immediately may have a significant pay-off in the future, since shortages then will be less severe. This, of course, assumes that available reserves may be insufficient in the face of a longer-term drought.

For irrigation, knowledge of higher or lower streamflows in the immediate, short-run future would have only limited value. In the case of greater than average flows, more water could be released now. However, this additional water would presumably have little marginal value

TABLE 3

POTENTIAL BENEFITS BY USE CATEGORIES FROM IMPROVED STREAMFLOW FORECASTS IN THE SHORT, MEDIUM AND LONG RUN

USE CATEGORY	Potential Benefits		
	SHORT RUN Days to weeks	SEASONAL	MULTI-SEASONAL
DOMESTIC, URBAN & INDUSTRIAL WATER SUPPLY	NO	YES	YES
IRRIGATION	SOME	YES	SOME
HYDRO-ELECTRIC POWER	SOME	YES	YES
COOLING FOR THERMAL POWER STATIONS	NO	NO	NO
WATER QUALITY MANAGEMENT	SOME	SOME	NO
NAVIGATION	SOME	SOME	SOME
RECREATION	YES	YES	YES
FLOOD CONTROL AND PROTECTION	YES	YES	SOME

if the irrigation system is designed to supply sufficient water at average flow conditions. It would probably be more sensible to retain the additional flow in storage if it is available; however, in this case (i.e., with available storage capacity) fore-knowledge of higher flows does not by itself provide any benefits. Benefits might be somewhat greater than marginal, however, in areas where average water availability is low relative to irrigation use, where additional storage is lacking and where application of additional water to a growing crop might increase growth significantly. Such situations are likely to be rare, however.[14] In the opposite case, i.e., when forecasts call for lower than average flows in the short-run, immediate water use restrictions may prove to be beneficial, provided that the available storage capacity in the system is quite low so that the projected low-flows may lead to total depletion in the short-run if current water use is maintained. Such situations also are likely to be uncommon, however. Far greater benefits could be expected from a more accurate knowledge of seasonal streamflows, particularly if this knowledge is available prior to planting time. Since this is the subject of Section II of this report, this important case will not be discussed here. Finally, accurate fore-knowledge of multi-season streamflow patterns may have some benefit to those irrigation farmers who have limited or unsecure water rights, by allowing them to make appropriate longer-term investment decisions for machinery, processing or similar facilities that are crop specific. This assumes, of course, that these crops have different water requirements, and that higher value, higher water using crops would be planted if long-term water forecasts are favorable.

For hydro-electric power systems knowledge of short-run streamflow variations have only limited value. Generating patterns are generally determined by demand; unless flood protection objectives interfere (this important case is the subject of the analysis in Section III of this report), streamflow will be either used for generation, will be stored for future use or spilled, if no further storage capacity is available.

Only in mixed systems with significant thermal power components could the knowledge of short-run excess flows result in the reduction of thermal generation, provided unused hydro generating capacity is available in the system. However, the same operating decision would be made on a day to day basis (i.e., without secure fore-knowledge of short-run future flows), unless the storage capacity of the system is close to exhaustion. Again, in the latter case, the operating decision with or without knowledge of short-run future flows would probably be to refill the reservoirs first, hence no major benefit from the improvement in forecast accuracy would be derived. On a seasonal or multi-seasonal basis, however, benefits from improved knowledge of future streamflows could be substantial, provided the accuracy of these forecasts would be relatively high, or sufficient stand-by capacity is available to the system. For an all-hydro system without the latter and without interconnections to other systems (such systems no longer exist in the United States, although they are not uncommon in Canada or elsewhere), greater accuracy of seasonal or multi-seasonal forecasts would be of limited value, short of almost complete certainty with respect to their accuracy. This is so because the cost of electricity, relative to the value of output it helps to produce, is rather low. In most industries, for example, the cost of electricity amounts to less than two percent of the value of output.[15] Hence, the overall costs of failure of supplying electricity to the utility's customer as a result of an erroneous streamflow forecast would be exceedingly high. In such a system without stand-by supplies, therefore, total reliability of supply even under the most adverse conditions would have almost always priority over potential reductions in average generating costs, which would represent the benefit from using improved, but not wholly certain streamflow forecasts. However, a utility system which has at its disposal alternative sources of supply that could be utilized if streamflow forecasts turn out to be wrong (i.e., too high) overall generating costs could be minimized by making use of the improved streamflow forecasts as long as the average probability of failure (i.e., forecast too high) is approximately known; the penalty of an over-optimistic forecast than would simply be the probability of having relied on a forecast that was too high times the resulting shortage in energy production from the hydro system times the additional costs incurred from having to utilize alternative, higher-cost generating or supply sources in the amount of the shortage. This penalty can then be compared with the cost saving resulting from relying on the expected value of the streamflow forecast, rather than on the usual much more conservative criteria used.[16] If, on the other hand, the forecasts turn out to be too low, the value of the additional, unexpected streamflow might be low or non-existent, unless the system, at the time of the excess flow, has unused storage capacity available, or has excess hydraulic generating capacity that could be utilized as a substitute for higher-cost thermal capacity in the overall power system.

Little benefits can be expected from improvements in forecasts for thermal power station cooling water requirements. These plants have to be designed (whether they are based on once-through cooling systems or cooling towers that require only make-up water) to supply the required cooling capacity even under the most adverse conditions. Hence, while residual streamflow or water temperature below the plant's intake might vary, depending on streamflow conditions, operating characteristics of the power plant are not likely to vary as a result of improved forecasts. The exception might be when water flows, and hence temperature, could be regulated through upstream storage. In such a case reliable forecasts of below average streamflows in the future might result in lower water releases now (at the expense of higher water temperature in the river) in order to avoid even worse conditions in the future. However, the beneficiary from such a strategy would not be the powerplant as such (unless the predicted future low-flow would require curtailment of power production or shut-down of the plant, but the users or beneficiaries of the river water downstream who would be adversely affected by the thermal pollution effects of higher water temperatures.

Water quality management objectives might, under some specific circumstances, benefit both from improved streamflow forecasts in the short-run and on a seasonal basis. Little, if any gains could be expected on a multi-seasonal basis, however, unless such forecasts led to deliberate changes in the construction and installation of pollution abatement facilities. This is not very likely to be the case. In order to benefit from increased streamflow forecast accuracy even in the short-run or over a flow-season, however, it would be necessary that these forecasts could be used to reallocate the waste assimilative capacity of the respective water course. If this were possible, either because of the existence of retention lagoons for waste waters or storage facilities on the stream itself, then improved streamflow forecasts could provide a basis for upgrading the average water quality of a stream over time. For example, if forecasts were to call for an above average flow in the future, higher water releases of reservoir water could be made now. This would improve the assimilative capacity relative to existing waste water discharges and, hence, increase present water quality. Alternatively, waste water discharges from retention basins could be reduced now because higher streamflows than normal are predicted for the future. This would have the same effect. If, on the other hand, the forecast were to predict lower than an average flow in the future, the opposite strategies would be called for, i.e., relatively lower reservoir and/or higher waste water releases now than normal. While this would decrease present water quality, it would lead to a relatively higher water quality in the future when normal streamflow is below average. Given the highly non-linear relationships between streamflow and assimilative capacity[17], such a strategy could well prevent in some cases such highly undesirable and frequently costly effects as total oxygen depletion with its attendent anaerobic conditions, fish kills, etc.

Higher forecast accuracy might have some benefits to navitation interests in the short, the medium as well as the long-run. Generally these benefits would be limited to situations in which streamflow is projected to be lower than average so that available channel depth would restrict the loading capacity of ships. Forecasts of higher than normal streamflows would be of benefit only if they indicate flood conditions dangerous to shipping. Almost all the benefits in the very short, medium or long-run from the knowledge of lower than average streamflows would be related to scheduling of ship movements, forecasts of load capacity etc. For the iron are shipments from Labrador to the Great Lakes, for example, fore-knowledge of low-water conditions could lead to more intensive shipping schedules to make up for the anticipated reduced load capacity, greater stockpiling of ore at smelters, etc. In the multi-season forecasting case, changes (intensification) of dredging operations could be another strategy that would help to reduce expected losses resulting from projected low water levels.

Recreation interests are likely to benefit from improved streamflow forecasts throughout the spectrum from the very short to the very long-run. Reservoir operations could be altered to reduce fluctuations in water levels; forecasts of flow conditions would be of immediate benefits to fishermen, canoeists and other users, and long-run forecasts of either above or below average water levels (as for example on the Great Lakes) would enable operators of docks, moving facilities, boat launches and beach facilities to better adopt their service facilities to the expected long-run water levels.

For the purposes of flood control improvements in the short-run as well as seasonal forecasts would be of rather significant benefit provided the accuracy of these forecasts is sufficiently high so that the costs incurred in preparing preventive measures (which are certain) are lower than the probability of a forecast flood times the damages that will be incurred from such a flood in the absence of these preventive measure. Both lead-time and forecast accuracy would be important variables for the size of the benefits that may result from forecast improvements. These issues are being discussed in a more formal and rigorous fashion in Chapter IV of this report. Long-run, i.e., multi-season forecasts, are likely to have only limited value for flood protection measures, unless, of course, they lead to an acceleration of structural measures (construction of flood protection facilities) or to a change in flood-plain management techniques for areas (zoning, avoidance of further development of flood-threatened areas, etc.)

What can be said in general, then, is that many of the major water use categories could likely benefit from improved streamflow forecasts. However, for a significant number of them such benefits would become significant only when forecast accuracy becomes very high. Given presently known forecasting techniques such a high level of accuracy is not likely to be available for forecasts dealing either with the short or the very long run, particularly in those areas where streamflow depends largely on rainfall events. However, in areas where streamflow is predominantly determined by runoff from accumulated snow-parks, the prospects for substantive improvements in forecast accuracy at rather reasonable costs are high. At the same time, benefits from such seasonal forecast improvements could also be high as the subsequent discussions will show.

FOOTNOTES

[1] These data are based on natural run-off only, i.e. they do not show the stream flow and supply modifications available through reservoir storage or groundwater utilization.

[2] Clifford S. Russell, David G. Arey, and Robert W. Kates, Drought and Water Supply, (Baltimore, Johns-Hopkins, 1970).

[3] Maurice M. Kelson, William E. Martin, Lawrence E. Mack, Water Supplies and Economic Growth in an Arid Environment, The University fo Arizona Press, Tucson, 1976.

[4] The Value of Water in Alternative Uses, A Study conducted by a special committee under the direction of Nathanial Wollman (Albuquerque, N. M.: The University of New Mexico Press, 1962).

[5] National Research Council, Committee on Water, Water and Choice in the Colorado Basin: An Example of Alternatives in Water Management: A Report (Washington, D. C.: National Academy of Sciences, 1968).

[6] Orson W. Israelsen and Vaughn E. Hansen, Irrigation Principles and Practices (2nd ed.; New York: John Wiley and Sons, Inc., 1967), p. 379.

[7] Ibid., p. 330.

[8] Jack Hirshleifer, James C. DeHaven, and Jerome W. Milliman, Water Supply: Economics, Technology, and Policy (Chicago: The University of Chicago Press, 1960), p. 239, and U. S. Department of Agriculture, Selected Problems in the Law of Water Rights in the West, by Wells A. Hutchins, Miscellaneous Publication 418 (Washington, D. C., 1942), pp. 379 ff.

[9] Ibid., Hirshleifer et al., Water Supply, pp. 236-242.

[10] Loyal M. Hartman and Don Seastone, Water Transfers: Economic Efficiency and Alternative Institutions (Baltimore and London: The Johns Hopkins Press, 1970).

[11] Loyal M. Hartman and Raymond L. Anderson, "Estimating the Value of Irrigation Water from Farm Sales Data in Northeastern Colorado," Journal of Farm Economics, XLIV (February, 1962), pp. 207-13.

[12] Raymond L. Anderson, "The Irrigation Water Rental Market: A Case Study," Agricultural Economics Research, XIII No. 2 (1961), pp. 54-58.

[13] Robert A. Young and William E. Martin, "The Economics of Arizona's Water Problem," The Arizona Review, XVI, No. 3 (1967), pp. 9-18.

[14] See also Section III of this report.

[15] See Gunter Schramm, "The Effects of low-cost hydro power on Industrial Location," Canadian Journal of Economics, Vol. II, No. 2, May, 1969.

[16] For example Manitoba Hydro, the provincially-owned utility supplying the province of Manitoba in Canada, an almost-all hydro system, defines as firm (i.e., reliable) anual energy supply the energy equivalent of the three minimum streamflow years on record plus the existing available water storage capacity of the system, divided by three. This means, of course, that much of the storage capacity is rarely ever used.

[17] Allen V. Kneese and Blair T. Bower, Managing Water Quality: Economics, Technology, Institutions, (Baltimore, Johns-Hopkins, 1968), Chapter 4.

CHAPTER II

CONCEPTUAL EVALUATION OF BENEFITS FROM IMPROVED FORECASTS

As a first step in presenting the methodology for evaluating benefits from increased accuracy, a brief review of several techniques for conceptual treatment of decision-making under uncertainty is presented.[1,2,3]

Decision Theory

In its simplest formulation, decision theory involves situations in which the individual or organization is confronted with a series of alternative possible courses of action (strategies) and a set of data on the laws of randomness or the "states of nature."[4] In the complete ignorance case, the decision-maker has no idea as to the likelihood of occurrence of the various states of nature. However, he generally has two other sets of information on which to base his decision. These are (1) an evaluation of the consequences or payoff (or loss) from nature being in each of its possible states, and (2) some estimation of the desirability of each possible outcome of the situation.[5] In the case of less than complete ignorance, the decision-maker may have some idea of the relative frequencies of the occurrence of the various states of nature on which to base his decision. Further, he may perform an experiment so as to be in a position to better judge the probabilities of occurrence. The irrigator's use of streamflow forecasts corresponds to this latter case.

Whether the decision-maker has knowledge of the likelihood of occurrence of the various states of nature or not, he consciously or unconsciously relies on some form of rule in the process of reaching a decision. Because personal financial situations differ among individuals and different people have different attitudes toward taking chances, there can be no generally valid rule for telling the decision-maker how to choose among the strategies open to him.[6] Accordingly, the literature on decision theory deals with several proposed decision criteria.

Proposed criteria in the case of complete ignorance such as minimizing the expected loss (maximin criterion), minimizing the expected regret (minimax risk), Bayes strategies, and certainty equivalents are among some of the more widely known proposed rules for decision-making in the case of complete ignorance as to the likelihood of occurrence of the "states of nature."[7] A brief description and discussion of these four cases is presented below.

Maximin Criterion

In this criterion, each strategy is evaluated by the minimum return that would result should the most adverse state of nature occur. The strategy with the highest minimum return is then selected as the optimal one. For example, if three different strategies resulted in the payoffs listed in Table 4 for each of three states of nature, it can be seen, based on this criterion, that strategy 2 would be the optimal one.

TABLE 4

PAYOFF MATRIX

	States of Nature		
Strategies	A	B	C
1	30	16	0
2	20	10	8
3	35	9	1

This approach suffers from at least one obvious defect. It is extremely conservative, since it pays no attention to the possibility of returns in any state of nature except for the most adverse ones for that decision.[8] If state of nature C is very rare, then the maximin criterion is not very appealing. A closely related criterion proposed by Baumol called maximax would involve choosing the strategy with the highest single payoff which would result in the selection of strategy 3. This criterion suffers from the same defects as the maximin approach.

Minimax-Risk Principle

The general idea behind this approach involves calculation of the opportunity cost of an incorrect decision.[9] To do this one must construct a second matrix based on the first one. Looking first at state of nature A and strategy 1 the maximum regret is 5 (35-30). For state of nature B it is 0 and for state of nature C it is 8. The other calculations are shown below in Table 5.

TABLE 5

REGRET MATRIX

	States of Nature		
Strategies	A	B	C
1	5	0	*8
2	15*	6	0
3	0	*7	7

The criterion upon which to base the selection of strategies now calls for applying a minimax rule to the regret matrix. The maximum regret element in each row is noted and the strategy which contains the lowest maximum regret element is selected[10] (in this case strategy 3). As with the other criteria, the minimax-risk principle suffers from the defect that only the largest regret figure in each row is considered, ignoring all of the other data that may be available to the decision maker.

Bayes or Laplace Criterion

Since no information at all is available on the likelihood of occurrence of the various states of nature, in this case equal probabilities are assigned to each possible outcome and the strategy with the highest expected payoff is chosen.[11] Let us assume that there are three possible states of nature and three strategies that can be followed. The assumed payoffs are shown in Table 6. Application of the Bayes criterion would call for choosing strategy 1 since the expected payoff under equiprobable occurrence of the three states of nature A, B, and C is greatest.

TABLE 6

EXPECTED PAYOFF WITH EQUIPROBABLE OCCURRENCE

	States of Nature			
Strategies	A	B	C	Expected Payoff
1	30	16	0	15.3
2	20	10	8	12.6
3	35	9	1	15

As Baumol points out, this criterion suffers from a serious limitation, since it is not clear in advance what unknown occurrences are to be considered equally probable.[12] For example, the relevant choice in the above simple example might be between B and C. Since no advance information is available, it is plausible to argue that these two possibilities are equally likely and should be assigned equal probabilities. Upon doing this it is easy to see strategy 2 now becomes the optimal one with an expected value of 9.

Certainty Equivalents

The basic principle here is that for every uncertain outcome that the decision-maker faces there is a certain one to which he is indifferent. Referring to Table 4, one could imagine a situation where the decision-maker faced with alternative one would prefer a certain outcome to zero return. On the other hand, he would prefer a guaranteed return of 30 to the uncertain situation. Between the two extremes there must be some guaranteed return with which he would be just as satisfied as with the risky situation. The criterion for selection among strategies then involves choosing that strategy which has the highest certainty equivalent. However, as Dorfman points out, this procedure really comes right back to the basic issue. The decision-maker is still without a rational criterion, since there is no consistent mechanism for establishing the certainty equivalent.

Proposed Criteria in the Case Where Historical Knowledge Exists

There are other criteria for dealing with the conceptual problems of decision-making where there is knowledge as to the frequency of occurrences of the states of nature. These include gamblers indifference maps and risk discounting as discussed by Dorfman. These concepts will be touched on briefly here based on Dorfman's presentation.[13]

Gambler's Indifference Map

In this conceptual treatment of the decision problem, it is assumed that the only items of importance to the decision-maker are the expected value and standard deviation of the probability distribution for any given strategy.* This is represented graphically as shown below in figure 1.

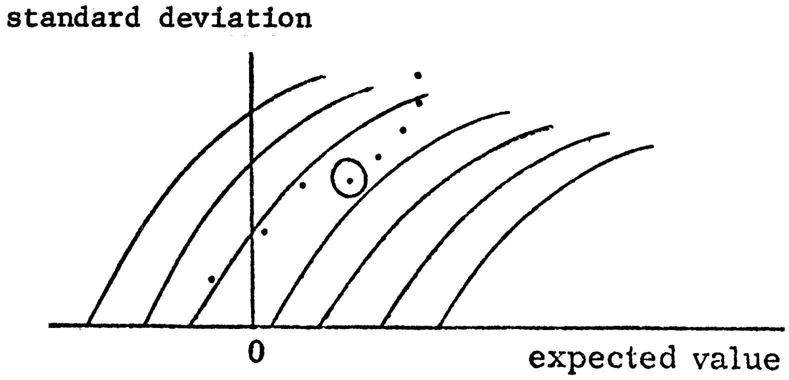

Fig. 1. Gambler's indifference map.

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*The expected value or first moment of the distribution is the sum of the value of each outcome times the probability of observing the outcome. The standard deviation is a measure of the dispersion of the outcome values about the expected value.

The curved lines connect points of expected value-standard deviation which are indifferent to each other. The criterion for selection of any given strategy is to pick the one which puts the decision maker on the highest possible indifference curve corresponding to the chosen strategy. The necessity of deriving meaningful indifference curves makes this approach difficult to use for analysis of practical problems. It also assumes knowledge as to the probability of the outcome.

Risk Discounting

In this approach to decision making under uncertainty, the expected value of a given alternative is multiplied by a factor between one and zero in order to arrive at a certainty equivalent. The factor becomes proportionally smaller as the risk is higher. Dorfman uses the formula $\frac{1}{1 + k\sigma}$, where σ denotes the standard deviation of outcomes and k is a behavioral constant.[14] If B represents the expected net benefits from a given strategy or course of action, then the risk discounted benefits, or certainty equivalent is $\frac{B}{1 + k\sigma}$. Dorfman differentiates* this expression to show that $\frac{k}{1 + k\sigma}$ is

> ...the percentage increase in expected net benefits necessary to compensate for a one-unit increase in the standard deviation of the outcome distribution, so that (k) expresses the additional enticements required to compensate for additional risks.[15]

While the above approaches or their more sophisticated variations are of interest, they do not shed much light on a technique for eval-

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*Certainty equivalent = $\frac{B}{1 + k\sigma}$ setting the total differential of this expression equal to zero gives:

$$0 = d[B(1 + k\sigma)^{-1}]$$

$$0 = d\,B(1 + k\sigma)^{-1} + B\,d(1 + k\sigma)^{-1}$$

$$0 = d\,B(1 + k\sigma)^{-1} - B(1 + k\sigma)^{-2}$$

$$0 = d\,B - B(1 + k\sigma)^{-1}k \text{ by (multiplying through } (1 + k\sigma)^{1}$$

$$\frac{dB}{B} = \frac{k}{1 + k\sigma}$$

uating the benefits from improved accuracy in streamflow forecasts. In this case the decision-maker is given some information as to the state of nature. What is under examination is potential improvements in that information and the economic value of that improvement.

The only technique from the decision theory literature which readily fits the problem under consideration is Bayesian analysis. Before this technique is presented, however, it is necessary to examine the nature of streamflow forecasts and their inherent inaccuracies.

The Nature of Forecast Inaccuracy

Seasonal forecasts of expected water supply in Western basins are issued monthly from January to May each year by both the U. S. Weather Bureau and the Soil Conservation Service (in cooperation with state and local agencies). At the time when the early forecasts are made, only a portion of the winter snow pack will have accumulated so that predictions of the May-September water volume must be based on certain assumptions regarding subsequent weather conditions, including the amount of snow that will accumulate between the date of the first forecast and the end of the snowfall period. By early May, generally the majority of the snowpack has accumulated so that forecasts can be based on actual measurement of the snow depth, water content, soil moisture deficit and other factors as well as on certain assumptions as to summer precipitation and weather conditions. Various techniques have been proposed to improve the accuracy of forecasts. However, a detailed investigation of these improvements is beyond the scope of this work. (For a brief discussion, see Chapter III.) What is of importance here is a specification of the nature of the inaccuracies and of the likely impact of increased accuracy. The relationship between these can be demonstrated by means of figure 2 below.

In the figure, which is based on the Regulation Manual for the Pine Flat Reservoir in California, the forecast of 400,000 acre-feet is based on the assumption of median precipitation and snowpack increments after the date of the forecast.[16] The likely degree of departure of actual runoff from forecast runoff for the date of the forecast is determined by the historical frequency of the various weather and precipitation conditions other than those considered median. For example, if a forecast of 400,000 acre-feet based on median weather conditions is made on May 1, there is a 10 per cent probability that the actual runoff will be greater than 550,000 acre feet and a 90 per cent probability that it will be greater than 250,000 acre feet.

U. S. Weather Bureau forecasts follow the same principle as illustrated in figure 2. Though it has not yet been possible to forecast summer precipitation 60 to 90 days in advance, it is possible to use climatological records to establish probability estimates of future snowfall and precipitation. Weather Bureau forecasts of estimated runoff are presented in probability terms as listed below:[17]

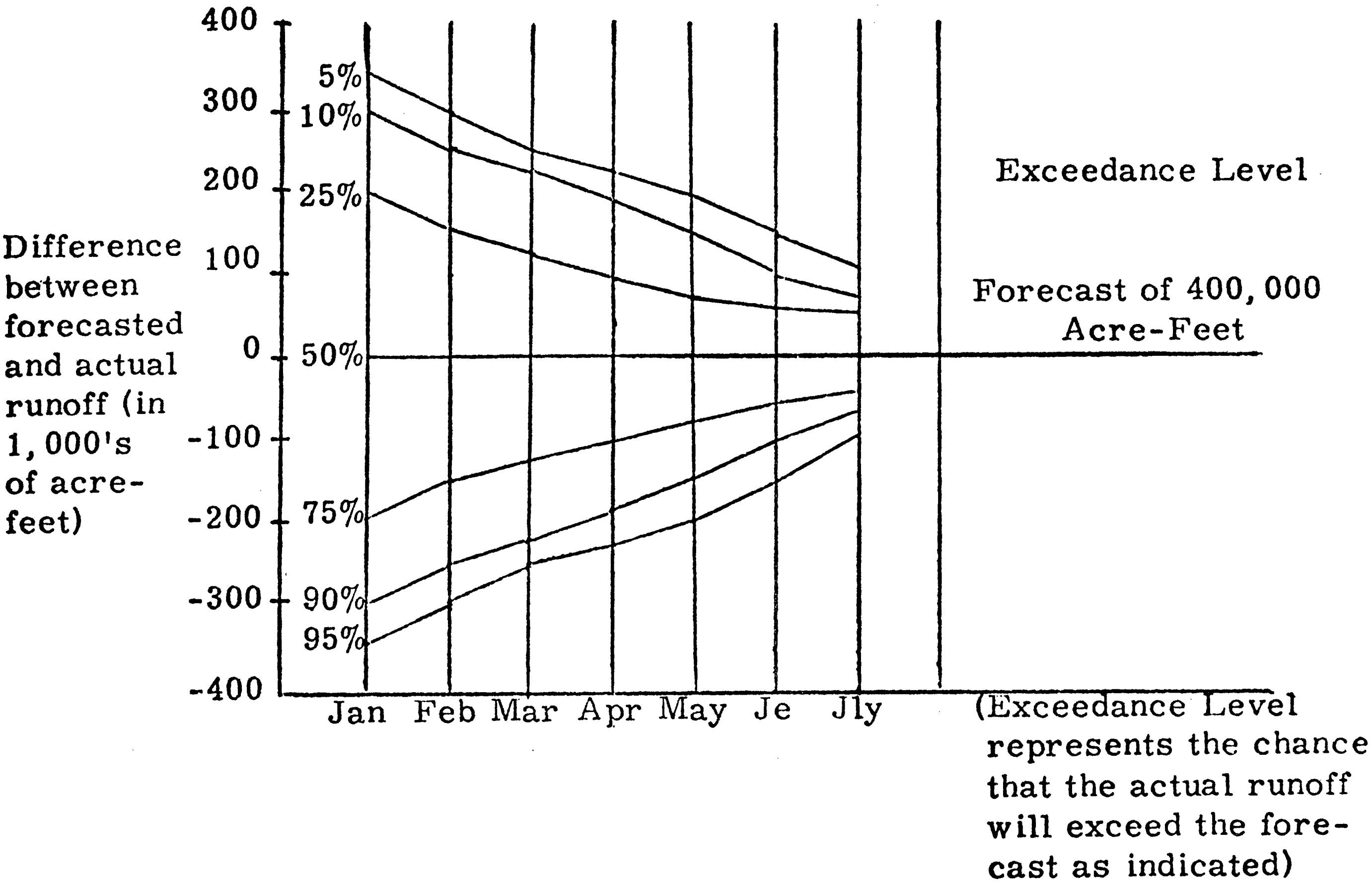


Fig. 2. Probable degree of departure of actual runoff from predicted runoff.

1) Most probable--The quantity of runoff that is expected to occur if precipitation subsequent to the date of forecast is median.

2) Reasonable maximum--The quantity of runoff which is expected to occur if precipitation subsequent to the date of forecast is equal to the amount which is exceeded on the average once in ten years.

3) Reasonable minimum--The quantity of runoff which is expected to occur if precipitation subsequent to the date of forecast is equal to the amount which is expected on the average once in ten years.

The Decision Problem

As will be discussed in the second section, there are many forms of risk and uncertainty which affect the water user. In order to isolate the variables of interest, it will be assumed initially that the only risk important to the decision process is the one due to a variable and imperfectly predicted water supply.

A review of the recent literature reveals two theoretical approaches dealing with the area of economics of forecasts. The first is a Rand study by Nelson and Winter dealing with the economic benefits from improvements in weather forecasts.[18] The second is a model for decision-making under uncertainty presented by Bullock and Logan in a recent issue of Agricultural Economics Research.[19] In both of these works, the relationship of forecasts to the decision-maker is cast in terms of Bayesian decision theory. The Bayesian framework seems most appropriate to a conceptual analysis of the problem at hand and is presented below. The discussion is based on the general relationships between streamflow forecast accuracy and irrigation decision processes.

Impact of Increased Forecast Accuracy in Terms of Bayesian Analysis

In a decision problem for which no information exists on the states of nature other than their relative frequencies, the probabilities that are derived are termed a priori. By performing an experiment, often further information can be obtained on the likely state of nature. When this information is combined through use of Bayes' theorem, a new probability distribution termed the a posteriori or conditional distribution is obtained. As Hymans points out, essentially this distribution combines the two kinds of information in order to arrive at a new probability distribution of the various states of nature.[20] Thus the a priori probability distribution contains only the information as to the states of nature that is available prior to the experiment while the a posteriori or conditional probability distribution incorporates all the information that becomes available as a result of the experiment.

As was discussed in the section reviewing previous attempts to estimate benefits, one can interpret the information that is generated by streamflow forecasts in terms of conditional probability distributions. Since prior information exists in the form of historical frequency distributions of flow, the forecasts create an additional bit of information from which a conditional or a posteriori probability distribution could be calculated. This method of analysis provides the proper frame of reference for conceptually demonstrating increases in accuracy since accuracy can be though of in terms of the dispersion of the actual streamflows about any given forecast flow.

Let S_j be a one-column array or vector representing different volumes of streamflow where $j = 1, \ldots, n$. Further, let the relative frequencies of observing n different volumes of streamflow be given by the one column array or vector $P(S_j)$ where $j = 1, \ldots, n$. The values of $P(S_j)$ sum to one by definition and can be thought of as the probabilities of observing the various water volumes or states of nature based on historical records. Thus the irrigator is assumed to have knowledge of the probability distribution associated with the various water supplies that could possibly be available to him. Within limits the irrigator has a number of options open to him which he can pursue in light of the nature of his water supply which is both variable and not specifically known for any given irrigation season. Examples of such options include expansion or contraction of the total acreage planted, variation in the types of crops planted, and variation in the amount of water and other inputs utilized in producing the crops. For purposes of exposition, assume that these various alternatives can be grouped into m meaningful categories designated A_i where $i = 1, \ldots, m$. By specifying what the results will be in each of the S_j states of nature for each alternative A_i a table or matrix of outcomes designated a_{ij} can be constructed. The results in this case are assumed to be the net farm income realized for the occurrence of each water supply S_j given the decision to follow alternative A_i. If the net income figure in the matrix is multiplied by the probability of observing the state of nature which produced the income, the matrix would be altered to represent the expected income from the various alternatives A_i given the various states of nature S_j. Let the expected income for each element of the matrix be represented by $\hat{a}_{ij} = P(S_j)a_{ij}$. This matrix is shown below in Table 7.

If it can be assumed that the decision-maker's satisfaction or utility from each of the outcomes is proportional to his money income over the relevant range of operation (which means that he is neither a risk averter nor a risk taker and also means that his marginal utility of income is constant), then the criterion for selecting among the various alternatives is to choose the one with the highest expected income. That is, based on the information which the decision maker has on the frequency of occurrence of the different water supply conditions, he should choose that alternative which, on average, returns the highest income. In this situation the decision-maker is said to be operating under conditions characterized by risk since the only information available about the state of nature is the relative frequency of occurrence of the various water supplies. If there were no information available as to the relative

TABLE 7

MATRIX OF EXPECTED INCOME FOR
N STATES OF WATER SUPPLY
AND M ALTERNATIVE
STRATEGIES

	States of Nature		
Alternatives	S_1, ...,	S_j, ...,	S_n
A_1	$\hat{a}_{11}$, ...,	$\hat{a}_{1j}$,.......,	$\hat{a}_{1n}$
A_i	$\hat{a}_{i1}$, ...,	$\hat{a}_{ij}$,.......,	$\hat{a}_{in}$
A_m	$\hat{a}_{m1}$,....,	$\hat{a}_{mj}$,......,	$\hat{a}_{mn}$

frequencies of streamflow then the decision-maker would be subject to conditions of complete uncertainty. When information exists as to the relative frequency of occurrence, formally the decision criterion is given by Max $a_i = {}_j \, a_{ij} \, P(S_j)$; i.e., choose the alternative for which the expected income is maximum.

In the case of western rivers, streamflow forecasts provide data which can supplement the information obtained from historical records. By combining the two types of information, the historical or prior probability distribution can be converted into a conditional or posterior probability distribution of the likelihood of observing different volumes of runoff for any given forecast. Let forecast (F) with results F = (F = $(F_1, \ldots, F_k, \ldots, F_n)$ serve as a prediction of the seasonal volume of runoff S_j. If a reasonably long record of forecasts and their historical accuracy is available, this information in conjunction with the historical probability distribution $P(S_j)$ can be combined by means of Bayes' formula. Let $P(S_j/F_k)$ be the probability of observing streamflow S_j given forecast F_k and $P(F_k/S_j)$ be the historical accuracy of forecast F_k; i.e., the relative frequency with which forecast F_k is observed given streamflow S_j. The conditional probability $P(S_j/F_k)$ is derived using the historical probability distribution $P(S_j)$ and the Bayes formula shown below.

$$(1) \qquad P(S_j/F_k) = \frac{P(F_k/S_j)P(S_j)}{\sum\limits_{j=1} [P(F_k/S_j)P(S_j)]}$$

The term in the numerator of the right hand side of the equation is simply the joint probability of the event S_j and the event F_k ; i.e., the probability that the two events will both occur. The denominator is the sum of each of these joint probabilities. Weighting each component in the numerator by the sum of the components assures that the sum of the conditional distribution equals one. In other words, streamflow forecasts do not alter the states of nature, only the probabilities associated with observing given conditions for any one water supply season. Thus using the Bayesian formula it is possible to establish an nXn matrix of conditional probabilities as shown below in Table 8.

TABLE 8

MATRIX OF CONDITIONAL PROBABILITIES FOR N STATES OF WATER SUPPLY AND N FORECASTS OF THE WATER SUPPLY

		Forecasts				
		F_1		F_k		F_n
	S_1	$P(S_1/F_1)$	.	$P(S_1/F_k)$	.	$P(S_1/F_n)$
States	.					
of	S_j	$P(S_j/F_1)$	.	$P(S_j/F_k)$	.	$P(S_j/F_n)$
Nature	.					
	S_n	$P(S_n/F_1)$	.	$P(S_n/F_k)$	.	$P(S_n/F_n)$

If the forecast F_k were a perfect predictor of water supply S_j then those elements in the diagonal of the matrix would consist of ones and all the other elements would be zero. Since the forecasts are inherently inaccurate the hypothetical matrix would probably contain higher conditional probabilities along the diagonal with the other elements all being non zero. The decision criterion would still be to choose that action or alternative A_i which maximizes expected income. In this case expected income for each alternative and possible state of nature is determined by the conditional probability distribution such that $\hat{a}_{ij} = a_{ij}P(S_j/F_k)$ and the expected payoff for action A_i given forecast F_k would be $\hat{a}_i^k = \sum_j [a_{ij}P(S_j/F_k)]$. Since presumably only one forecast is observed at any given time the decision maker would take his actions based on the conditional probabilities of observing the various states of water supply for the given forecast and would choose that alternative which maximizes his expected income. Since the forecasts are dependent on those factors that determine a large portion of the warm season runoff, changes in these parameters from year to year will result in variation in the forecast conditions. This in turn implies that the conditional probabilities associated with observing each of the states of nature will vary from year to year and so too will the strategy which the irrigator follows to maximize expected income.

Representation of increased accuracy through an improved forecast scheme is straight forward in terms of equation 1. Increase in accuracy can be represented by altering the values for the historical accuracy of each forecast which are given by the probability distribution $P(F_k/S_j)$. This "improvement" is accomplished by reducing the dispersion of the historical accuracy distribution. Thus for $P(F_k/S_j)$ close to the actual state of nature and volume of runoff, the historical accuracy value is increased whereas for volumes of streamflow unlikely to occur given the snowpack and watershed conditions, the historical accuracy value is decreased. The result is a change in the particular conditional distribution which reflects increased accuracy. In terms of the discussion at the beginning of this chapter, improvements in accuracy which tighten the conditional probability distribution associated with each forecast also serve to reduce the exceedance level of each forecast. In order to estimate the value of the increased forecast accuracy it is necessary to compare the average income the irrigator can expect if he follows forecasts at one level of accuracy each year with the expected income that would result if he followed a more accurate forecast scheme each year. Bullock and Logan discuss this computation in the context of introducing a forecast scheme into a situation where no forecasts existed previously. They state:

> The expected value of the data strategy is calculated by multiplying the expected value of the optimum action for each experimental result by the probability of observing the appropriate experimental result, P(Z) [$P(F_k)$ in our case] and summing over all possible results.[21]

This is given by equation (2):

$$\hat{Y} = \sum_k \left[\sum_j a_{ij} P(S_j/F_k)\right] P(F_k) \quad , \tag{2}$$

where $P(F_k)$ is the probability of observing forecast F_k and $\hat{Y}$ is the expected annual income if the irrigator bases his decisions on the forecasts each year. Improvements in forecast accuracy represented by tightening the historical probability distribution will alter the conditional probability distributions as well as the frequency distribution for the various forecasts ($P(F_k)$). The expected additional benefits from any incremental improvement in the accuracy of the forecast scheme is given by equation (3).

$$(3) \qquad B = \sum_k [\sum_j a_{ij} P(S_j/F'_k)' P(F'_k) - \sum_j a_{ij} P(S_j/F_k) P(F_k)] \ ,$$

where $P(S_j/F'_k)'$ is the conditional probability distribution resulting from the improved forecast F'_k under the new forecast scheme. The expected benefit from each incremental increase in the accuracy of the forecast scheme is simply the difference in expected annual income between the two levels of accuracy.

One practical objection to the benefit formulation presented in equation (3) needs to be mentioned. Increases in forecast accuracy which increase expected income but do not alter the optimal strategy chosen would not be considered as producing financial benefits to the user of the forecast. However, if the structure of the irrigation decision process consists of highly divisible components so that changes in irrigation decisions result, it is more likely that the formulation in equation (3) will represent the financial benefits realized.

In assessing improvements in forecast accuracy, it must be assumed that either present forecasts are used by the irrigator or that present forecasts are so inaccurate that they are not relied upon. A situation in which forecasts are not employed because of lack of dissemination of information or ignorance as to forecast value is not under consideration.

Two final considerations must be mentioned to complete the conceptual treatment of benefits from improved forecast accuracy as presented in equation (3). First, the benefits from increased accuracy must be expected to accrue annually over a fairly long span of time. Hence any attempt to estimate these benefits in an investment analysis setting must be in terms of present value. Second, any significant increase in the accuracy of the forecasts of water supply will probably result in an overall increase in production efficiency. If this increase in production efficiency results in the non-marginal expansion of the output of various crops, price effects could result, other things equal. To the extent that this happens in any particular basin, alterations in the optimal strategy would occur. If the irrigator is given a highly accurate forecast of a good water year and he knows that this means other irrigators will be expanding or contracting similar crops, he may choose not to alter his cropping plans to the degree he would if there were no market effects associated with the forecasts.

The preceding discussion is necessarily only a general description of the nature of the problem and the conceptual relationships involved. More detailed elaborations of some of the complexities are discussed in sections II and III.

FOOTNOTES

[1] Robert Dorfman, "Basic Economic and Technological Concepts: A General Statement," in _Design of Water Resources Systems, New Techniques for Relating Economic Objectives, Engineering Analysis, and Governmental Planning_ (Cambridge: Harvard University Press, 1962).

[2] William J. Baumol, _Economic Theory and Operations Analysis_ (2nd ed., Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1965), p. 550.

[3] Herman Chernoff and Lincoln E. Moses, _Elementary Decision Theory_ (New York: John Wiley and Sons, Inc., 1959).

[4] _Ibid._, p. 1.

[5] Dorfman, "Basic Economic and Technological Concepts," p. 130.

[6] Baumol, _Economic Theory and Operations Analysis_, p. 130.

[7] Chernoff and Moses, _Elementary Decision Theory_, p. 163.

[8] _Ibid._

[9] Baumol, _Economic Theory and Operations Analysis_, p. 555.

[10] _Ibid._, p. 556.

[11] _Ibid._, p. 554.

[12] Dorfman, "Basic Economic and Technological Concepts," p. 131.

[13] _Ibid._, pp. 146-48.

[14] _Ibid._, p. 148.

[15] Ibid.

[16] United States Army Corps of Engineers, "Reservoir Regulation Manual for Pine Flat Project, Kings River, California, U. S. Army Engineer District, Corps of Engineers, Sacramento, Cal., November 1, 1953, Revised February 1962, p. 31.

[17] U. S., Department of Commerce, Environmental Science Services Administration, Weather Bureau, Water Supply Forecasts for the Western United States, Vol. XX, No. 5, May 1, 1968.

[18] Richard R. Nelson and Sidney G. Winter, Jr., "Weather Information and Economic Decisions: A Preliminary Report," (unpublished report prepared by the Rand Corporation for the National Aeronautics and Space Administration, August 1, 1960).

[19] Bruce J. Bullock and S. H. Logan, "A Model for Decision Making under Uncertainty," Agricultural Economic Research, XXI, No. 4 (1969), 109-115.

[20] Saul H. Hymans, Probability Theory, with Applications to Econometrics and Decision-Making (Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1967), p. 269.

[21] Bullock and Logan, "A Model for Decision Making under Uncertainty," p. 114.

CHAPTER III

STREAMFLOW FORECASTING: TECHNIQUES AND POSSIBILITIES FOR IMPROVEMENT IN ACCURACY

Introduction

This chapter deals with a description of the two basic methods used in streamflow forecasting and with a description of present and foreseeable improvements in the accuracy and lead time of these forecasts.

Forecasts of likely spring-summer runoff for many western rivers are made starting as early as January 1 of each year. The period the forecasts cover is generally either April through September or April through July. Such forecasts are valuable where foreknowledge of probable runoff is operationally important. Beneficiaries of such advance information typically are reservoir operators (power, flood control functions) and irrigated agriculture. Foreknowledge of probable runoff permits operational alterations which may result in increased net benefits or reduction in potential losses.

The earliest forecasts were initiated in western states as early as 1910. The first successful one was for the inflow to Lake Tahoe on the Truckee River on the California-Nevada border. The economic value of foreknowledge of seasonal runoff was demonstrated during the dry years of the middle thirties.[1] Today seasonal or annual forecasts are made for most of the western rivers.

Types of Forecasts

Using Linsley's breakdown, river forecasts can be divided into three separate categories.[2] The first is storm period--rainfall runoff relations. This type of forecast deals with very short-term relations and is therefore outside the scope of this study. The second type of forecast deals with short period runoff relations involving rain or snow. While these forecasts are also of a short-term nature, Wisler and Brater indicate that such short term forecasts are often used when runoff from melting snow continues during the entire spring and early summer, as in mountain basins of the western portion of the United States.[3] This type of forecast is important, since they are used to improve the knowledge of timing of runoff and to update volume estimates. The third type of forecast made is for extended period precipitation runoff relations, better known as seasonal forecasts. Such forecasts are possible when the annual or seasonal volume of streamflow can be related to antecedent conditions on the given watershed, which can themselves be measured in advance and correlated to streamflow.

There are two different techniques used in seasonal flow forecasting, both of which give comparable results when properly employed. The technique used by the U. S. Weather Bureau is based on the premise that seasonal streamflow forecasts can be made directly from precipitation data collected at long-established stations. The other technique involves use of the relationship between seasonal streamflow and the water equivalent of the mountain snowpack as measured by snow surveys.[4] The remainder of this section will be devoted to a description of the mechanics of the two types of seasonal forecasts and to an assessment of improvements in the accuracy of these forecasts. This assessment is based on private correspondence with researchers working with streamflow forecasts and on published articles dealing with the subject. Where possible, the degree of increase in accuracy is specified; otherwise, impact of potential improvements is described in qualitative terms.

The Mechanics of Seasonal Forecasts Based on Precipitation Data

In order to establish a relationship upon which forecasts based on precipitation data can be made, the following procedure outlined in standard hydrology textbooks is employed. First, each station month record is weighted to reflect its time of year and the particular station characteristics. This is done because not every area in a basin will contribute evenly to observed runoff. Therefore, different weights are assigned to each station in proportion to its estimated contribution to observed runoff from recorded precipitation. Linsley states that:

> Logically a least squares correlation between winter precipitation at various stations and subsequent runoff from the basin should be expected to yield regression coefficients which in themselves represent the best possible weights. However, because of the high intercorrelations between precipitation at adjacent stations, the regression coefficients of a four-or five-station correlation are generally found to differ greatly, with negative coefficients being not at all uncommon.[5]

Therefore, weights are assigned in rough proportion to the regression coefficients, but tempered toward an arithmetic average.

After station weights have been determined, effective monthly precipitation for the period of record must be computed. Effective precipitation is defined as the sum of the precipitation values for each station multiplied by the respective station weights. In order to determine a correlation between annual runoff and recorded precipitation, it is then necessary to compute effective monthly precipitation. This is done, since much fall-summer precipitation goes toward recharging ground basins. Winter precipitation generally in the form of snow adds to the accumulating snowpack, with little of this going to recharge the basin. Therefore, the effectiveness of precipitation in producing streamflow depends on the time of year in which it occurs.[6] To determine the monthly weights, a multiple correlation between effective monthly precipitation and runoff can be computed. Linsley states, however, that a multiple correlation with several independent variables (the number of months used) based on 25 to 35 years of record is likely to produce erratic regression coefficients. To counter this, effective monthly precipitation can be plotted against the month of occurrence, and a smooth curve fitted through the points. The curve should give a better representation of true seasonal trend than would the individual points. Using the respective monthly weights multiplied by the sum of the monthly effective precipitation values, a seasonal precipitation index is constructed.[7]

In construction of the final precipitation runoff relationship, antecedent conditions must be taken into consideration. Where quantities of ground water carried over from the previous season are small, this can generally be represented by the precipitation index for the preceding year. A three-variable correlation between precipitation for two successive years and runoff for the second year can be used with the regression coefficients being converted to weights. From these weights, a total precipitation index is computed for each year of record by adding to each season's index, a fraction of the index for the previous year.[8]

The final product is a relationship between runoff and the total precipitation index as depicted below.

The U. S. Weather Bureau's forecasts for both seasonal and annual runoff are issued starting January 1 and run monthly through May 1. The January 1 forecast is computed based on actual knowledge of precipitation from September to December, plus knowledge of the effect of precipitation in the previous season. To this known information is added the median of the historical precipitation for the balance of the season to provide a forecast of runoff. As more data become available, the accuracy of the forecast improves. Thus the April 1 forecast is more accurate than the January 1 forecast. Of course, the possibility that the precipitation following the forecast will be far from the assumed median value always exists. To anticipate this circumstance, estimates can also be made on the assumption that precipitation will equal the extremes and the quartiles of record.[9] Forecasts for the period April through September or any other such similar period are derived by subtracting observed or predicted flow up to the date of the forecast (April 1)

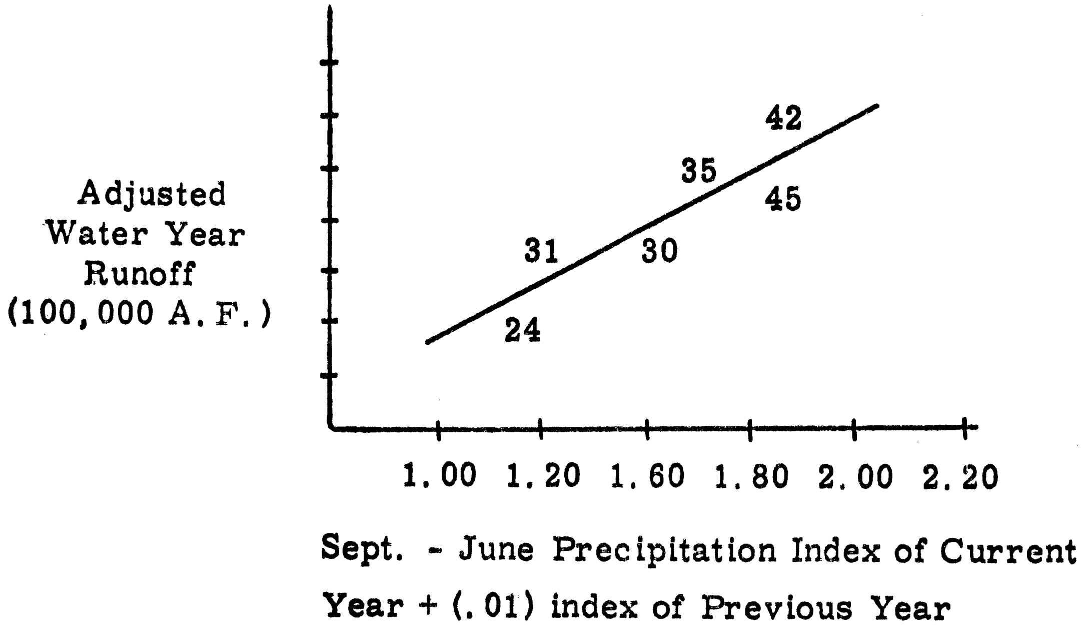


Fig. 3. Relation between runoff andthe total precipitation index.

from total water year forecast.

A serious problem presently encountered in seasonal water supply forecasting arises from the small number of sample points in any basin. Whether the data input obtained at the sampling point is precipitation data or water content of the snow pack, the deviation of conditions at non-sample points from the normal is unknown. Both precipitation and snow course sampling points are chosen on the basis of their degree of correlation with the historical runoff and stations are added and deleted as points with a better correlation are identified by experimental monitoring. In addition, the experiments by both the Corps of Engineers-Weather Bureau at their co-operative Sierra Snow Laboratories and the Forest Service at the Fraser Experimental Forest have fairly well determined the relationship between sampling points and various physiological characteristics of basins.[10] These relationships determine the weights by which the sample results are adjusted as mentioned earlier. The small number of sample points is a major problem in runoff forecasting. It may be more significant than the uncertainty of future snowfalls because the latter uncertainty decreases as the season progresses, whereas the lack of sample points continues through the season.[11]

Operational Forecasts

Shorter term operational forecasts present problems very different from those encountered in the seasonal water supply forecasts. The objective in this operation is to forecast the river hydrograph at the points of interest for a certain period. The fundamental factors are the condition of the snow pack, the temperature forecasts for the period, the precipitation forecasts for the period and the streamflow routing characteristics of the river in question. The steps involved are to forecast the snowmelt for the period, convert that into runoff reaching the stream, add any precipitation that might augment the snowmelt runoff and route the flow downstream to the critical point of interest. The procedure is discussed in more detail in the following paragraphs.

To compute the day's predicted snowmelt requires knowledge of the amount and condition of the snow to be melted and the amount of heat available for melting. The first data input will come from recent snow surveys augmented by aircraft observation flights over the snow pack to observe the recession of the snow line to higher altitudes. The heat available to melt the snow is obtained for short term forecasts by a temperature index method. This uses a single air temperature measurement (which may be obtained as an average from several stations in or around a basin) as an index for snowmelt. Correlation tests have shown that the appropriate index is the number of degree days above 32 degrees represented by the maximum daily temperature (e.g., on a day when the maximum temperature reaches 42 degrees F the temperature index is 10 degree-days).

To utilize the number of degree-days as an index of snowmelt a conversion factor (known as a "degree-day factor") is required. This indicates the number of inches of melt (at a point or over the snow covered area) per degree-day above 32 degrees F. <u>Snow Hydrology</u> reports a mean degree-day factor of .052 for point melt and the observation of rates[12] and degree-day factors between .038 and .064 for several different basins and for the basin-wide snowmelt rate in May.[13] These degree-day factors are calculated by noting the change in water equivalent of the snow pack on a course for several days and relating it to the accumulated temperature index for the same period.

Degree-day factors on basin-wide snowmelt are difficult to calculate because of the changing character of the snow in various areas of the basin and because of differences in forest cover. If, however, degree-day factors can be established for a basin, <u>Snow Hydrology</u> indicates they will be fairly constant. Some increase in the factors over time (especially in large basins where the range of elevation is great) will be caused by:[14]

(1) increasing ripeness of the snow pack
(2) decrease of the snow surface albedo (rate of reflection)
(3) depletion of the snow cover
(4) increase in isolation (the amount of solar radiation incident on a horizontal surface)
(5) increase in the percentage of sheltered snow-covered area and
(6) increase in the mean elevation of the snow covered area.

Thus the snowmelt computation using the temperature index method is completed by multiplying the historical degree-day factor by the number of degree-days in the period.

Determination of Excess Water

The next step in the forecast procedure is the development of parameters indicating the excess water from snowmelt available to become runoff. In snowmelt hydrograph construction the slowness of the runoff process leads to the inclusion of many factors which in rainfall hydrograph analysis are considered to be losses to runoff. Thus the only losses subtracted from snowmelt to obtain the excess water are permanent losses; i.e. water which will never be recorded at the gauging station. The two categories of this types of loss are evapotranspiration and deep percolation. The loss to evapotranspiration is a function of heat supply and wind velocity, thus any snowmelt runoff index assumes that losses are directly related to the supply of heat and of the snowmelt.[15]

Subsurface flow, recharge of soil moisture and depression storage do not materially affect the water excess and runoff calculations. The runoff period is sufficiently long that the subsurface flow is counted in the hydrograph of the snowmelt event. Soil moisture recharge and depression storage losses are not recurring events (except for replacement of evapotranspiration losses) and are completed early in the snowmelt season.

Methods of Streamflow Routing

The two preceeding sections have described the method of ascertaining how much excess water or runoff is generated in a drainage basin by melting snow. This section describes the methods for developing the time distribution of the streamflow (known as the streamflow routing) resulting from the runoff.

Streamflow routing is the process of predicting the rate of movement and amount of flow resulting from a given hydrologic event (in this case snowmelt).[16] The storage routing method often used in short term forecasting treats the basin as a storage reservoir at the outflow of the basin. This is a rough approximation of the situation. A closer approximation is to consider the basin to be a sequence of storage reservoirs and to route the flow through each of them sequentially. This is the method utilized by Rockwood et al. for their "SSRR" forecasting procedure on the Columbia River system.[17]

The streamflow routing of the storage type is based on the equations:

(1) $dS/dt = (I-O)$ where	dS/dt is the change in storage per unit of time I is the rate of inflow O is the rate of outflow
(2) $S = T_s O$ where	S is the storage T_s is a predetermined proportionality factor between storage and outflow (this approximates the length of time water is stored)
(3) $dS/dt = T_s\ (dO/dt)$	obtained by differentiating (2) with respect to time
(4) $dO/dt = I_t - O_t/T_s$	obtained by substituting (3) into (1). I_t, O_t are inflow and outflow at specified times t.

Equation 4 is the basic storage equation utilized by Rockwood in his routings for simulating streamflow from postulated snowmelt.

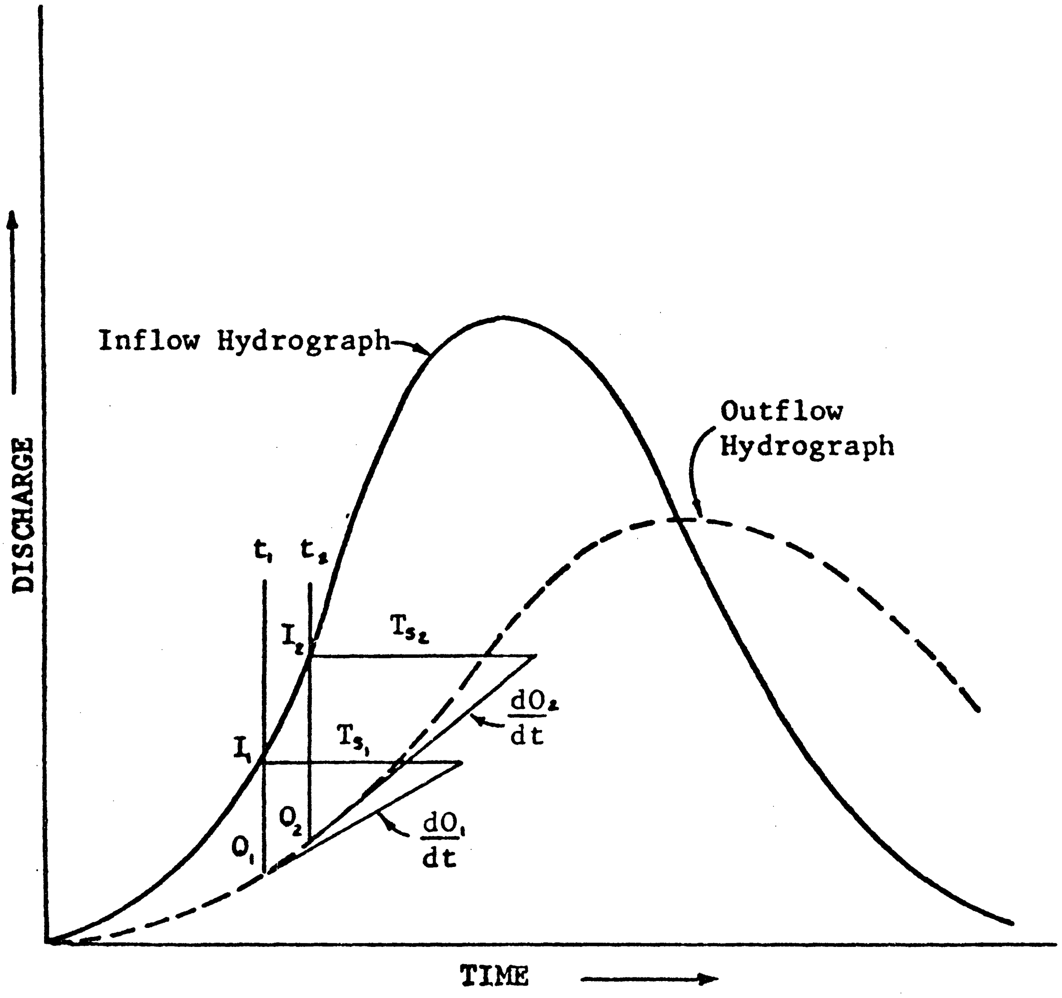
Rockwood illustrates the use of equation 4 as shown schematically in Figure 4. The discrete time interval for the routing is $t_1\ t_2$ and the values of dO/dt and T_s are known from previous investigations. Thus rearranging equation 4:

$$O_t = I_t - T_s\ (dO/dt)$$

when the values of I_1 and I_2 are provided, O_1 and O_2 may be determined. Note that the value of T_s assumes that the basin or river reach acts as a reservoir with an uncontrolled low level outlet. The volume of storage in the reservoir determines the rate of outflow and this re-

Figure 4

Lake Storage Evaluation



Source: David M. Rockwood and Mark L. Nelson, "Computer Application to Stream Flow Synthesis and Reservoir Regulation", International Commission on Irrigation and Drainage. Transactions of Sixth Congress (New Delhi, India, 1966), Figure 3, p. 22.84.

lationship is known for each storage and outflow level. The essence of Rockwood's method is to treat the basin as if it were a series of reservoirs[18] through which the excess water had to flow with each reservoir storing an additional amount.

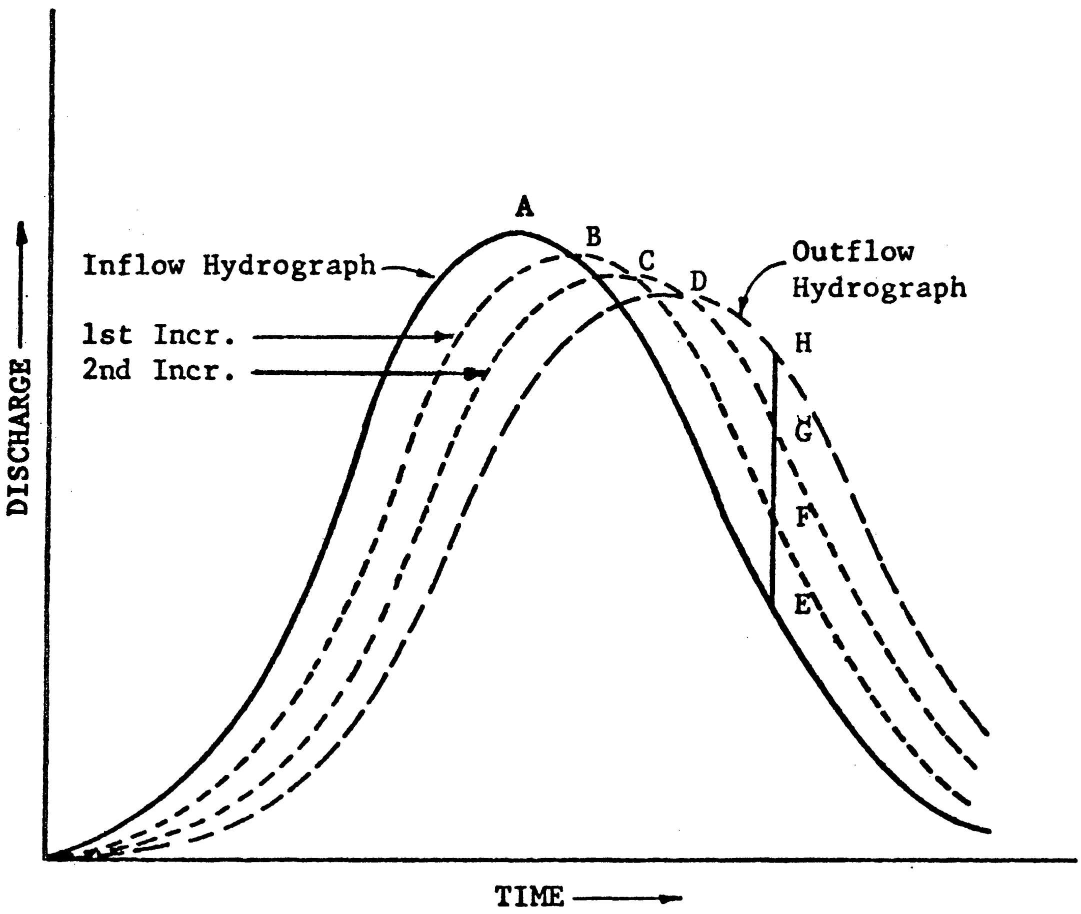
This concept is illustrated in Figure 5. The inflow hydrograph represents the excess snowmelt to be routed through the basin. The hydrograph marked 1st incr. represents the outflow from the first "storage reservoir" and the inflow to the "second storage" reservoir. This hydrograph is derived by using equation 4 as illustrated in Figure 4. Hydrograph 2nd incr. is also derived using equation 4 and constitutes the outflow from the "second storage" reservoir and the inflow to the third "storage reservoir." The process is continued until the inflow has been routed through the basin providing the final outflow hydrograph. In terms of Figure 4, O_1 is being routed into the second increment of storage as I_2 is entering the first increment of storage. Thus each hydrograph rise progressively through time to its peak but the peak of each succeeding hydrograph is reduced by the storage effect. (Note that $A>B>C>D$) The other effect of the storage is that the final outflow hydrograph has a higher flow than the inflow hydrograph or intermediate storage outflow hydrographs for sometime after their peaks have been reached. (Note that $H>G>F>E$)

One of the difficulties with this storage routing method of streamflow forecasting is that the surface and subsurface flows must be separated. The subsurface flows are routed separately in the Streamflow Simulation and Reservoir Regulation (SSARR) program. The practical determination of the portions of excess water to route as surface and subsurface flows is difficult even through computer simulations have improved the procedure. The other method of routing streamflows, the unit hydrograph, does not have this difficulty and is commonly used.

The two methods of routing are interrelated however. By varying the number of increments of storage routing, the time of storage per increment and the value of the assumed coefficient for subsurface flow Rockwood's method generates the various unit hydrographs displayed in Figure 6. The nature of these hydrographs is discussed in the next section.

Figure 5

Channel Storage Evaluation



Source: David M. Rockwood and Mark L. Nelson, "Computer Application to StreamFlow Synthesis and Reservoir Regulation", International Commission on Irrigation and Drainage. Transactions of Sixth Congress (New Delhi, India, 1966), Figure 4, p. 22.85

The Unit Hydrograph

The unit hydrograph is a base-line standard to which all other hydrographs or time distributions of runoff can be compared. The unit hydrograph is the hydrograph created by an inch of runoff occurring over a given area. The concept was developed on the hypothesis that identical storms with the same antecedent conditions should produce identical hydrographs. Thus a storm of duration and area identical to that generating the unit hydrograph should have an identical hydrograph except that the ordinates will be a fixed multiple (equal to the quantity of runoff produced - measured in inches over the area) of those of the unit hydrograph. In terms of snowmelt runoff, if antecedent conditions, snow pack ripeness, soil moisture, etc., are identical and the duration of the melting is the same, the two melting periods should produce identical hydrographs vertically displaced according to the difference in amount of snowmelt produced - again measured in inches over the area.

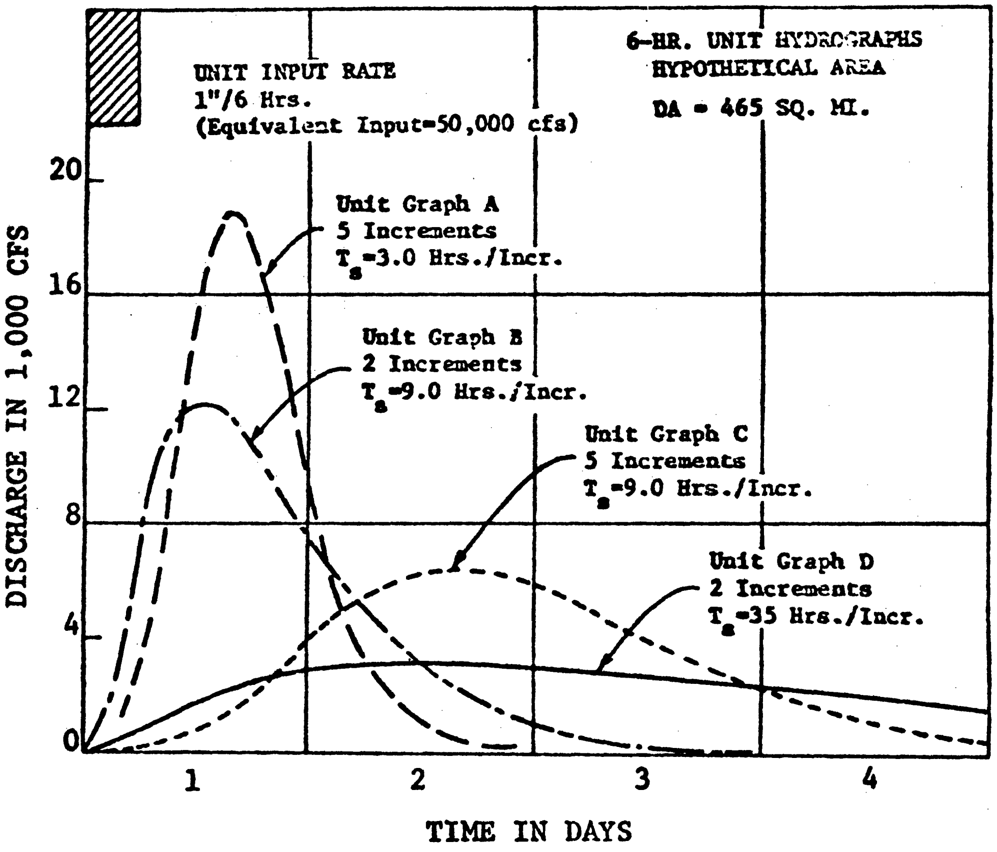
Unit hydrographs generated for snowmelt events would not be suitable for rainfall events. In the construction of a snow unit hydrograph, all of the snowmelt (except for minor amounts lost to evapotranspiration or deep percolation) is accounted for by the unitgraph. The rain storm hydrograph is constructed on a shorter term basis and a considerable amount of the incident rainfall is lost to ground water and subsurface flows which will not enter the water course until after the time period shown by the unitgraph. The recession (or base) flow of the stream and the date of starting the hydrograph is added to the computed hydrograph in the snowmelt case.

In Figure 6 the striped area represents an input volume of water to a river reach at a rate of 50,000 cfs for a period of six hours (approximately 2,500 acre-feet). The unit hydrographs show the reach or basin outflow from routing the inflow through the specified number of "reservoirs" having T_s factors as indicated. For example unitgraph A is the unit hydrograph resulting from the inflow through five increments of storage ("storage reservoirs") each of which have a T_s of 3.0 hours. (See the preceeding section for definition of these variables and discussion of the derivation.)

The more conventional method of generating unit hydrographs makes

Figure 6

Hypothetical Unit Hydrograph Derival by Basin Incremental Storage Routing



Source: David M. Rockwood and Mark L. Nelson, "Computer Application to Stream Flow Synthesis and Reservoir Regulation", International Commission on Irrigation and Drainage. Transactions of Sixth Congress (New Delhi, India, 1966), Figure 7, p. 22.87.

use of a device known as the S-hydrograph. This method is more complex than Rockwood's and will not be discussed here.

Rain-on-snow events present a unique problem. Since the ground will generally be frozen there will be little absorption or losses to ground water. The condition of the snow pack will effect runoff however. Snow Hydrology[19] indicates that because of the high intensity of rainfall that is the norm in these events, the direct rainfall runoff can be considered the primary effect while any accretion to snowmelt is secondary. If the snow pack is dry, large quantities of rainwater may be stored in it (in the same way as soil with a moisture deficit does) and the runoff will be delayed. If the pack surface presents an impermeable barrier, such as an ice crust, then the runoff may be accelerated and the normal rain losses may not occur. Also, if the pack is ripe, the water holding capacity of the pack, the soil moisture deficit and the ground surface storage may all be filled leading to no delay and small losses of runoff.[20]

Summary of Operational Forecasting

Again it should be obvious from the above, that the problems associated with operational forecasting involve a lack of knowledge of what is occurring in the pack and inadequate forecasts of meterological events. One of the major sources of uncertainty stems from the practice of making snow surveys only once each month. This is being overcome to some extent by increased use of aerial surveys, satellite pictures, and telemetry equipment which will report conditions at the location on call. This ground-located automatic telemetry equipment will probably solve many of the snow condition data problems when it is used more widely. The current equipment, more commonly used, is a snow pillow which is a pillow filled with a liquid of a known specific gravity (alcohol) which measures the weight of the snow (and hence its water content) by measuring the displacement of the alcohol. This data is then transmitted to the monitoring station on call. While this provides more frequent data, it provides only a one point sample rather than a ten to fifteen point sample as did the snow courses. For this reason it will probably be used to augment snow courses and surveys that are too difficult or costly to reach. (The California Cooperative Snow Survey indicates that one reading of a snow course costs about $100 depending on the accessibility. Snow pillows installed on site costs about $5,000, but generally do not have to be serviced during the winter months when accessibility is difficult and costs high.) (One problem encountered so far with the snow pillow is that they have been attacked by bears coming out of hibernation. However, camouflage tactics have been devised and it is felt that this problem has now been solved.)[21]

The problem of accurate weather forecasts is probably the most significant for operational streamflow forecasting. This situation was discussed by almost every reservoir operator and streamflow forecaster with whom I talked. The current situation is that synoptic forecasts of temperatures and precipitation can be obtained for periods of three to five days in advance. After that, all that is available is an outlook using median values from the period of record and the maximum probable and minimum probable temperature sequences. (According to one meteorologist in the River Forecast Center in Sacramento the 40-day outlook is probably no better than the probable outlook based on the historical pattern.)

Potential Improvements in Precipitation Based Forecasts

Improvements in long range weather forecasting probably offer the most hope for increasing the accuracy and lead time of seasonal forecasts based on precipitation data. Advance knowledge of likely precipitation over a given geographic area would permit more accurate and earlier estimation of subsequent seasonal runoff. This would reduce the extent to which median precipitation values have to be used to produce the water year forecasts made early in the season. This would also permit more accurate specification of estimated precipitation to follow the last forecast preceding the summer runoff. In this regard, work that is being carried out presently at MIT shows promise in the area of possible breakthroughs in long range forecasting.[22] The objective of this work is to demonstrate that there exists meaningful predictability of monthly and seasonal U. S. temperature anomalies at rather long range. Successful experiments using two different techniques, one employing pressure predictors and the other using temperature predictors, accomplishes this purpose. Further, it is shown that monthly precipitation anomalies can be statistically related to monthly temperature anomalies on a contemporary basis. Thus, long-range monthly and seasonal precipitation pattern prediction is a meaningful pursuit.

Mr. Hurd C. Willett, director of the above research project, made the following observations in private correspondence.[24] The statistical tools that are being developed for long-range forecasting, particularly temperature forecasts, represent a substantial breakthrough in forecasting three to six months ahead. These improvements are a developing thing, so that it is not possible to say how much further they can be taken with a combination of high speed computers and high powered statistics. He states that the quality of long-range statistical forecast performance cannot be determined until it has been applied to an extended series of independent data. Development of long-range pressure-precipitation forecasting capability would permit advance estimation of the amount of precipitation contributing to the seasonal runoff. Though this capability probably is not foreseeable in the near future, Linsley states that:

> ...if reliable quantitative forecasts of the various weather elements affecting streamflow were possible, these forecasts could form the basis of river forecasts, exactly as do the data reported from the networks (precipitation stations).[25]

Other improvements in forecasting streamflow, such as application of telemetry, computers, and improved data acquisition systems, apply both to forecasting based on precipitation data and forecasting using snowpack measurement. Therefore, these techniques will be discussed under improvements in forecasts based on snowpack measurement.

Potential Improvements in the Accuracy of Forecasts Based on Snowpack Measurement

It seems likely that there is substantially greater possibility of improving the range and sophistication of forecasts based on spring runoff from snowmelt than there is of streamflow at other times of the year, for two reasons.[26] Snowpack is regionally more uniform and accumulates months ahead of runoff. It is therefore a much better known phenomenon on which to base a forecast than is warm weather precipitation. Secondly, heavy warm-weather precipitation is highly variable both regionally and in time and is, therefore, extremely difficult to forecast.

Potential improvements in this method of forecasting can be divided into three categories:

1) Better understanding and measurement of the factors affecting the areal volume of the snowpack which eventually contributes to runoff;
2) Increased use of telemetry, computers, remote sensing, and automation of stations;
3) Development of better long-range weather forecasting capability.

Better Methods for Estimating Areal Volume of Snowpack

Looking first at this area, research by the Soil Conservation Service in Casper, Wyoming, has resulted in a method for including the effect of evapo-sublimation on the winter snowpack.[27] They found that over the periods snow surveys have been made of the North Platte in Wyoming, there have been substantial variations in the quantity of runoff from a given snowpack. No combination of snow course data, soil moisture deficit and late spring precipitation accurately correlated with observed April to September runoff. The relation varied in some years as much as 30 per cent from the mean curve. It was further discovered that for the years 1936 to 1956 a three-year moving mean of the acre feet of runoff per inch of the precipitation column plotted in a cycle similar to the since curve and that this relation was inversely proportional to the November, December, March, and April anemometer records at Cheyenne, Wyoming. In other words, the alpine snowpack on the North Platte watershed was undergoing losses that were directly proportional to the speed of the winter winds. This loss from evapo-sublimation was not being reflected in the forest protected snow course data.[28] Evapo-sublimation takes place whenever there is a vapor deficit over snow.

The rate of evapo-sublimation is then determined by air temperature, intensity of solar radiation, the velocity of the wind at the snow surface, and the magnitude of the vapor deficit. Peak states that:

> ...snowmelt runoff equations for watersheds with alpine areas or open range at deep snowpack elevations must contain factors that adjust for the variable and substantial evapo-sublimation losses. Forecasts will not reach the accuracy desired until local alpine wind, temperature, insolation, and humidity data become available.[29]

In an article in the Western Snow Conference Proceedings, Peak describes the results of inclusion of a wind correction parameter.[30] For example, on May 1, 1959, snow survey data and soil moisture deficiency indicated 110 per cent of normal runoff at Northgate, Colorado. Inclusion of a wind correction parameter reduced the estimate to 78 per cent of normal runoff. Actual runoff proved this large correction to be justified.[31]

Eugene L. Peck describes another method for improving the measurement of areal distribution through differentiation of storm types. He states that identical indices of the same parameter for two different seasons may not represent the same areal distribution. The April 1 water equivalent for the snowpack or the total October-April precipitation for two different years may be the same, but if storm types during the two seasons were not essentially the same, the areal distribution of the precipitation might be very different. This might be the case if precipitation occurred mostly during the winter months during the one season, but during the fall or early spring during the second season.[32] Peck does not suggest that all of the difference in the precipitation runoff relationship is due to a change in storm type. Differences in ground water carryover, variations in weather conditions outside the period covered by winter precipitation, ecological or man made changes in the basin, as well as climatic trends, probably influence the precipitation-runoff relations. Even though relative causes for the time trends probably vary from basin to basin, Peck suggests that perhaps not enough attention has been given to the possibility that variation in storm type accounts for at least part of the shifts in observed precipitation-runoff relations in the Western United States.[33] He states that:

> ...the value of observed precipitation as indices for areal distribution may be enhanced by correlating storm or even shorter period amounts with upper air parameters, thereby eliminating the need for storm typing. Many storms are not clear cut cases but have characteristics of several types.[34]

No information was found indicating possible improvement in forecast accuracy from inclusion of such information.

Telemetry, Computers, and Remote Sensing

Application of telemetry, on-site instrumentation, remote sensing, and computers will be very important in improving the accuracy of both methods of seasonal forecasting and in improving residual forecasts as decribed below. Shannon states that development of electronic telemetry equipment and sensing devices permits automatic interrogation and recording of data from high mountain data collection sites. Thus "real time" information can be collected and analyzed by automatic data processing procedures. This process will permit establishing relationships between precipitation, accumulation, melt rates, stream peak, volume, and residual flows.[35] He goes on to state that

> ...the use of telemetry also means that other forecast factors including solar radiation, wind movement, air temperature, soil temperature and moisture, and humidity can be recorded along with total precipitation and water equivalent of the snowpack. It has been determined that electronic telemetry data will permit studies to determine the reason for missing a forecast and need for formular correction.[36]

Looking briefly at residual forecasts. Price states that application of remote sensing technology can be expected to do much toward improving snowmelt forecasts. He states that:

> ...research has shown that residual volume forecasts during the melt season can be considerably improved by including as a primary variable the extent of snow covered area as measured by aerial surveillance.[37]

While this type of forecast is more a short-term relation, its use is important in practical application of streamflow forecasts. Work being done at the Rocky Mountain Forest and Range Experiment Station in Fort

Collins, Colorado, is aimed at developing a method of making up-to-date residual flow forecasts in central Colorado. The procedure is based on: (1) aerial photographs of the extent of snow cover during the melt season; (2) a precipitation index based on peak snowpack measurements (usually at the end of April) which can be adjusted for subsequent precipitation during the melt season. Price states that their experience indicates that successive adjustments of precipitation indices at various stages of snow cover depletion can reduce forecast errors from 25 per cent initially to around 10 per cent. This relatively high accuracy, he feels, can be attained even when residual flows are 75 per cent or more of the seasonal total.[38]

Recent developments in the use of satellite for surveillance of mountain snow holds promise for the above type of forecasting. It has been demonstrated that snow cover distribution in regions of mountainous terrain can be reliably identified and mapped from satellite photography. Barnes and Bowley state that:

> ...the accuracy with which the snowline can be located is well within the accuracy of the 10 miles that was determined from previous studies of flat terrain regions. Although this mapping accuracy is marginal for optimum hydrologic use, it is sufficient to allow snow-line elevation to be monitored throughout the snowmelt season.[39]

They go on to state that:

> ...since satellite photography cannot provide direct measurement of water equivalent, studies should be carried out to determine whether useful information can be derived from relationships between areal snow distribution and snowpack volume, and between snow line retreat and stream flow.[40]

Difficulties arise in precise determination of snow mapping accuracy attainable from satellite photography in mountainous areas because of the lack of suitable ground truth data. Aerial snow survey data in addition to ground based measurements are required for further analyses. Also, the effects of forest cover on snow identification appear to be more complicated than in regions of flatter terrain.[41] Because current data collection methods often cannot provide either the desired areal coverage or frequency of observation, the capabilities of remote sensing from earth-orbiting satellites offer promise for the development of improved snow surveillance techniques. Barnes and Bowley state that the:

> ...satellite has obvious advantages, as it provides a rapid coverage of large areas, regardless of the remoteness of the region, the type of terrain, or political boundaries. Although ground based measurements are extremely accurate at the location where they are made, the horizontal sampling distribution is poor. Remote sensing, on the other hand, may never be as accurate at any single location, but the number of sample points is unlimited. For prediction of snowmelt and the subsequent runoff in a large watershed, snow surveillance from a satellite coupled with a relatively few ground station observations should prove more useful than either type of data alone.[42]

In general, snow mapping can be carried out on mountainous terrain as accurately or more accurately than on flat terrain because of the number of terrestrial landmarks available for geographic referencing of the pictures. Problems that limit the potential for use of satellites alone in snow surveillance include cloud interference, which limits the number of usable satellite observations; heavy vegetation, which may influence the placement of the snow line; and the fact that estimation of snow depths of more than a few inches or water equivalents in mountain snowpacks is not possible.[43]

With regard to the use of computers, Price states that the computer has done much and will continue to improve streamflow forecasts, particularly when short time intervals are involved.[44] Willett feels that computer treatment of all of the factors involved in spring runoff should push the skill and range of this type of forecast much further than it has been pushed.[45] The value of the computer lies in its speed and efficiency of computation in handling many variables and in its use in developing improved forecast equations. For example, Codd and Farnes found that in comparing forecasts from pre-computer formulas issued by the Soil Conservation Service for Montana in 1959 with computer developed equations, the computer derived formulas showed considerable increase in accuracy. They found that using sixty-six comparable forecasts at twenty-six stations, the average error was decreased from 11.3 per cent to 6.6 per cent.[46]

Breakthroughs in Long-Range Weather Forecasting

This area, as was discussed in the section on improvements in seasonal forecasts based on precipitation data, holds much promise for also improving the accuracy of forecasts based on snowpack measurement. Kohler states that greater accuracy in seasonal forecasts will probably be achieved through more reliable long-range weather forecasts.[47] Price feels that the reliability of early season forecasts can be substantially increased, as it becomes possible to make long-range (60- to 90-day) weather forecasts accurately.[48] No quantitative specification of the degree of increase in accuracy from the development in long-range weather forecasting is possible.

Qualitative Assessment of Research Impact on Forecast Accuracy

While it is not possible to specify what degree of increase in accuracy will result, other than the few results mentioned in the previous pages, it is possible to specify the qualitative effects that different improvements could have. Improvements in forecast accuracy can be reflected by stating the reduction in the average error of the forecast for a given stream; or improvement could be reflected by reduction in the exceedance level of departure of forecasts from actual runoff as depicted by figure 2 in Chapter II. Any reduction in the magnitude of dispersion of actual runoff from forecast runoff would represent an improvement in forecast accuracy.

Looking at improvements in determination of the winter snowpack index, inclusion of an indicator of the amount of evapo-sublimation can reduce forecast error in some areas, as was demonstrated by Peak.[49] It is difficult to specify degree of reduction in average forecast error, but an initial forecast correction of 30 per cent was made on this basis and proved to be realistic in light of observed runoff. The effect of such improvements on the exceedence level will likely be to reduce the level of exceedence primarily for the later season forecasts such as April. This is because forecasts based on early season precipitation or snowpack water equivalent cannot incorporate future meteorological conditions, which will affect the rate of evapo-sublimation and thus the volume of the snowpack which produces the spring-summer runoff. By April, the accumulated snowpack and the effect of evapo-sublimation or other phenomenon on areal volume can be assessed, based on actual data rather than median values, thus improving the accuracy of the seasonal runoff forecast.

Use of telemetry, computers, and remote sensing would likely reduce the exceedance levels evenly for both early and late winter forecasts. Application of these technologies will permit both broader coverage of the watershed areas and more rapid processing of information obtained from automated stations.

Looking at long-range quantitative precipitation forecasts, realization of this capability would go a long way to reduce the exceedance levels of January-February forecasts. Advances in this area also would serve to reduce the error of the later forecasts as it would become possible to predict summer precipitation to some degree, which is presently impossible. Overall, the early winter forecasts probably would be affected most significantly, due to the inherent uncertainty in present capabilities for making this kind of prediction. No quantitative effect on reduction in average error can be specified.

Improvements in the ability to make residual forecasts in basins where snowmelt continues well into the summer will reduce the level of exceedance for later season forecasts. Forecasts for central Colorado show reductions in forecast errors from 25 per cent to around 10 per cent when such techniques are employed.

Summary

Overall, then, the above research on methods and techniques directed at improving the accuracy of seasonal streamflow forecasts, points both to areas that hold immediate practical promise and to areas for informed speculation. Whether forecasts are based on precipitation measurement or measurement of water equivalent of winter snowpack, it seems likely that a combination of long range quantitative precipitation forecasts, increased application of telemetry, computers, and remote sensing, and improved knowledge of monitoring of the factors affecting snowpack volume and runoff could produce significant increases in forecasting accuracy.

FOOTNOTES

[1] U. S., Department of Agriculture, Snow Surveys in Colorado, p. 1.

[2] Ray K. Linsley, Jr., Max A. Kohler, and Joseph L. H. Paulus, Applied Hydrology (New York: McGraw Hill Book Company, Inc., 1949), p. 405.

[3] C. O. Wisler and E. F. Brater, Hydrology (2nd. ed., New York: John Wiley and Sons, Inc., 1959), p. 16.

[4] Linsley, op. cit., p. 433.

[5] Ibid., p. 436.

[6] Ibid., p. 437.

[7] Ibid.

[8] Ibid.

[9] Ibid., p. 638.

[10] U. S., Dept. of the Army, Corps of Engineers, North Pacific Division Summary Report of the Snow Investigations, Snow Hydrology (Portland, Oregon: 1956); W.U. Garstka et al., Factors Affecting Snowmelt and Streamflow, Report to the U.S. Dept. of Interior, Bureau of Reclamation and the U.S. Dept. of Agriculture, Forest Service, March, 1958 (Washington, D.C.: Government Printing Office, 1958).

[11] Morlan Nelson, Snow Survey Chief, Soil Conservation Service, Boise, Idaho, personal interview, July 1970.

[12] Corps of Engineers, Snow Hydrology, p. 244.

[13] Ibid., p. 248.

[14] Ibid., p. 249.

[15] A more detailed analysis of evapotranspiration is presented in Ibid., pp. 99-106.

[16] Ibid., Ch. 9 and Ray K. Linsley Jr.; Max A. Kohler; L. H. Paulhus; Applied Hydrology (New York: McGraw-Hill, 1949), Ch. 19.

[17] David M. Rockwood and Mark L. Nelson, "Computer Application to Streamflow Synthesis and Reservoir Regulation," International Commission on Irrigation and Drainage. Transactions of the Sixth Congress (New Delhi, India: 1966) pp. 22.72-22.102.

[18] These reservoirs are created by a widening of the streambed, sandbars, holes in the river bottom etc.

[19] Corps of Engineers, Snow Hydrology, p. 323.

[20] Ibid., Ch. 9 and Linsley, Ch. 17.

[21] Kit Carr, California Cooperative Snow Surveys and Glen Castle Corps of Engineers, personal interview, Sacremento, California, July 1970.

[22] John T. Prohaska and Donald B. Devorkin, Significant Advances in Statistical Long-Range Forecasting, Final Scientific Report WBE-49-68 (G) Prepared in Accordance with the Administrative Provisions for Grants Made by the Environmental Science Services Administration (Cambridge, Mass., 1969).

[23] Ibid., Abstract.

[24] Letter from Hurd C. Willett, Professor Meteorology, Massachusetts Institute of Technology, January 19, 1970.

[25] Linsley, Applied Hydrology, p. 640.

[26] Letter from Hurd C. Willott, Ibid.

[27] U. S., Department of Agriculture, Soil Conservation Service, A Manual for Forecasting Snowmelt Runoff, by George W. Peak, Soil Conservation Research Paper (Casper, Wyo., April, 1969).

[28] Ibid., p. 1.

[29] Ibid., p. 24.

[30] George W. Peak, "Snow Pack Evaporation," Western Snow Conference. Proceedings of the Thirtieth Annual Meeting (Cheyenne, Wyo., April 16-18, 1962), p. 32.

[31] Ibid.

[32] Eugene L. Peck, "The Little Used Third Dimension," Western Snow Conference. _Proceedings of the Thirty-Second Annual Meeting_ (Nelson, B. C., Canada, April 21-23, 1964), p. 34.

[33] _Ibid_., p. 37.

[34] _Ibid_.

[35] Letter from W. G. Shannon, Chief Water Supply Forecasting Branch, Engineering Division, U. S. Department of Agriculture, Soil Conservation Service, January 20, 1970.

[36] _Ibid_.

[37] Letter from Raymond Price, Director, Rocky Mountain Forest and Range Experiment Station, U. S., Department of Agriculture, Forest Service, Fort Collins, Colo., March 9, 1970.

[38] _Ibid_.

[39] James C. Barnes and Clinton J. Bowley, _Satellite Surveillance of Mountain Snow in the Western United States_, Final Report, Contract No. E-196-68, prepared for U. S., Department of Commerce, Environmental Science Services Administration, Allied Research Associates, Inc. (Concord, Mass., June, 1969), p. 75.

[40] _Ibid_.

[41] _Ibid_.

[42] _Ibid_., p. 1.

[43] _Ibid_., p. 2.

[44] Letter from Raymond Price, _Ibid_.

[45] Letter from Hurd C. Willett.

[46] Ashton R. Codd and Phillip E. Farnes, "Application of the Electronic Computer to Seasonal Streamflow Forecasting," Western Snow Conference. _Proceedings of the Twenty-eighth Annual Meeting_ (Santa Fe, N. M., April 12-14, 1960), p. 22.

[47] Letter from Max A. Kohler, U. S. Department of Commerce, Environmental Science Services Administration, Weather Bureau, Silver Springs, Md., January 20, 1970.

[48] Letter from Raymond Price, *Ibid*.

[49] George W. Peak, "Snow Pack Evaporation."

CHAPTER IV

A CONCEPTUAL MODEL FOR THE EVALUATION OF FLOOD PROTECTION BENEFITS FROM FORECAST IMPROVEMENTS

The value of flood warnings for the demand side, (i.e., the possibility of making preparations to minimize the damages rather than attempting to prevent or minimize floods) can be analyzed at several levels of abstraction. Unfortunately, as factors are added to make the analysis more realistic, it also becomes more difficult to apply to a practical situation. The approach taken here will be to develop a highly simplified model in some detail and then discuss in general terms the intractable aspects.

The problem that will be considered is this: suppose a community is told that flooding is imminent with some given probability and at some cost it could take measures to minimize the damage. The goal of the analysis is to determine the benefits from flood warnings as a function of their dependability and the length of the warning time. The first step is to determine the minimum probability with which a flood can be forecast that will elicit the flood-protection response. Forecasts of flooding at lower probability levels would not provide benefits because nothing would be done about them.

The principle involved can be illustrated with a simple model taken from game theory. We suppose that the community being threatened acts as a unified, rational decision-maker whose goal it is to maximize the expected value of income net of flood losses and flood-protection expenses. To simplify the exposition, we will assume there is only one possible level of flooding and only one possible flood protection alternative. The extension to more complex cases is not difficult. Let Y represent the income that would be obtained if there is no preparation for flood and no flood; C be the cost of flood protection; and D_p and D_n be the amount of damages from flooding with protection and with no protection, respectively. We assume $C > 0$ and $0 < D_p + C < D_n$. If the values of these variables are known, they can be used to construct a "payoff matrix" which shows the ultimate net income resulting from each combination of decision and contingency:

		Streamflow contingency	
		Flood	No Flood
Decision	Protection	$Y-C-D_p$	$Y-C$
	No Protection	$Y-D_n$	Y

Let f be the forecast probability of a flood. Then the expected values of the outcomes of the decisions to protect and not to protect, V(P) and V(N) respectively, can be computed to be,

$$V(P) = f(Y-C-D_p)+(1-f)\ (Y-C) = Y-C-fD_p$$

$$V(N) = f(Y-D_n) + (1-f)Y \qquad = Y-fD_n.$$

As f approaches zero, it will be optimal to choose not to protect and as f approaches unity protection will be called for. The critical value of f at which the decision changes will be designated f* and can be found by setting V(P)=V(N):

$$f^*D_n = C+f^*D_p$$

$$f^*= C/(D_n-D_p)$$

To compute the value of this flood warning system, we need to have some information about its accuracy. Let F represent the set of circumstances that lead to a flood and NF the set of those that do not. Thus, $\text{Prob}(f>f^*|F)$ is the probability that a flood will be forecast with sufficient confidence to elicit flood protection given that a flood is actually going to occur. To simplify the notation, let

$P_{ff}=\text{Prob}\ (f>f^*|F)$

$P_{fn}=\text{Prob}(f> f^*\ |NF)$

$P_{nf}=\text{Prob}\ (f< f^*|\ F) = 1-P_{ff}$

$P_{nn}=\text{Prob}(f< f^*|\ NF) = 1-P_{fn}$

P_F=Prob (F)

P_f=Prob (f>f*).

The expected value of income without the flood warning system is:

$$Y-P_FD_n \quad .$$

With the system, it is:

$$P_FP_{ff}(Y-C-D_p)+P_FP_{nf}(Y-D_n)+(1-P_F)\ (P_{fn})\ (Y-C)+(1-P_F)P_{nn}Y$$
$$= Y-P_F((P_{ff}(C+D_p)+P_{nf}D_n))-(1-P_F)P_{fn}C$$
$$= Y-P_fC-P_F(P_{ff}D_p+P_{nf}D_n) \ .$$

The value of the system is the difference between these two expressions:

$$Y-P_fC-P_F(P_{ff}D_p+P_{nf}D_n) \quad - \quad (Y-P_FD_n)$$
$$= -P_fC-P_F(P_{ff}D_p+P_{nf}D_n)+P_FD_n$$
$$= -P_fC-P_FP_{ff}D_p+P_FD_n(1-P_{nf})$$
$$= -P_fC-P_FP_{ff}D_p+P_FP_{ff}D_n$$
$$= P_FP_{ff}(D_n-D_p)-P_fC \quad .$$

The two terms in this expression are the damages averted and the cost of heeding warnings due to the system.

The proportion of warnings that the system gives which turn out to be justified is P_FP_{ff}/P_f. As was shown earlier, warnings will only be useful at all if this proportion is greater than $C/(D_n-D_p)$. If a warning system meets this criterion, its value will be that given by the expression above.

The streamflow forecasting with which this report is concerned is for periods longer than standard weather forecasts. For floods caused by late-season snowmelt, it is possible that they could be foreseen quite some time in advance. Where floods are the result of extraordinary weather patterns, warning times of several weeks would seem to be an optimistic goal. Flood protection alternatives that cannot be implemented within the forecast period are clearly not useful. Neither need we consider alternatives that can be implemented within a few hours or days (i.e., after the onset of a flood is clearly apparent) because such warnings is typically already available. Since the accuracy of predictions rises as the time involved becomes smaller and the costs of protection alternatives that require disruption of normal activities will in general rise with the length of time they are in force, it is in general appropriate to "wait until the last minute." Therefore, the flood protection measures which it is appropriate to consider in our context are those that require at least several days but no more than several weeks to implement.

What might such measures be? Sandbagging is the traditional means of temporarily adding to the effective height of dikes and levees and for erecting temporary barriers. The time required would of course depend on the relative sizes of the barriers to be built and the community resources available to do the job, but this time may frequently be in the range appropriate to this study. However, sandbags are of limited usefulness because they cannot be built up very high and the costs rise steeply with height.

More substantial water containment mechanisms than sandbags are probably not often useful as responses to individual flood threats because they would not be cheaper than permanent structure.

It is frequently easier to move valuables away from flood-threatened areas than to keep the water out. This strategy has a general advantage over that of water-containment in that it allows for selective protection. Unfortunately, it is not generally possible to protect the bulk of a community's property in this way. Structures cannot be moved. Movable property evacuation is limited by transportation facilities, lack of appropriate places to move it to, and the costs involved in having goods away from their normal places. Since this "disruption cost" is increasing with the length of time involved, it combines with the logistical problems to create a kind of "scissors" limiting the effectiveness of evacuation: long evacuations are too costly and short ones cannot be very effective.

This view is perhaps unduly pessismistic because it considers only "management" alternatives. It may be that "structural" changes could be made that would make "long-range" flood warnings more useful. Flood protection methods as they now exist have developed in a world in which flood frequencies and short-term warnings were the only available information. If dependable longer-range warnings are developed, it seems likely that means will be developed to take advantage of them that are not presently available. Mobile homes might be made moveable on shorter notice, for example. Inventories of commercial and industrial establishments might be made easier to evacuate.

Perhaps the best way to explore these possibilities would be to make an engineering-economic study of a community which had been flooded to determine what could have been done had the flood been foreseen various numbers of weeks in advance. The costs of each measure could be related to the value of the losses saved in order to determine the certainty level of the forecast that would have made the action worthwhile. Such a study would be useful to meteorologists and hydrologists not only by indicating the potential value of their research in flood prediction, but also by estimating the appropriate trade-off between dependability of prediction and the time-span of the prediction.

We have thus far dealt with the problem as though communities had unitary decision-makers and were rational and risk-neutral. None of these assumptions is generally true, so it is necessary to consider how these and other behavioral factors would effect the results of the analysis.

People may not be rational in anticipating floods (or other disasters). The natural tendency to feel that "it can't happen here" is reinforced by the fact that the cost of preparation is immediate and certain whereas the benefits are in the future and problematical. This will create a tendency to ignore threats. Also, preparing for floods is a non-routine activity whereas ignoring the threat requires doing nothing unusual and requires only one, relatively simple and straightforward, decision. These factors produce a bias away from flood protection.

Risk-aversion works in the opposite direction, leading people to protect property even when an actuarial accounting would indicate it would be better to take one's chances on a flood.

Insurance arrangements can work against flood protection if losses from water damage are covered but the cost of protection is not. Government disaster relief is an implicit form of insurance that has the same effect. This result is not inevitable, however, since an insurer can require that certain precautions be taken as a condition of insurance. Insurance against "flood threats" could also be designed in such a way that it pays off the costs of protection as well as flood damages per se.

A serious complication in evaluating flood warnings that is overlooked by the game-theory model above is the redistributional effects that warning announcements would have on real estate and other values. Individuals who had planned to sell are hurt by the announcement, while the prospective buyers are helped. Sandbags, trucks, and high-and-dry storage space may all come into heavier demand while sales of home furnishings may decline. Construction workers may find they are laid off of new construction projects and/or hired to build emergency flood protection structures. The threat of an imminent flood could cause large changes in many relative prices and thus cause a redistribution of income and wealth since not everyone owns a similar collection of assets or provides the same kinds of services. The redistribution is away from those who own damage-prone property in the effected area and toward those who own competitive property elsewhere and those who can provide goods and services to prevent or alleviate flood damages. There is probably a net redistribution out of the community. Because of these anticipatory effects governments are likely to be hesitant to issue warnings unless the degree of certainty that a flood will actually occur is very high. It is clear, then, that any more detailed, empirical analysis of the benefits from greater accuracy of streamflow-flood forecasts has to take these potential anticipatory and income redistributional effects into account.

APPENDIX

RECENT LITERATURE REVIEW

In an effort to put the present study in the perspective of related work which has been published over the last several years, three annual indeces (1971-2-3) of Selected Water Research Abstracts and recent issues of selected journals were searched under over two dozen subject headings. About ninety abstracts were examined to judge the availability and relevance of the articles. Twenty survived this screening. These were read in whole or in part and the half which appear to provide possibly helpful "leads" to related investigations are listed below. Listing is by Selected Water Research Abstracts index number.

W71-00281 "Multireservoir Operation Studies",
T.G. Roefs and L.D. Bodin, WRR April 1970.

An attempt was made to derive an optimal operational regimen for a three-reservoir system for hydro-power objectives over a 36-month planning horizon.

W71-03220 "Optimal Policy for Reservoir Operation"
R.C. Harboe, F. Mobasheri, and W. W.-G. Yeh,
Journal of Hydraulics Division Proceedings A.S.Civ.E.
Nov, 1970.

A policy is developed for a reservoir using 1901-1950 streamflow records. This kind of "perfect hindsight" model may provide useful data against which to compare the usefulness of proposed operating schemes based on improved forecasting.

W71-10515 "A Method for Incorporating Agricultural Risk into a Water Resource System Planning Model",
J.R. Conner, R.J. Freund, and M.R. Godwin, WRB June, 1971.

A model is developed and an example worked out of the response of farmers to hydrologic uncertainties. The consequences for optimal design of the water system are computed. This type of model would seem to be the appropriate starting point for an investigation of the "structural" effects of improved forecasting.

W72-0C399 "Effects of Reservoir Operating Policy on Recreation Benefits", J.M. Morgan and P.H. King, WRB Aug., 1971.

A regression analysis with weak data fails to find a relationship between fluctuating reservoir levels and visitor-days.

W72-01139 "An Economical Device for Optically Detecting Snow Depths at Remote Locations", I. Dirmhirn and C. Craw, WRR Oct., 1971.

It consists of a silican cell ladder integrated into a telemetering system.

W72-10874 "Application of Statistical Decision Theory to Water Use Analysis in Sevier County, Utah", J. C. Anderson, H.H. Hiskey, and S. Lackawathana, WRR June, 1972.

This article reports on a study which used techniques similar to those used in one of the case-studies included in this report to analyze the value of pre-season information about snow-pack and reservoir content as predictors of late-season water supply to farmers in a county in central Utah. The findings in $/acre/year are:

	snow-pack and reservoir data relative to no data	perfect predictor relative to no data
Range beef farm	1.36	1.69
Feeder farm	2.18	2.87
Small dairy farm	0.74	1.36

The low values are accounted for by a lack of flexibility on the part of the farmers: "There are no really high value crops that can be grown extensively" to take advantage of years with optimistic water forecasts.

W73-00636 "Optimizing Flood Control Allocation For a Multipurpose Reservoir", F.K. Duren and L.R. Beard, WRB Aug. 1972.

A computerized model was used in an attempt to "derive the economically optimal flood control diagram" for a multi-purpose reservoir. The computer found six distinct local optima when runs were made from as many initial points in its optimization routine.

W73-00672 "Cost-Benefit Approach to Hydrometric Network Planning", K.C. Wilson, WRR Oct, 1972.

This article is concerned with evaluating the benefits of intensification of the density of hydrometric networks. It estimates the savings in construction and operating costs of water control structures from improved knowledge of mean-, flood-, and dependable-flows. Similar "structural" benefits could be achieved from improved year-to-year predictability of stream-flows if this allowed the use of smaller structures.

W73-01017 "New Approach to Water Allocation Under Uncertainty", G. Thomas, A. Whinston, and G. Wright, WRR Oct. 1972.

This and several other articles by the same authors explore alternative institutional forms of water contract featuring different prices for different probabilities of delivery. The welfare implications are discussed and the "optimal contract" is characterized. If such a system were implemented the benefits of improved forecasting would be easily calculated because the relationship between the value of water and the confidence with which its delivery was foreseen would be subject to market tests.

W73-13137 "Climatic Uncertainty Effects on Management and Design of Reservoir-Irrigation Systems", N.J. Dudley, Proceedings Vol. II, Int'l. Symposium on Uncertainties in Hydrologic and Water Resource Systems (Tucson Dec., 1972).

This paper reviews models presented elsewhere which optimize reservoir capacity, acreage developed for irrigation, and water management policies. The models take into account the importance of the timing of irrigation during a season as well as the cumulative total.

Modernization of National Weather Service River Forecasting Techniques" W.T. Sittner, WRB Aug., 1973, pp. 655-59.

Describes the progress and problems of the National Weather Service River Forecast Centers in changing from index type catchment modelling to computerized conceptual hydrologic models. The most notable improvement in forecast accuracy expected is the modelling of river response during and after long dry spells. The article discusses the problems of choosing a computer system, hydrologic model and the necessary parameterization and data collection as well as manpower training aspects.

SECTION II

BENEFITS TO IRRIGATED AGRICULTURE

CHAPTER V

THE RELATION OF STREAMFLOW FORECASTS TO IRRIGATED AGRICULTURE

The Issues

The implication of less than perfect knowledge as to the state of factors that affect economic decisions depends on their relative importance to the production process, or in some cases the degree to which these conditions adversely affect production. In agriculture, advance knowledge of many factors important to production is either impossible to obtain or not always accurate. Hence, decisions must often be made under conditions loosely defined as uncertainty. Heady and Jensen discuss several important areas of uncertainty involved in any typical farm operation.[1] Prices, more than any other aspect, introduce uncertainty into the farmer's decision problem. Furthermore, in all farming and particularly in arid and semi-arid areas, weather and water availability affect crop yields. Likewise pests and crop diseases have significant impacts on the latter. Longer term technical changes and economic conditions will also introduce substantial uncertainty into longer range planning. Government policy in the form of decisions on crop support prices, acreage allotments and production control, storage programs, crop insurance and international trade policies affect farm product prices. Depending on the individual farmer's financial position, his family responsibilities and his tendencies to be a risk averter or a risk taker, he will adjust his cropping plans in face of the above uncertainties, all of which can directly or indirectly affect his income. For some of these hazards, insurance exists which can offset the potential financial loss to individuals.[2] Insurance against drought, however, is generally not available.

Though all of the above factors have important effects on agricultural decisions, this investigation must necessarily be confined to only one aspect that creates difficulties in the decision process of Western irrigation; i.e., the impact on planting and production decisions caused by the variable and only partially predictable runoff from mountain watersheds, the magnitude of which is usually not known until well after the majority of planting decisions have been taken. Since receipt of adequate quantity and timing of water supply is vital to successful irrigation, other things equal, one would expect inability to accurately predict wide variations in supply to have a pronounced effect on the optimal level and intensity of cultivation. This is so because the decision-maker is required to make more or less irreversible commitments of some productive resources (seed, fertilizer, labor, and machine time, some water, and other supplies) prior to receipt of full information on the available water supply throughout the growing season.

Streamflow forecasts provide at least some advance knowledge to the irrigator about the water supply conditions which will affect the profitability of his operation. These forecasts of seasonal streamflow are based on two techniques, described in detail in Chapter III. Forecasts published by the Soil Conservation Service and cooperating state and private interests are based on the estimated relationship between seasonal streamflow and water equivalent of the mountain snowpack, while forecasts made by the U. S. Weather Bureau are based on precipitation data collected at long established stations. The seasonal forecasts published by these two agencies are generally for the period from April through July or May through September and are in terms of a total volume of water expected during the forecast period. Though the forecasts contain inherent inaccuracies, due both to problems of measurement and to the unpredictable nature of longer range weather conditions subsequent to the date of the forecast, they do provide irrigators with some basis for making adjustments in their crop planting decisions. These adjustments may serve to increase their annual net income by increasing their gross income or reducing their annual losses. If the overall accuracy of these forecasts could be improved, then additional economic benefits are likely to accrue to the various affected interests.

While the insights from several disciplines will be brought to bear in the analysis, the economic decision variable of interest is the potential increase in net income that may result if crop acreages and types planted are altered in response to increased accuracy of the water supply that will be available after planting has taken place. Because of the continuous nature of the decision process, where commitments and considerations not directly related to planting bear on the planting decision, the technique of isolating one factor for the sake of analysis may not produce realistic results. On the other hand, it is exceedingly difficult to handle a highly complex problem without resorting to simplification. By enumerating the factors which may qualify the results derived from analysis of a single variable, the realism of the results can at least be kept in perspective. Thus the economics of the situation under consideration involve potential gains in net income due to better information on conditions that effect a more or less irreversible decision which generally has to be taken before the conditions (water supply and summer weather) are realized.

Review of Previous Work

In focusing on the evaluation of the nature of the benefits to irrigated agriculture from increased forecast accuracy, a review of previous investigations was undertaken. The available literature on the subject dealt with either qualitative response to expected conditions or benefit estimates associated with forecast use. A review of the literature on the nature of response of irrigators to forecasts of seasonal supply is presented in Appendix I and summarized below.[3,4,5,6,7] General responses may involve three different types of adjustment in planting. Adjustments to expected below normal water supply include reduction in the total acreage planted, planting of crops which require less total water per acre, and planting of crops that mature early to take advantage of early season water. Adjustments to expected abundant supplies would involve just the opposite, including expansion of total acreage planted, planting of crops with high payoff and high water requirements, and planting of crops that produce greater returns but are sensitive to drought.

Attempts to evaluate the monetary benefits from the utilization of forecasts have generally focused on either the dollar savings resulting from alteration of planting decisions when the strong probability of a poor water year is forecast or imputation of the benefits that accrue when forecasts of probable surplus flow result in additional releases to agriculture from reservoir systems. In a paper presented at the 1969

Western Snow Conference, Morlan Nelson summarized the results of several studies dealing with the benefits from use of forecasts.[8] For example, in a study by Carroll Dwyer and Vernon W. Baker, [9] analysis of farm budgets in the Salmon Falls tract in south central Idaho indicated the following:

> ...$23.00/acre was realized in additional farm income by those who followed the forecasts in 1955, a 70 per cent water supply year, compared with farm and ranch operators who seeded the same acreage each year regardless of water supply. On this tract alone, savings amounted to $378,850 for irrigated land, which ranged from 12,000 acres in a dry year to 24,000 acres in a heavy snow season. These savings were realized because the farm and ranch operators, who followed forecasts and limited their operation according to the amount of water available did not preirrigate, fertilize and seed land for which tere was not enough water to mature a crop. The amount of water saved by not preirrigating was then used on the better land on each farm to mature a crop. The combination of this knowledge and operation in irrigation resulted in these savings.[10]

In another paper in the proceedings of the Western Snow Conference, Robert E. Moore discusses use of the forecasts in the Salt River system in Arizona.[11] In 1960 the forecast for the Verde, a tributary of the Salt, indicated the possibility of snow melt water exceeding storage capacity during the forecast period. This information resulted in the decision to release water from storage in the Verde system to be able to control the expected snow-melt runoff. This water was diverted to irrigated land in the valley. The quantity of water involved was estimated to have value of $201,000 to irrigation alone.[12] (no description of the estimation procedure was given).

The only study found which used a generalized approach was one by James Shelton, an economist with the Soil Conservation Service in Boise, Idaho.[13] The results of this analysis are presented below in the graphical form used by the author and are based on agricultural data from southern Idaho and the following assumptions and relationships. Two farm models with 200 acres each and water rights under normal conditions to adequately water 75 per cent of each farm, or 150 acres, are assumed. In order to evaluate the benefit from forecasts, the author further assumes that the irrigator operating under conditions of complete uncertainty will always plant 150 acres on the basis of receiving the normal water supply. On the other hand, the irrigator operating with the aid of a forecast is assumed to plant in proportion to the amount of water predicted; i.e., for a forecast of 66 per cent of normal water supply, he would plant 100 acres. Although the author states that use of the forecast changes the situation from one of uncertainty to one of risk, where risk becomes the actual volume of water available under perfect knowledge,[14] this is a misuse of the normal definition of the terms* based on Knight's classic work.[15] The graphical analysis below actually depicts the difference in net income between uncertainty and complete certainty, rather than between uncertainty and risk. Avoiding this issue for the moment, the two lines in Figure 7 are derived as follows.

Annual fixed costs for both farms are estimated at $5,000 (including taxes, insurance, water charges, fencing, ditch maintenance and machinery amortization, but excluding interest charges or any annual crop production expenses). Studies showed that per-acre weighted net return equals approximately $80.00 for every acre fully irrigated in the area studied (southern Idaho). Net income for the farm using the forecast would then be equal to the acreage planted (in proportion to the forecast water supply) X $80.00/acre - $5,000 annual fixed costs. This relationship is depicted by the upper line in Figure 7.

Under uncertainty, however, operators plant their acreage each year based on the assumed availability of the "normal" water supply. Studies in southern Idaho showed that for a water year which is 50 per cent of normal, loss per acre varied from $10.00 to $50.00, depending upon the intensity of cultivation. For the cropping pattern used in the model, the weighted per acre net return for a 50 per cent water year was a minus $32.60. To derive the curve for net income under uncertainty, the author determined the loss for a 50 per cent water year (150 acres X (-$32.60/acre) - $5,000 fixed costs) and then assumed a curvilinear relationship up to normal supply.

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*Correctly defined, uncertainty is associated with situations in which no knowledge of the likelihood of future conditions can be obtained. Risk is associated with a situation in which specific outcome can be defined and probabilities attached to each of the outcomes. Certainty, of course, is defined as a situation in which the decision-maker has perfect knowledge of the outcome of any future events which might affect him.

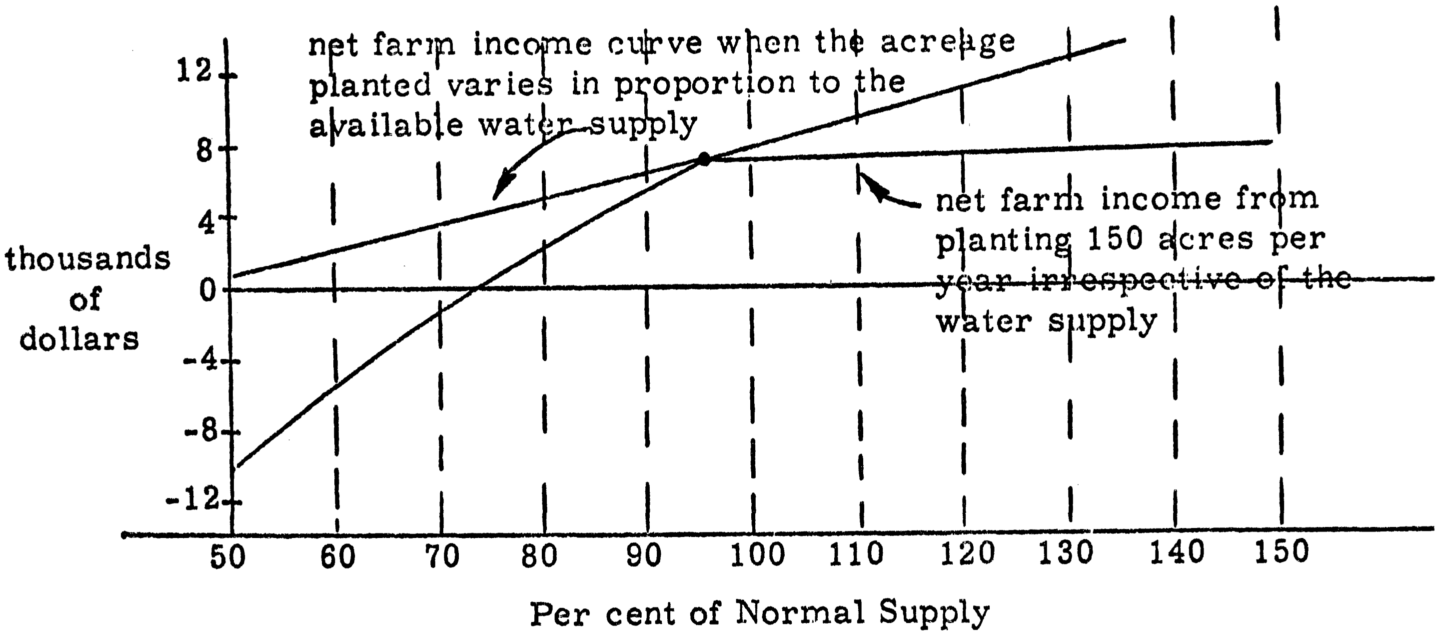

Fig. 7--Net farm income with and without available water supply forecast

In terms of this model, the total value to the irrigator from following the forecast is the area between the two lines. These results were generalized by using the above model, and a similar one developed for a cow-calf operation. A variation of 25 per cent above and below normal was assumed in order to determine forecast value. These annual figures were \$14.00 per acre for general farming and \$6.45 under cow-calf operation. Netting out the irrigated acreage served by Bureau of Reclamation projects, Nelson estimates that there are about 13,000,000 acres in the West, excluding land serviced by Bureau of Reclamation projects, on which forecasts have a definite or potential use by irrigators. Assuming that the land is evenly divided between general farming and cow-calf operations, the average value of forecasts would be about \$10.00 per acre. Based on the mailing lists of the Soil Conservation Service, it is estimated that 25 to 50 per cent of the farms and ranches make significant alternations in their operations based on water supply forecasts. The increase in farm income based on these assumptions would be between \$32,500.00 and \$65,000.00. Nelson indicates that the land on which forecasts are not followed, or where operations are flexible, includes large areas served by pumping from ground water.

The above model proceeds from assuming only the end points of a continuum with certainty or perfect knowledge at one end and uncertainty or no knowledge as to water supply at the other. The designation of the forecast situation as being one involving risk is incorrect, since risk is generally defined as a situation in which the frequency distribution for the outcomes of a series of events is known. Even with forecasts, there is no assurance that a prediction of 60 per cent of normal water supply will actually result. Due to several factors including errors in measurement and warm weather precipitation, runoff could be 130 per cent of normal or 70 per cent of normal, or any other physically possible occurrence. Further, while irrigators may plant the same acreages each year, this does not necessarily imply a situation of complete uncertainty. Since the normal water supply is the one which occurs most often, without specific knowledge each year as to water supply, the "best bet" is to plant on the basis of normal. In this sense the irrigator is operating in a situation characterized by risk rather than uncertainty in that he knows the historical frequency distribution of water supply but does not know for any given year what his supply will be. The first settlers in some of the western basins may have operated under situations which would be characterized as completely uncertain. After several years of observation, the lack of any knowledge as to what water supply would be was modified by historical observations, which would permit establishment of at least an implicit frequency distribution. It might be pointed out that even if early irrigators operated under conditions approximating uncertainty, it probably made little difference economically since their demands relative to an uncertain and variable water supply may not have exceeded the supply even in bad years.

Introduction of streamflow forecasts adds a new dimension to the problem in terms of additional information. The forecasts change the situation from one where only historical probabilities of various flows can be approximated to one where some knowledge of the range of likely flows for a given season can be obtained. In technical terms, the forecasts permit establishment of a conditional probability distribution of the occurrence of various flows. This term is explained in any introductory statistics text and is used in Chapter II to present a conceptual model for analyzing the problem. If the forecasts were perfectly accurate, of course, there would be no probability distribution associated with the prediction of a given seasonal water supply. However, this is not the case, so that the forecast can be conveniently thought of as a probability distribution of observing various magnitudes of streamflow (contrary to the analysis above).

Rather than examining the value to irrigated agriculture from a completely accurate forecast, the objective of the study is to examine the benefits associated with incremental increases in forecast accuracy. Concepts such as risk and conditional probability are important to the development of such an analysis and are the subject of the next chapter.

FOOTNOTES

[1] Earl O. Heady and Harold R. Jensen, Farm Management Economics (Englewood Cliffs, N. J.: Prentice Hall, Inc., 1959), p. 516.

[2] Ibid., p. 523.

[3] Israelsen and Hansen, Irrigation Principles and Practices, pp. 15-16.

[4] William Johnson, "Benefits of Forecasting Data of Low Snow to Water Users of the Carson River," Western Snow Conference. Proceedings of the Twenty-Ninth Annual Meeting (Spokane, Wash., April 11-13, 1961), p. 82.

[5] U. S., Department of Agriculture, Soil Conservation Service and Colorado State University Agricultural Experiment Station and Colorado State Engineer Co-operating, Snow Surveys in Colorado, by Jack W. Washichek, Homer J. Stockwell, and Normal A. Evans, General Series No. 796 (Fort Collins, Colo., 1963), p. 32.

[6] R. A. Work, "Snow Water," Soil Conservation, U. S., Department of Agriculture, Soil Conservation Service, March, 1956, p. 182.

[7] R. N. Irving and Morlan W. Nelson, "Snow Surveys Made by and for the Water Users," Soil Conservation, U. S., Department of Agriculture, Soil Conservation Service, March, 1956, p. 182.

[8] Morlan W. Nelson, "Social and Economic Impact of Snow Survey Data and Water Supply Forecasts," Western Snow Conference. Proceedings of the Thirty-Seventh Annual Meeting (Salt Lake City, Utah, April 15-17, 1969).

[9] George D. Clyde and Clyde E. Houston, "Benefits of Snow Surveying," Western Snow Conference. Proceedings of the Twenty-First Annual Meeting (Victoria, British Columbia, 1951).

[10] Nelson, "Social and Economic Impact of Snow Survey Data and Water Supply Forecasts," p. 2.

[11] Robert E. Moore, "Economic Considerations of Water Yield Forecasting for the Salt River Valley, Arizona," Western Snow Conference. Proceedings of the Thirtieth Annual Meeting (Cheyenne, Wyo., April 16-18, 1962). p. 88.

[12] *Ibid.*

[13] Morlan W. Nelson, "Effects of Water Supply Forecasts on Conservation and Economic Use of Water" (paper presented at the Economics of Conservation Society of America, Utah State University, Logan, Utah, August 25-28, 1963).

[14] *Ibid.*, p. 70.

[15] Frank F. Knight, *Risk, Uncertainty and Profit* (Boston: Houghton Mifflin Company, 1921), p. 233.

CHAPTER VI

ELABORATION OF THE GENERAL CASE

The conceptual framework presented in Chapter II provides the necessary theoretical foundation for analyzing potential economic benefits from increased accuracy in streamflow forecasts. The complexities of irrigation water supply relationships, however, require elaboration and refinement of the general model.

While a generalized description of the structural and institutional nature of irrigation water supply necessarily overlooks facets that are particular to any given irrigation area, it is important to consider first an abstraction of the problem. Excluding warm weather precipitation and initial soil moisture at the time of planting, seasonal water supply comes from one of three sources: from direct streamflow; from water stored in reservoirs; or from irrigation wells. In many cases, all three sources may be utilized in varying degrees. Institutionally, direct flow and storage water are usually provided to the individual irrigator through the distribution facilities of mutual ditch companies. There are a variety of arrangements under which water is delivered to the individual farms served by the ditch companies. Several of these are discussed by Anderson and Maass.[1] They can generally be classified as: (1) fixed percentage systems; (2) priority systems; (3) demand systems; and (4) combination systems. In the first system, each farm receives a fixed percentage of the variable water supply available in each time period. Determination of the percentage is based on either the number of shares the farmer owns in the system or on reservation of specific times for receipt of water. In the second system water is allocated on the basis of some fixed order of priority such as location, time of settlement, or crop type. In the third system, water supply for the season is stored in reservoirs or ground water and is available on demand. The fourth system is most typical of reality in which various combinations of the first three categories are used to deliver water. For purposes of this analysis, it will be assumed that irrigators receive water in proportion to the number of shares they own in the system and that the water supply is delivered through a combination system.

Under the law of prior appropriation which generally prevails in western areas, ditch companies are granted rights to divert specified rates of flow from a given river. When the rate of flow of the river falls below the sum of the total rights on the river, the water right last in time is first to be cut off. Often a ditch company may hold water rights of different priorities, which then involves a series of reductions in rate of flow to the given ditch as the total rate of flow of the river recedes during the course of the irrigation season. In addition to direct flow rights, ditch companies may also hold or have options to purchase rights to water stored in reservoirs.

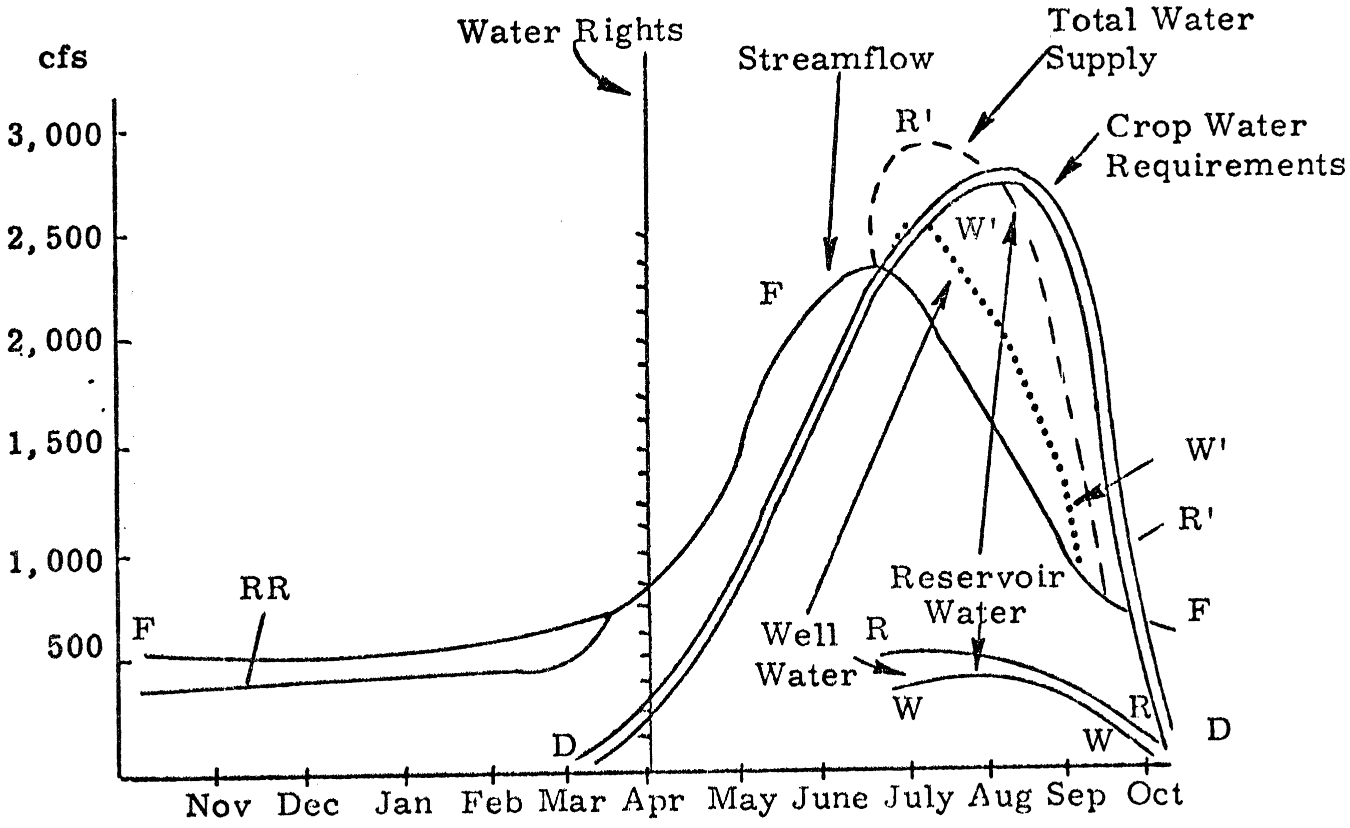

Fig. 8.--Components of Irrigation Water Supply

Graphical presentation of the dynamics of a typical irrigation region helps to clarify the relationships involved. On the horizontal axis of Figure 8, time is measured in intervals of one month. On the vertical axis, river flow is measured in cubic feet per second. Line F represents streamflow, including return flow from irrigation during the irrigation season. The vertical crossed line represents individual blocks of water rights in cubic feet per second. In addition to surface flow, many irrigation areas have ground water pumping capacity. While oftentimes farms on ditches with adequate surface rights may also have wells, it will be assumed for purposes of exposition that well water supplements surface flow for those ditches with inadequate surface rights. Well pumping capacity is represented by line W, which is added on to surface supply as W' . Further, most irrigation areas have some reservoir storage capacity and many rely heavily on reservoir water to meet irrigation needs. Reservoir storage adds to seasonal flow by redistributing water in time, either from spring floods to later summer or between years, depending on the storage capacity of the reservoir system and the institutional and engineering arrangements for operation of the system. Storage water may also be procured through projects for geographic redistribution. Line R represents storage water and is added to the total supply as Line R'. If reservoir water comes from earlier flow in the given year, R should be subtracted from F. If the reservoir water is from overseason storage, then R' is a net addition to water available in the given year. Addition of the separate components thus represents the total water available to an irrigation area excluding preseason soil moisture and warm weather precipitation.

Line DD represents estimated irrigation requirements. These will vary from year to year depending on temperature, wind, humidity, precipitation, and initial soil moisture and type of crops planted. Very broadly, the requirements are calculated as the average total consumptive use of the crops grown in a given region divided by the irrigation efficiency of the region. The consumptive use requirement is the average quantity of water which will be transpired by a growing crop and evaporated from the soil and foliage during the season if an adequate supply of soil moisture is available.[2] Irrigation efficiency has many components (see Israelson and Hansen[3]), but for purposes of this discussion, it will be defined as the percentage of water entering a total irrigation system which actually meets consumptive use requirements. Inefficiencies result primarily from transmission and distribution losses to ground water, losses to deep percolation in the field, losses to tailwater, use by phreatophytes (plants whose roots extend to the water table), and other losses such as evaporation from reservoirs. Thus potential irrigation requirements for a given season will depend on the types of crops planted, the number of acres planted, total irrigation efficiency, weather characteristics, and soil types.

The stochastic nature of several of the components of irrigation water supply, particularly streamflow, weather, and often reservoir storage, introduce risk in the annual decision processes of irrigators. The physical control over timing of the water supply introduced by reservoir storage and ground water pumping capacity in conjunction with the priority system of water rights serves to create an indirect relationship between the conditional probability of observing forecast states of nature (streamflow) and the actions and payoffs actually open to irrigators. Refinement of the general model requires inclusion of three additional factors, namely priority of water rights, available reservoir storage, and groundwater pumping capacity. Modifications in the benefit function resulting from these factors provides the theoretical structure for the total net benefit function to irrigated agriculture from increased accuracy in streamflow forecasts.

Representation of Water Rights

The necessity of priority in appropriation of surface water often creates a situation in which "junior" or later decrees on a given river may only be satisfied early in the season and inadequately, if at all, late in the season or during low water years. Abstracting from the complexities of transferring water from areas of excessive use to areas of shortage within a basin (which is a problem of non-equimarginal returns), the crucial element becomes one of knowing approximately how long one will have surface water during the season. Generation of this type of information requires the use of a technique known as low flow forecasting which is of extreme importance to junior water right holders.[4]

The use of this technique is discussed in two papers in the Proceedings of the Western Snow Conference.[5,6] As Pearson and Peck state:

> ...full primary rights in some sections of the Sevier River (Utah) are satisfied up to approximately the time that streamflow drops to certain values at specific gaging stations. These values represent the sum of decreed rights within those sections and are of concern when river flow is on the recession limb of the hydrograph. Since the general form of the hydrograph is related to the volume of runoff during the high water period, the volume forecast may be used to estimate the date when specified flow values will occur.[7]

While no attempt will be made to investigate the extent to which improvements in volumetric forecasts can be translated into improvements in forecasting specific low flows, it is assumed that there would be such improvements. Thus improvements in volumetric forecasts in conjunction with estimates of the date on which streamflow will fall below a given rate would provide important information to the irrigator. The important operational question involves the percentage of water right that can be expected and how long duration of flow will be. Pearson and Peck state:

> The percent of primary water right that will be received in any given year is principally related to the volume of water in the river. Preparation of volume forecasts for basins such as the Sevier River (Utah) where streamflow is dependent upon current year snowmelt, groundwater carry over, return flow, low to intermediate elevation precipitation and soil moisture conditions, requires as thorough knowledge of the sources of water for the particular section being studied.[8]

Volumetric forecasts of streamflow give an indication of per cent and duration of flow, but individual irrigators must intuitively extrapolate from the forecast in order to arrive at an estimate of their own particular situation. Low flow forecasts, as indicated above, increase the information available for this assessment.

In terms of the model, the state of nature of concern to the individual irrigator is determined by the water rights of the ditch company under which he farms. For ditches with very senior water rights, the conditional probability of receiving their decreed amount of water would be very high, regardless of the "bigger picture" as estimated by forecasts based on snowpack and watershed conditions. For those ditches with less secure rights, there would be a broader conditional probability distribution that forecasts based on snowpack and watershed conditions indicate rate of flow great enough to assure various percentages of full decreed water rights. For junior or flood rights, the conditional probabilities of receiving the full decreed flow given various forecasts would likely be low. Though forecasts of flow to specific ditches are not routinely made, Figure 14 in <u>Snow Surveys in Colorado</u> shows that the number of acre-feet per share delivered by one ditch company compared to the April-September streamflow.[9] Development of the model will proceed on the assumption that river forecasts can be translated into meaningful predictions of water supply for individual ditch companies.

Thus in a given irrigation area, the state of nature $S = (S_1, \ldots, S_j, \ldots, S_n)$ determined by snowpack, watershed, and weather conditions, will indirectly determine the state of nature faced by the irrigators under a given ditch company. Those ditches with very senior water rights may have adequate water in all but the most adverse years, whereas ditches with junior rights on the same river may have adequate supplies only in years when runoff is very heavy and prolonged. To incorporate this relationship in the generalized benefit function (equation 3, Chapter II), the following adjustments are necessary. Rather than conditional probabilities being given for streamflow S_j given Forecast F_K, the conditional probabilities will now be those of receiving a given percentage of decreed surface rights for a specified ditch company given the forecast F_K. More formally, let R_d be the decreed surface rights of ditch company d. Let $Z_1, \ldots, Z_j, \ldots, Z_n$ be the percentage of surface rights received by ditch company d, where $0 \leq Z < 1$ and each Z_j corresponds to the larger state of nature S_j (rate of flow in the river from which ditch d draws its supply). Further, there may be snowpack-watershed-weather circumstances in which beyond a certain rate of river flow, S_j the ditch company receives its complete water right. Thus the possible states of nature facing our hypothetical ditch company d are $R_d = (R_d Z_1, \ldots, R_d Z_j, \ldots, R_d Z_n)$ where beyond Z_j, $Z = 1$; i.e., the rate of flow in the river from which the company draws its water is great enough so that the complete surface flow right R_d is satisfied. In other words, for basin-wide states of nature exceeding S_J, $Z_j, \ldots, Z_n$

is one and the full surface right R_d is obtained. Thus, in theory, for a given forecast F_k, there would be a conditional probability distribution $P(R_d Z_j / F_k)$.

The first revision in the theoretical treatment of potential net benefits from increased accuracy involves incorporation of the above considerations. Let the net value to ditch d be B_d, then

$$(4) \qquad B_d = \sum_k [\sum_j a_{ij} P(R_d Z_j / F_k')' P(F_k') - \sum_j a_{ij} P(R_d Z_j / F_k) P(F_k)]$$

where all symbols are the same as listed on page 15 and $P(R_d Z_j / F_k')'$ is the conditional probability after increase in the accuracy of the forecasts. Since the actual benefit accrues to the farms under ditch d, equation (4) contains the implicit assumption that B_d is equal to the sum of the benefits to the individual farms on ditch d. This requires the further simplifying assumption that each farm shares equally in the fortunes of the ditch company and that shares are owned in proportion to the quantity of land that is owned.

Aggregate annual benefits would be estimated by summing benefits to individual ditch companies in each basin and then summing over basins. Ideally adjustments would have to be made for any expected price effects that resulted from increased forecast accuracy.

In terms of the matrix of outcomes (a_{ij}) relating states of nature (j) to different planting strategies (i), the state of nature an irrigator faces will now be determined by the interaction of streamflow and the character of the water rights of the ditch company under which he farms. For farms under ditches with very good water rights, the optimal course of action on the part of the individual irrigators would not vary appreciably from year to year as a result of variations in the runoff from mountain snow and warm weather precipitation, other things equal. For farms under ditches with later priority rights and thus less secure surface supply, the optimal strategy would change from year to year and increased accuracy in volumetric-low flow forecasts, a priori, should produce benefits.

Representation of Reservoir Supplies

This situation involves those irrigation areas where storage for the purpose of redistributing water to the times of greatest demand plays a significant role. These are usually the middle and end of the summer when crop water requirements are greatest. Storage capacity gives the irrigator physical control of water supplies and the ability to offset maldistribution in the timing of water availability. Redistribution may be from periods of heavy runoff early in the season or in some cases from surplus runoff from the previous year or from interbasin diversions. Storage is generally provided by multi- or single-purpose Federally-built reservoirs or by smaller privately financed reservoirs, often owned by ditch companies.

The control or partial control of the annually variable water supply is quite different from the situation in which the water supply comes entirely from direct flow. In analyzing the nature of this case, those variables for which forecasts play an important role from the irrigator's point of view must be specified. A paper by J. R. Barkley given at the 1959 meeting of the Soil Conservation Society of America, discusses this point with regard to the Colorado-Big Thompson project serving the South Platte Basin in northeastern Colorado.[10] Barkley lists four criteria that are of importance to operating decisions as follows:

1) They carryover storage in the given reservoir or in the system of reservoirs;
2) The quantity of water carried over in reservoirs of the ditch company systems throughout the irrigation area;
3) Soil moisture conditions in the irrigated area as of late winter;
4) Runoff prospects as indicated by the mountain snow survey-soil moisture data available the first of each month beginning in January.

In the case of the South Platte Basin, Barkley goes on to say that by conveying the results of their (Northern Colorado Water Conservancy District) studies to the various ditch companies and by setting their first allocation of water (the percentage of a full acre foot for each alloted unit of project water[12]) in late March, each company may appraise its individual position. This appraisal involves consideration of the amount of available storage each ditch has at the start of the season, the amount of District project water available at the start of the season and an estimation of its share of prospective runoff based upon the available streamflow as forecast. The farm operators under each ditch company are then

> ...advised of the probable water supply conditions with which they must contend for the oncoming crop season. By similarly conveying any required adjustments based on the April, May, and June snow measurements or water supply forecasts, the ditch companies and individual farmers may alter their seasonal plans accordingly.[13]

Physical control, in terms of ditch company storage at the beginning of the season and in terms of project water which can be redistributed both in time and space, gives the irrigator an increased degree of certainty as to the availability of water when it is needed. Timing is usually the crucial factor. Increased certainty due to physical control over a portion of the supply would be reflected by the payoff from the optimal strategy chosen. Depending on the other factors necessary for successful irrigation farming such as soil characteristics, financing, climate, managerial and farming skill, and proximity to markets or distribution systems, the increase in control over the supply would increase farm income. Control permits more intensive, more efficient agriculture from the point of view of the irrigator.

For example, Miles observes that, on the average, less than 25 per cent of the total surface water deliveries in the Arkansas Valley of Colorado are made during July and August. Because many of the more profitable crops require most of their water during this time,

> ...less profitable cropping programs have been followed, excessive water has been applied during times of availability and the yields are often greatly depressed because of lack of water in August.[14]

In another paper, Miles states in reference to the Arkansas Valley:

> Acreages of the various crops vary considerably from year to year with farm programs, prices, and water supply. Also it can be expected that a dependable and better timed water supply would result in a considerable change in cropping practices. For example, much of the present

> acreage of alfalfa and small grains is a result of the ability of these crops to make use of large quantities of spring water. On the other hand, corn and sugar beets require large amounts of water in July and August. An imported water supply will result in a shift to more profitable crops.[15]

The important question in refining the model is the role that streamflow forecasts play in the irrigator's decision problem. Pearson and Peck discuss the nature of the forecast problem for the Sevier Basin in Utah. They state:

> At present the total water that will be available for storage each year is not being forecasted. To be of most value for planning, forecasts of the water available for storage from winter flow must be made in late fall or early winter. By April 1 this is, of course, determined by reservoir storage.
>
> Since the winter flow is primarily a residual from the previous year's streamflow, this can be readily estimated in the late fall months. To date, however, the river commissioner's reports have not segregated the winter storage water from other rights. The winter storage of previous seasons is currently being developed by the commissioners. Water available for storage during the spring months is related to peak flow. When total flow exceeds 400 cfs in Sevier Valley and 360 cfs in the reach from Vermillion Dam to Gunnison, water is available for use by those with storage rights in Piute and Sevier Bridge Reservoirs. In order to determine the amount of water that may be available for storage, it was necessary to prepare forecasts of amounts of water expected to exceed the primary flow rights of 360 cfs and 400 cfs.[16]

The irrigator in this case is faced with a different state of nature than in the case of no spatial or temporal redistribution of the water supply. While the snowpack and watershed conditions combine to produce the "macro state of nature," the impact on the irrigator from these broader phenomena is considerably altered by storage and surface rights. Depending on whether a project is multi or single purpose, the operating regulations, storage capacity relative to demands, the nature and distribution of storage rights, and the extent of private storage facilities and their rights to streamflow, water from periods of heavy runoff will contribute to overseason storage or to storage to be drawn on to meet irrigation requirements toward the end of the growing season. Alternation of the benefit function to reflect the interaction of streamflow and reservoir storage is accomplished by a change in the factors that determine the conditional probability distribution $P(S_j/F_k)$. Assuming a possible state of streamflow that ditch d could receive designated R_dZ_j ($j = 1, \ldots, n$) and m possible quantities of reservoir water designated C_dZ_j (where C_d is the maximum quantity of reservoir water ditch d could receive and Z_j ($j = i, \ldots, m$) are percentages such that $0 \leq Z_j \leq 1$). The total number of states of nature that ditch d could face would be $n \chi m$; i.e., all the possible combinations of surface and reservoir water that could occur given ditch d's surface water rights and access to storage water. In probability terms, the decision maker is now faced by a joint probability that a given state of nature will occur, namely the probability that the combination $R_dZ_j + C_dZ_j$ will occur. For purposes of the general case, it will be assumed that the two events are dependent in the probability sense. In other words, it is assumed that years of high runoff will normally be years in which the quantity of water in reservoirs also tends to be high. There are, of course, many other possibilities, such as situations in which over-year storage provides ample reservoir water, but streamflow is low, or cases where streamflow is adequate but little water is available from storage. All of these possibilities depend on a complex set of storage and surface flow rights, particular to each basin and state. Investigation of potential changes in state laws affecting water rights and designed to utilize the available supplies more efficiently is beyond the scope of this study; therefore, the matter will be left in the simplified form as stated above. The conditional probability would now be written as

$$(5) \qquad P(R_dZ_j + C_dZ_j/F_k) = \frac{P(F_k/R_dZ_j + C_dZ_j)P(R_dZ_j + C_dZ_j)}{\sum_{j=1}^{n \chi m} [P(F_k/R_dZ_j + C_kZ_j)P(R_dZ_j + C_dZ_j)]} .$$

This is simply the Bayesian formula that was presented on page 12 modified so that the states of nature involve all the possible combinations of surface and reservoir water. In order to simplify notation let W_{sd}, $s = 1, \ldots, n \chi m$, represent the possible combinations of water supply so that equation (5) becomes

$$(6) \qquad P(W_{sd}/F_k) = \frac{P(F_k/W_{sd})P(W_{sd})}{\sum_{j=1}^{n \chi m} [P(F_k/W_{sd})P(W_{sd})]} ,$$

where $P(W_{sd}/F_k)$ is the conditional probability of observing the s different states of nature facing ditch d where $s = 1, \ldots, n \chi m$, the possible combinations of surface and reservoir water. As in the case with surface flow, the ditch company receives an amount of reservoir water determined by its storage rights and the larger states of nature $s_1, \ldots, s_j, \ldots, s_n$. There may be snowpack-watershed-weather circumstances in which for conditions exceeding S_j the ditch company receives the complete quantity C_d of storage water. In other words, for basin-wide states of nature exceeding S_j, $Z_j, \ldots, Z_n$ is one and the full quantity from storage C_d is obtained. It is also possible that the supply of reservoir water has some elasticity above the institutional constraints faced by the individual ditch company. This would be the case where transfers are structurally possible and where markets and mechanisms of exchange between users have developed. A case study by Raymond L. Anderson describes this type of situation in the South Platte Basin in Colorado.[17]

Substituting equation (6) into the annual benefit function for ditch d gives

$$(7) \qquad B_d = \sum_k [\sum_j a_{ij} P(W_{sd}/F_k')'P(F_k')] - \sum_j a_{ij} P(W_{sd}/F_k)P(F_k)] \quad .$$

The key assumption in the above equation is that there exists a mechanism for transforming forecasts of snowpack and watershed conditions into explicit predictions relevant to the individual decision units. Such information would need to cover both predicted percentage of decreed surface rights as well as a prediction of the flow that will be available to individual ditches from surface storage in those cases where supplies are not completely known at the start of the irrigation season.

Other aspects of this case do not bear directly on the equation form of the model, but their discussion is necessary for completeness. As Miles points out, the ability to control timing of water enables irrigators to expand the acreages of the more profitable crops which are more sensitive to drought at critical periods in their growth. This physical control is not reflected by the formulation of equation (7), though it would be possible in the general model to change $P(W_{sd}/F_k)$ to represent conditional probabilities of observing different quantities and temporal distributions of those quantities. For example, a forecast might involve both a prediction of volume and a prediction of possible seasonal distribution. The ability to make a distributional prediction would involve prediction of longer range weather patterns, particularly temperatures and timing of warm weather precipitation.

In addition to the likely effect on net farm income from increased control over timing, differences in per-acre-foot costs of project and private reservoir water and water secured through surface flow rights would affect the net incomes realized under various planting strategies and water supply conditions. If low surface flow from below normal snowpack and watershed conditions can be offset, crops can be saved at a cost.

Actual assessment of the extent of total reservoir development for irrigation purposes is not possible from available published data. However, Bureau of Reclamation Crop Reports do provide figures on all land supplied by Bureau projects in eleven western states. These figures are presented in Appendix II and are compared with estimated total irrigated acreage in the same states. The proportions vary from 13 per cent for Nevada to 68 per cent for Washington. The average is 30 per cent. Also, it must be noted, that these figures do not include private reservoir storage which is extensive in some areas.

Representation of Well Water

Many agricultural areas in the West are irrigated partially or wholly from wells. Figures showing estimated acreages irrigated from well water and volumes applied for eleven western states are presented in Appendix II. The percentage of total acreage irrigated by ground water varies from an estimated 2 per cent in Wyoming to an estimated 67 per cent in Arizona. As in the case of water supplied through reservoirs, the importance of ground water lies in the physical control it gives the irrigator in timing his water applications to crop needs.

While ground water availability may vary depending on hydrologic conditions, the nature of the aquifer from which water is withdrawn, and the aggregate effect many wells can have on an aquifer, it will be assumed here that well water represents a non-stochastic input to total irrigation supply. Thus ground water does not enter into the forecast of water supply, though it cannot be ignored in the formulation of the general case since the existence of pumping capacity introduces the opportunity for substitution in sources of water inputs, particularly in years when surface or storage water is not abundant. Precise inclusion of this component must wait until Chapter VII where an operational model is developed. However, in rather generalized terms the existence of a maximum area pumping capacity designated $\bar{G}$ can be incorporated into the benefit function in a fairly straight forward manner. Let W_{sd} (Total possible water supply condition available to ditch d) now be

$$W_{sd} = R_{dz_j} + C_{dz_j} + \bar{G} \quad .$$

The number states of nature does not change, since W_{sd} $W_{sd} = n \chi m \chi 1 = n \chi m$. Thus the formulation of the benefit function in equation (7) remains unchanged. However, if well water costs exceed the costs from surface or reservoir sources, net incomes realized in years when surface and reservoir water is not abundant will be reduced even if the same types of crops are planted.

The discussion of this case so far has rested on the implicit assumption that the sum of private pumping costs equals the social costs. In dealing with a common property resource such as ground water, this is often not true. Two very broad cases are involved--one in which the rates of pumping tend to deplete surface flow thus conflicting with already adjudicated surface rights, the other where ground water is being mined at a rate which does not maximize present discounted value.

In the case of mining, too rapid a rate of extraction is due to the common property characteristics of the resource. The indefinite nature of future availability of the water fosters an undervaluation of future benefits and a more rapid rate of withdrawal.[18] Social costs result from the fall of the water table in given areas and the resultant additional increase in pumping costs. In terms of the generalized formulation of the benefit function, an estimation of the social costs imposed by too rapid extraction could be reflected by reduction in the net incomes for each state of nature and planting strategy. In other words, net private income resulting from the various alternatives would be reduced to indicate the social costs imposed by the heavier pumping to offset below normal supplies from other sources.

In cases where there is interconnection between surface and ground water, development of regulations promoting conjunctive use of surface and ground supplies is required. In terms of the model, such regulation could be reflected in variable quotas or in taxes on excessive pumping rates. This general area is one of interest from the standpoint of present and future efforts at cyclic management of the resource which involves policies under which surplus runoff in some years is percolated to existing aquifers in order to be drawn upon in years in below average runoff. Likewise, other situations may involve heavy pumping during the irrigation season, with natural or artificial replenishment during periods of heavy runoff. Essentially, underground storage capacity is created in aquifers by pumping before periods of heavier runoff. These possibilities are discussed with reference to specific basins and aquifer characteristics by McGuiness in The Role of Ground Water in the National Situation.[19]

Summary

Pumping capacity, storage facilities, senior and junior surface rights, and rights to storage water, produce a complex set of interdependent factors in irrigation water supply. In addition to the variance in importance of these supply sources among irrigation areas in the West, environmental characteristics such as soil, summer precipitation, length of growing season, and temperatures vary widely over the areas in which streamflow forecasts are of value.

The nature of regional benefit functions for improved accuracy in forecasts varies considerably depending on the characteristics of the local water supply, particularly the degree of physical control that a decision unit has over the timing of its water. In the formulation of the model, the larger the proportion of total irrigation water supply that is under control with respect to the timing of delivery, the lower the potential value will be from increased accuracy in the forecast.

The factors producing a high degree of physical control and increased certainty may be adequate pumping capacity, senior water rights, or adequate storage in either Federal or private reservoirs, or a combination of these factors. Though the notation of the structural form of the general benefit function has been given in the preceding pages, it will be presented here for the purpose of consolidation. The general form of the net benefit function to irrigated agriculture from increased accuracy in forecasts is given by equation (7)

$$B_d = \sum_k [\sum_j a_{ij} P(W_{sd}/F'_k)' P(F'_k) - \sum_j a_{ij} P(W_{sd}/F_k) P(F_k)]$$

where

B_d = the annual benefit to ditch d ;

$P(W_{sd}/F_k)$ =the conditional probability for ditch d of observing various quantities of water (W_{sd}) from a combination of surface, well, and reservoir sources, given the forecast F_k ;

a_{ij} =

$P(F_k)$ =the frequency distribution of the various forecasts ;

$P(F'_k)$= the frequency distribution of the improved forecasts.

In the extreme, the frequency distribution for forecasts based on a continually improving forecasting technology would approach the frequency distribution for the states of nature being forecast $P(S_j)$; i.e., perfect forecasts would predict the state of nature precisely and the distribution $P(F'_k)$ would approximate the distribution for $P(S_j)$. The nature of the accuracy problem, discussed in Chapter II, however, does not permit perfectly accurate forecasts to enter the analysis. This is due to the effect weather, subsequent to the last forecast, has on the accuracy of the forecast. Since long range precipitation predictions are not likely to become a reality, at least in the immediate future, unpredictable weather places an upper bound on the increase in accuracy.

Thus the value to improved forecasts for ditch d is the difference between the expected annual income under forecast F_k and F'_k or

$$\sum_j a_{ij} P(W_{sd}/F'_k)'P(F'_k) - \sum_j a_{ij} P(W_{sd}/F_k)P(F_k)$$

summed over all forecasts k. Total net present discounted benefits would, in theory, be estimated by summing the discounted benefits for the farms under ditch company d over the period of analysis, summing discounted benefits for the ditch companies in each basin and summing over the basins in which forecasts are used.

This chapter has provided a conceptual background for understanding the nature of the potential benefits from increased accuracy. In the next chapter the general case will be used to develop an operational scheme for testing the nature of benefits to irrigated agriculture in the context of a hypothetical area under assumed water rights and pumping capacity.

FOOTNOTES

[1] U. S. Department of Agriculture, Economic Research Service, and John Fitzgerald Kennedy School of Government, Harvard University Cooperating, *A Simulation of Irrigation Systems: The Effect of Water Supply and Operating Rules on Production and Income on Irrigated Farms*, by Raymond L. Anderson and Arthur Maass, Technical Bulletin No. 1431 (Washington, D. C., 1971), pp. 5-7.

[2] Donald L. Miles, "Consumptive Use Estimates in Planning for Conjunctive Use of Surface and Ground Water in the Lower Arkansas Valley of Colorado" (paper presented at the Arkansas River Basin Interagency Task Force Committee meeting, March 5, 1968), p. 4.

[3] Israelson and Hansen, *Irrigation Principles and Practices*, pp. 288-94.

[4] William Johnson, "Benefits of Forecasting Data of Low Snow to Water Users of the Carson River," Western Snow Conference. *Proceedings of the Twenty-ninth Annual Meeting* (Spokane, Wash., April 11-13, 1961).

[5] W. T. Frost, "Low-Flow Forecasts on the Rogue River," Western Snow Conference. *Proceedings of the Twenty-Ninth Annual Meeting* (Spokane, Wash., April 11-13, 1961).

[6] Gregory L. Pearson and Eugene L. Peck, "Critical Flow Forecasting for Irrigation Requirements in the Sevier River Basin, Utah," Western Snow Conference. *Proceedings of the Twenty-Ninth Annual Meeting* Spokane, Wash., April 11-13, 1961).

[7] _Ibid_., p. 92.

[8] _Ibid_., p. 97.

[9] U.S. Department of Agriculture, Soil Conservation Service, and Colorado State University Agricultural Experiment Station and State Engineer, Colorado Co-operating, _Snow Surveys in Colorado_, by Jack N. Washicheck, Homer J. Stockwell, and Normal A. Evans, General Series No. 796 (Fort Collins, Colo., 1963), p. 34.

[10] J. R. Barkley, "Agricultural Uses of Snow Surveys and Seasonal Water Forecasts" (paper presented at the 14th annual meeting of the Soil Conservation Society of America, Rapid City, S. D., August 27, 1959).

[11] _Ibid_., p. 8.

[12] Northern Colorado Water Conservancy District, _Thirty-Second Annual Report_, 1968-1969 (Loveland, Colo., 1969), p. 2.

[13] _Ibid_., p. 9.

[14] Donald L. Miles, "The Importance of Water and Irrigation" (paper presented to the Advertising Club of Denver, Denver, Colo., November 2, 1967), p. 5.

[15] Miles, "Consumptive Use Estimates in Planning for Conjunctive Use of Surface and Ground Water," p. 5.

[16] Pearson and Peck, "Critical Flow Forecasting for Irrigation Requirements in the Sevier River Basin," p. 97.

[17] Anderson, "The Irrigation Water Rental Market: A Case Study."

[18] John D. Bredehoeft and Robert A. Young, "The Temporal Allocation of Ground Water--A Simulation Approach," _Water Resources Research_, VI, No. 1 (1970), p. 4.

[19] U. S. Department of the Interior, Geological Survey, _The Role of Ground Water in the National Situation, With State Summaries Based on Reports by District Offices of the Ground Water Branch_, by C. L. McGuiness, Geological Survey Water-Supply Paper 1800 (Washington, D.C.: Government Printing Office, 1963).

CHAPTER VII

A METHODOLOGY FOR TESTING THE GENERAL CASE

In order to carry the concepts presented in Chapter VI to the empirical level, a formal analytical procedure is required. This procedure would have to incorporate a wide variety of structural, economic, and biological phenomena, including estimated crop water requirements, an approximation of water-crop yield response, estimates of typical production costs and gross returns, provision for production flexibility so that different strategies could be followed, an approximation of the availability of the various components of water supply, and a simulation of increased accuracy in the streamflow forecast. Linear programming provides the most practical general method for inclusion and manipulation of the various phenomena whose interaction combine to determine the potential incremental benefits from increased accuracy in seasonal streamflow forecasts for any given geographic area. Decrease in the uncertainty associated with streamflow forecasts could be expressed in terms of an expected standard deviation about the mean. However, for assessing uncertainty from data where the items are irregularly distributed, a measurement based on the entropy concept seems most appropriate.

Background on Linear Programming

The typical linear programming format involves three basic parts:[1]

a) The objective function whose value is to be maximized or minimized.

b) A matrix of input-output coefficients and a series of structural or capacity constraints defining the availability of the various resource inputs.

c) Non-negativity conditions on the variables. In notation form, the program is usually written as: maximize (or minimize) $\pi = ZX$ subject to $AX = K$ and $X \geq 0$, where π = total net returns to the decision unit under consideration, Z is a $1 \chi m$ vector of net returns for each activity, X is a $m \chi 1$ vector of activity levels open to the unit, A = the $k \chi n$ matrix of input-output coefficients and K = the $k \chi 1$ vector of resources available.[2]

The various journals dealing with agricultural economics abound with discussions and case studies using linear, non-linear, and dynamic programming. These techniques have been used to estimated normative supply functions,[3] production response,[4] average cost curves,[5] and land use patterns.[6,7,8] The difficulties in using linear programming in an analysis of problems involving regional agricultural adjustment to varying conditions are many. Miller discusses some of these in an article dealing with the sufficient conditions for exact aggregation in linear programming models.[9] He notes that present research methodology often involves "scaling up the linear programming solution of a ' representative' farm to generate information about aggregate production behavior of the group or set of individual farms it represents."[10] The problem, of course, is that if individual farms in a given region do not respond alike to economic or other stimuli such as increased accuracy in forecasts, then any estimates of regional output response will be biased. In this regard, he discu-ses three possible methods for obtaining estimates of total output of a set of farms:[11]

1) Determine the optimum organization and output from each farm in the region and sum them into an estimate of aggregate response. Usually resources available for study preclude this approach.

2) Determine a representative farm within the region and approximate the optimal organization for this farm by linear programming techniques. Aggregate output is then determined by multiplying the representative farm by the number of farms in the region.

3) Consider the total resources available in the set of farms or in the region as the representative farm and then determine the optimum solution for the entire set directly. (Procedures 2 and 3 produce identical estimates.)

Aggregation bias occurs if the results obtained from considering the region as a whole do not correspond to those obtained by summing the solutions for the individual farms in the region.[12] Miller shows rigorously that stratification of farms into sets in which all farms "within the set meet the conditions of (1) identical input-output matrices and (2) qualitatively homogeneous output vectors,"[13] resolves the difficulty of aggregation bias.

Since testing of the model developed in Chapter II will involve a hypothetical region (area under a ditch company), it will be assumed that the sufficient conditions for avoiding aggregation bias developed by Miller are met. This assumption may approximate the actual situation in many cases, since the nature of the ditch company water rights will determine the type of crops and operations that are feasible for farms under a given ditch. If there were also similar soils, even distribution of shares in the ditch company, even distribution of pumping capacity, and similar managerial ability, one would expect to find approximately similar input-output matrices and qualitatively homogeneous output vectors. These assumptions would not necessarily be met in the acreage under any given ditch company. However, in order to develop the general case of the operational model, similarity of these factors will be assumed. It would be possible as a later extension of the model to relax some of the assumptions, particularly those on soil and managerial ability, by further stratifying the farms. Differences in soil would then be reflected by different crop yields and, perhaps, different water requirements for each crop. Differences in managerial ability would be represented by different variable costs and yields.

Aggregation bias is not the only problem resulting from the use of the representative farm as indicator of regional aggregate supply response. For example, Sharples indicates that the formidable data problems and changing structural nature of American agriculture limit the usefulness the representative farm can play in analysis of longer run aggregate supply response.[14] On the other hand, he states:

> The representative farm can play a potentially important role in short run aggregate supply response. Knowledge of the potential economic impact of a change in an instrument variable on a farmer's income and organization is valuable. However, the linkage between the firm and the aggregate may be necessity be an informal one.[15]

Based on the assumption that Miller's conditions are met and that the nature of the situation under consideration reduces the significance of the problems raised by Sharples, the approach employed in the development of a linear programming model will involve use of the region as the representative farm. It must be pointed out that new technologies, the cost-price squeeze, and other factors have resulted in significant structural change in agricultural methods in recent decades. One form of this change has been a trend to larger farm size, in part to make possible the economies of scale inherent in modern highly mechanized methods of agriculture. Where the effect of increased farm size, modern farming methods, and improved financial management result in increased operational flexibility, estimated benefits from improved forecast accuracy could be expected to be greater in the future than those derived on the basis of the assumptions in this study. Likewise, the possibility that highly accurate forecasts, in some cases, may contribute to structural change should not be overlooked. Since quantification of these factors is extremely difficult, the methodology for estimating benefits will not take them into account.

Linear Programming Model for Approximating the Increase in Expected Income from Increased Accuracy in Forecasts

Before the specific model for analyzing benefits from increased forecast accuracy is presented, it is necessary to develop the general concepts that will be employed. This requires a discussion of stochastic or probabilistic programming[16, 17, 18] in conjunction with linear programming techniques for predicting patterns of agricultural land use and for determining optimal water allocation on irrigated land.

In contrasting the stochastic programming format with that of the standard linear program, the notational symbols presented above are employed. In the typical linear program, an objective function designated as $(\max)\pi = ZX$ is maximized (or minimized) subject to a set of finite resources K and a series of input-output relationships AX where:

π = net income

Z = $1 \chi m$ vector of net returns for each activity

X = $m \chi 1$ vector of activity levels

A = $k \chi m$ matrix of input-output coefficients

K = $k \chi 1$ vector of resources available and

$$AX \leq K, \quad X \leq 0 \qquad .$$

The optimization procedure applied to the system of equations results in the selection of certain levels of the available activities as the optimal combination which maximizes returns subject to the limited resources. In the stochastic formulation of the linear programming problem the information contained in the vector Z and the matrix AX is replicated as many times as there are states of nature; however, each vector Z is weighted by P_j, the estimated probability of occurrence of each state of nature J. The probability distribution P is given by a Xn 1 vector such that $\sum_{j=1}^{n} P_j = 1$. Whereas in the standard L.P. formulation, the available resources are fixed in supply, in the stochastic program the decision variable is the quantity of productive resources to employ. The resource inputs [K vector] are chosen on the basis of certain bounds and with respect to the expected payoffs and operational flexibility represented by the input-output relationships. AX which are replicated in each state of nature. The resource combination ultimately selected in the optimization process is the one that produces the maximum expected value in light of the probability of occurrence of each state of nature and the condition that the ultimate resource level determined is binding in each state of nature. The problem in notational form is as follows:

$$\begin{array}{llllll}
\text{Max}\,\pi = & P_1[ZX] + & P_2[ZX] \ldots\ldots\ldots & P_n[ZX] & - & E\,K \\
& AX \ldots\ldots & \ldots\ldots\ldots\ldots\ldots & \ldots & - & K = 0 \\
& & AX \ldots\ldots\ldots\ldots & \ldots & - & K = 0 \\
& & & AX & - & K = 0 \\
& & & & & M\,K \leq U
\end{array}$$

where E K is a vector representing the unit costs associated with each of the resources in K, M is a matrix which places bounds on the elements of K and U is a vector specifying the bounds. As can be seen from the equations, since the resources must be committed prior to knowledge of the states of nature, the resource costs (EK) are certain, whereas the total returns [ZX] are weighted by the probability of receiving them. The vector K is the unknown whose elements are determined in the optimization process. This basic format is used in developing the program for evaluating increased accuracy in forecasts. The major difference is that the factor giving rise to the stochastic nature of returns is the water supply and the resources which are the decision variables in this case are the total acreages planted to various crops. Forecasts of the availability of the total water constraint serve as the probability distributions which in turn determine what the optimal crop pattern and total acreage planted will be.

Within the context of the stochastic programming format, the basis for the linear programming model developed here rests on an article[19] and book[20] by Richard H. Day, an article by James M. Henderson,[21] and an article in the Transactions of the American Society of Agricultural Engineering by Warren A. Hall and Nathan Burns.[22]

Because the optimal soluation to a linear programming problem involves the same number of positive valued activities as there are binding constraints, use of the most elementary form of linear programming in analysis of regional agricultural supply response would result in highly unrealistic results. For example, most agricultural areas show a wide variety of crop types. If the acreages of various crops are designated as the activities in the linear program and water, land, labor, and machinery are designated as the limited resources, without some restriction on the crop types planted, the optimal solution would involve only as many crops as there were binding constraints. If only two constraints were binding, then only two crops would be included in the optimal solution. Normally, agricultural areas produce a diversity of crops for a number of reasons. These include various practices of crop rotation, requirements for diversification to avoid the risks of market fluctuations, pests and crop diseases, and the effect of various government price support programs (wheat, cotton, and rice, for example).[23]

An existing model which takes the above factors into account is that of Day (Economic Analysis: Recursive Programming and Production Response). While Day's work focuses on developing a methodology for predicting the change in regional and interregional crop patterns over time, some of the techniques employed provide a useful starting point for approaching the problem at hand.

In order to assure that the optimal solution to the linear program will involve a realistic number of positive valued activities, the format of the Day program is set up so that the acreages that can be planted to various crops are constrained by upper and lower bounds and acreages actually planted become the input coefficients. A version of this approach is presented below, modified by the addition of a water constraint.

$$\text{Max}\ \pi\ (X) = Z_1X_1 + \ldots\ Z_iX_i + \ldots + Z_nX_n$$

$$\begin{array}{l}
X_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \le (1 + B_1\ \text{max})X_1^* \\
\ldots\ldots X_i \ldots\ldots\ldots\ldots\ldots \le (1 + B_1\ \text{max})X_1^* \\
\ldots\ldots\ldots\ldots\ldots\ldots\ldots X_n \le (1 + B_n\ \text{max})X_n^* \\
-X_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \le -[1 - B_1\ \text{min})X_1^* \\
\ldots\ldots -X_i \ldots\ldots\ldots\ldots\ldots \le -(1 - B_i\ \text{min})X_i^* \\
\ldots\ldots\ldots\ldots\ldots\ldots\ldots -X_n \le -(1 - B_n\ \text{min})X_n^*
\end{array}$$

$$X_1 + \ldots\ldots K_i + \ldots\ldots X_n \le X$$

$$W_1X_1 + \qquad W_iX_i \qquad W_nX_n \le \overline{W}$$

Where:

$\pi\ (X)$ = net regional income

Z_i = net return per acre

$Z_i = P_iY_i - C_i$

P_i = price of ith crop

$\overline{W}$ = total water available

B_i = percent adjustment, up or down

Y_i = yield per acre of ith crop

C_i = variable cost per acre of ith crop

$\overline{X}$ = total land available

X_i^* = planned acreage based on previous years planting.

w_i = per acre water requirement of the ith crop

The B_i coefficients are determined based on the factors discussed on the preceding page such as need for diversification, price support programs and rotation requirements. Implicit in this type of approach is the strong assumption that the supply of the various productive inputs is completely elastic over the relevant range of operation. On a regional basis, this is probably a fair assumption for such inputs as fertilizer, fuel, herbicides and pesticides and may even hold for labor and some types of machine services. On the other hand, in many regions, availability of labor at a profitable cost may place restrictions on what types of crops can be grown. Likewise, lack of rental services of certain types of machinery at a price which equals the marginal value product can be expected to affect cropping patterns. Thus expansion of acreage of certain crops, if on a large enough scale could be expected to affect input costs (C_i) as well as the price of the product. This is an important consideration but one which must be faced in terms of a general equilibrium analysis which is beyond the scope of this analysis. While the quantitative section of this work will be confined to a partial equilibrium approach, the issues involved in a general equilibrium approach will be discussed again in qualitative terms in Chapter IX.

The program developed here, for purposes of assessing potential increases in expected income due to better forecasts, will use the basic notation presented above. The format, however, will involve that of the stochastic program and will be based on the assumptions which are discussed below.

1) The region under consideration is the acreage served by a hypothetical ditch company with specified right to direct flow, rights or option on a variable quantity of reservoir water depending on storage and other factors, and a specified maximum area pumping capacity.

2) The strategies open to the irrigator are the various mixes and acreages of crops grown in the given region. Alternatives are discussed in Appendix I. Conservative alternatives, for example, consist of planting less water intensive crops instead of extensive acreages of high value water intensive crops or reductions in the total acreage planted. The area under consideration will not be the total land in farms but only the acreage actually planted to the crops grown under irrigation. The total area devoted to irrigation will vary among alternatives.

3) Crop water requirements are based on estimated crop consumptive use presented in Appendix III and on assumed irrigation efficiencies. As discussed in Appendix III, irrigation efficiencies will vary depending on the source of supply (surface, reservoir, or well).

4) A discussion of some of the literature on water-crop yield response is presented in Appendix III. This information forms the basis for representing the functional relationship between the magnitude of water application and the size of the expected output. The relationship is reflected in the objective function of the program by three different net returns for each crop and source of water as well as an activity representing crop loss due to inadequate water application. Variation in net returns for each crop are due to reduced yields associated with reduced water application as well as with changes in variable costs of production associated with reduced yields.

5) Production flexibility on the part of the irrigator is represented in the following manner. First, the program includes several crops with different water requirements, returns, planting costs, and losses from inadequate water application from which to choose in determining crop composition in light of forecast water supply. Upper and lower bounds on each crop which limit the ultimate flexibility of variation in crop composition are used to represent forms of risk other than stochastic water supply which irrigators must face. Second, the total acreage planted is variable within the total irrigable land available. Third, three different sources of water (surface, reservoir, and well water) are assumed to be available.

6) Planting of crops usually takes place over several weeks, and it is possible to plant and mature some types of crops later in the season. However, in order to simplify the analysis, it will be assumed that all planting decisions are made at approximately the same point in time and that they are irreversible once made.

7) Crop failure is represented by a negative per acre return equal to the planting and tending costs.

8) Assuming that the present composition of crops planted in the area will not change with increased accuracy in forecasts, costs will be represented by variable costs. In other words, improved forecasts are

not expected to alter the types of crops grown, thus requiring investment in different types of machinery and facilities. Use of this approach is supported by Henderson. He states that only the cost of planting, cultivating and harvesting the crop "are relevant for the determination of the farmer's current cropland utilization pattern."[24]

9) It would be possible to include a series of activities for dry land farming as alternative sources of income in years when water supply is forecast to be inadequate. Detailed information on which to base the relationship of dry land to irrigated farming under one operating system was not found, so no attempt was made to include dry land potentials.

10) Expected returns will depend on crop prices, yields, and costs. Ideally, the irrigator's expected return should be formulated on the expected crop yield and price fluctuation over time. Variation in yield in the model, however, is due only to variations in water supply and not to the other factors, such as disease, pests, and weather damage. Price expectations by necessity are based on average crop prices prevailing in years previous to the current season, rather than on expected price resulting from different prevailing market conditions at the time of harvest.

Because the prices of several crops are supported through various governmental programs, the marginal social valuation of any improvement in irrigation management due to increased forecast accuracy would not be precisely reflected by using market prices. For that portion of the estimated benefits that are derived from crops whose prices are supported, an overstatement of benefits would result to the extent that support prices exceed equilibrium price under a non-support situation. It is not possible to make allowance for this problem within the scope of this analysis, though it must be borne in mind when discussing any benefits that may result from increased forecast accuracy.

11) Assumptions about water costs also pose problems which require some elaboration. First, because of practical problems and institutional rigidities, transfer of water in most situations is difficult. Thus few markets develop and there is no actual social valuation of the input through the forces of supply and demand. Usually the cost incurred by ditch companies in providing water to the share holders does not reflect the opportunity cost or marginal value product of the water in its next

best alternative use. The same may hold for pumped water if intertemporal or spatial externalities exist. Cost of water supplied through Bureau of Reclamation projects is also undervalued due to the government subsidy of capital costs. These problems are important ones, but for the purpose of developing a methodology to estimate benefits from increased accuracy in forecasts, no attempt will be made to compensate for them.

Secondly, most ditch companies are financed through annual stockholder assessments for fixed and variable costs incurred. Therefore, total costs per acre foot of water will vary depending on how much water is received by the ditch company during the season and on how much variable costs fluctuate with the amount of water delivered through the system. While the variable costs of operating the ditch company may rise during a good water year, fixed costs generally constitute the major portion of total costs. In general the total cost of operating the ditch company will not vary appreciably from year to year; or if it does, usually an increase in capital expenditures is involved, which would be amortized over the life of the improvements. Since the irrigator pays his proportionate share of total ditch company costs regardless of the total quantity of water he receives during the season, surface water costs will be assigned to fixed expenses in terms of costing for the model. Thus surface water costs are not a factor in the decision as to what planting strategy to follow. On the other hand, the variable costs of pumping will be dependent on the quantity of water pumped and will be deducted from per acre income along with other variable costs. Costs incurred in using reservoir water also will be considered variable.

Specification of the variables to be used and the format for the linear program are presented below.

Definition of symbols

$\pi(X_i)$ = expected income that would accrue to the hypothetical ditch company from planting acreages of i crops where i = 1, ..., 7.

F_k = the seasonal water supply forecast where k = 1, ..., 7.

P^J/F_k = the conditional probability of observing state of nature J given forecast F_k where J = 1, ..., 21, designated by the letters A to U and k = 1, ..., 7 forecasts designated as "very low, low, below average, average, above average, high, and very high." Forecasts in this hypothetical situation are in terms of water expected to be received by the ditch company. (The reason for the numbers chosen is explained in Appendix III.)

Z_{ij} = the net returns where subscript i designates the crop (i = 1, ..., 7) and subscript j designates the water source, level of application, and crop yield.

j = 1,2,3 are the net returns associated with three different levels of surface water application, where $Z_{i1} > z_{i2} > z_{i3}$.

j = 4 is the loss when surface water is inadequate to bring the crop to maturity resulting in crop failure.

j = 5...7 are the net returns associated with three levels of reservoir water application where

$Z_{i5} > Z_{i6} > Z_{i7}$.

j = 8...10 are the net returns associated with three levels of well water application where

$Z_{i8} > Z_{i9} > Z_{i10}$.

$Z_{ij} = p_i y_{ij} - k_{ij} - L_i$

p_i = the price of the ith crop

k_{ij} = the per acre variable cost of production for the ith crop and jth source and level of water application. This excluses planting costs.

y_{ij} = the per acre yield for the ith crop and jth source and level of water application. In all cases

$y_{i1} = y_{i5} = y_{i8}$;

$y_{i2} = y_{i6} = y_{i9}$;

$y_{i3} = y_{i7} = y_{i10}$; and

$y_{i4} = 0$.

L_i = per acre planting costs for the ith crop, i = 1, ..., 7.

X_i^J = the acreage planted to crop i in state of nature J, where $i = 1, \ldots, 7$, $J = 1, \ldots, 21$.

X_{ij}^J = the acreage of crop i receiving water from source and level j in state of nature J.

$\overline{X}$ = total irrigable acreage

$\overline{R}^J$ = total quantity of surface water available to the ditch company in state of nature J

$\overline{C}^J$ = total quantity of reservoir water available to the ditch company in state of nature J

$\overline{G}$ = maximum pumping capacity available to the ditch company. Capacity is assumed constant over all states of nature. (This is a very strong simplifying assumption, but one that could easily be altered to include variation in pumping capacity over the various states of nature. Inclusion would involve expanding the total number of states of nature by a factor equal to the number of different levels of pumping capacity desired.)

r_{ij}, $i = 1, \ldots, 7$, $j = 1, \ldots 4$, represents the water requirements of the ith crop using surface water at three different levels of application, where level r_{i4} represents inadequate application resulting in crop failure.

c_{ij}, $i = 1, \ldots, 7$, $j = 5, \ldots, 7$ represents the water requirements of the ith crop when reservoir water is used at three different levels of application.

g_{ij}, $i = 1, \ldots, 7$, $j = 8, \ldots, 10$ represents the water requirements of the ith crop when well water is used at three different levels of application. In all cases

$$r_{ij} = c_{i5} \neq g_{i8}$$

$$r_{i2} = c_{i6} \neq g_{i9}$$

$$r_{i3} = c_{i7} \neq g_{i10}$$

The difference in water requirements when well water is applied is due to the greater efficiency usually associated with its application as compared to surface or reservoir water.

$B_{i\ max}$ = the upper bound on acreage planted to crop i

$B_{i\ min}$ = the lower bound on acreage planted to crop i

The generalized formulation of the model is presented below in detached coefficient form followed by the general formulation for one state of nature. Use of the model in approximating the economic value of increases in forecast accuracy is discussed in the remainder of this chapter.

Use of the model to approximate the regional benefits from increased forecast accuracy involves the following general procedure. The various possible states of nature facing the ditch company are represented by the water constraints $\overline{R}^J$, $\overline{C}^J$, and $\overline{G}$. The most adverse state of nature $[\overline{R}^A, \overline{C}^A, \overline{G}]$ would entail a severely restricted total water supply, as opposed to the most abundant state of nature $[\overline{R}^U, \overline{C}^U, \overline{G}]$ in which total water supply is plentiful relative to crop water requirements. The seasonal water supply forecast (F_k) serves to establish a conditional probability distribution of observing the various states of nature given the particular forecast. The shape and dispersion about the forecast conditions will depend on how accurate the forecasts are. The linear program is used to determine the acreages to be planted (X_i) based on (1) the planting costs $(-L_i)$. (2) the expected returns and losses $(P^J /F_k Z_{ij})$ for the various states of nature; (3) the seasonal forecast; and (4) the upper and lower bounds for the acreage devoted to each crop, whereby the boundaries represent other factors (prices, rotation requirements, diversification to offset disease or pest loss, etc.) that are not part of the conditional water supply probability distribution.

For each forecast at a given level of accuracy, the program will determine an optimal allocation of acreage to plant to each crop and will provide the expected regional income from those planting decisions. Increases in forecast accuracy will be reflected by a change in the crop acreages planted as well as a change in expected income. In order to evaluate the increased accuracy the procedure discussed in Chapter II is employed. This involves multiplying the expected incomes by the probability of observing the forecasts for the two different accuracy

TABLE T9a

GENERALIZED PROGRAMMING FORMAT

$\text{Max } \Pi(X_i) = -L_i$	$A/F_k PZ_{i1}$	$A/F_k PZ_{i2}$	$A/F_k PZ_{i3}$	$A/F_k PZ_{i4}$	$A/F_k PZ_{i5}$	$A/F_k PZ_{i6}$	$A/F_k PZ_{i7}$	$A/F_k PZ_{i8}$	$A/F_k PZ_{i9}$	$A/F_k PZ_{i10}$		$J/F_k PZ_{i1}$	$J/F_k PZ_{i5}$	$J/F_k PZ_{i10}$		$U/F_k PZ_{i1}$	$U/F_k PZ_{i5}$	$U/F_k PZ_{i10}$	
X_i	X_{i1}	X_{i2}	X_{i3}	X_{i4}	X_{i5}	X_{i6}	X_{i7}	X_{i8}	X_{i9}	X_{i10}		X_{i1}	X_{i5}	X_{i10}		X_{i1}	X_{i5}	X_{10}	
-1	1	1	1	1	1	1	1	1	1	1	= 0	0	0	0		0	0	0	
	r_{i1}	r_{i2}	r_{i3}	r_{i4}							$\le \overline{R}^A$								
					c_{i5}	c_{i6}	c_{i7}				$\le \overline{C}^A$								
								g_{i8}	g_{i9}	g_{10}	$\le \overline{C}^A$								
-1	0	0	0	0	0	0	0	0	0	0		1	1	1	= 0	0	0	0	
												r_{ij}			$\le \overline{R}^J$				
													c_{ij}		$\le \overline{C}^J$				
														g_{ij}	$\le \overline{G}^J$				
-1	0	0	0	0	0	0	0	0	0	0		0	0	0		1	1	1	= 0
																r_{ij}			$\le \overline{R}^U$
																	c_{ij}		$\le \overline{C}^U$
																		g_{ij}	$\le \overline{G}^U$

$1 \le B_i$ max

$-1 \le -B_i$ min

$1 \le \overline{X}$

TABLE 9b

FORMAT FOR ONE STATE OF NATURE

$\text{Max}\Pi(X_i)=-L_1-L_2-L_3\ldots-L_7$				A/F_k PZ_{11}	A/F_k PZ_{12}	A/F_k PZ_{13}	A/F_k PZ_{14}	A/F_k PZ_{15}	A/F_k PZ_{16}	A/F_k PZ_{17}	A/F_k PZ_{18}	A/F_k PZ_{19}	A/F_k PZ_{110}	A/F_k PZ_{71}	A/F_k PZ_{72}	A/F_k PZ_{73}	A/F_k PZ_{74}	A/F_k PZ_{75}	A/F_k PZ_{76}	A/F_k PZ_{77}	A/F_k PZ_{78}	A/F_k PZ_{79}	A/F_k PZ_{710}	
X_1	X_2	$X_3\ldots$	X_7	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_{19}	X_{110}	X_{71}	X_{72}	X_{73}	X_{74}	X_{75}	X_{76}	X_{77}	X_{78}	X_{79}	X_{710}	
-1				1	1	1	1	1	1	1	1	1	1=0	0	0	0	0	0	0	0	0	0	0	
	-1			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
		-1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
			-1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	$= 0$
				r_{11}	r_{12}	r_{13}	r_{14}							r_{71}	r_{72}	r_{73}	r_{74}							$\leq \bar{R}^A$
								c_{15}	c_{16}	c_{17}								c_{75}	c_{76}	c_{77}				$\leq \bar{C}^A$
											g_{18}	g_{19}	g_{110}								g_{78}	g_{79}	g_{710}	$\leq \bar{G}^A$
1				$\leq B_1$ max																				
-1				$\leq -B_1$ min																				
	1			$\leq B_2$ max																				
	-1			$\leq -B_2$ min																				
		1		$\leq B_3$ max																				
		-1		$\leq B_3$ min																				
			1	$\leq B_7$ max																				
			-1	$\leq -B_7$ min																				
1	1	1...1		$\leq \bar{X}$																				

levels, summing the values over the components in each forecast distribution and differencing to obtain the value. Increase in forecast accuracy is reflected by increasing the probability of observing the conditions near those forecast and in the extreme by reaching a level of accuracy in which conditions widely divergent from those forecast are assigned a zero probability of occurrence.

Representation of Increased Accuracy

Although the nature of the distributions used to represent water supply do not permit any precise measure of change in central tendency as a representation of increased forecast accuracy, there is a concept from probability theory called entropy which can be used to represent increased certainty in probability distributions. Khinchin describes the application of this technique in terms of mutually dependent schemes such as those used in this study.[25] The technique will be explained briefly and will then be applied to the problem at hand. Given various probability distributions, some may represent more certain situations than others. For example, a distribution with equal probabilities assigned to each event exhibits less certainty than a distribution in which one of the probabilities is very large and the rest small. By multiplying each element of a probability distribution by its logarithm (to an arbitrary but fixed base) and summing over all elements, an intuitively appealing measure of the certainty attached to the distribution can be calculated. The single number which is generated from this calculation provides an index or measure of the certainty of one distribution as opposed to another.

The strength of this approach rests on the mathematical relationship between fractions and their logarithms. In moving from 1 to 0 the corresponding logarithms increase in absolute terms at a rate faster than the decrease in the fraction. Above .10 the logarithm, when multiplied by the corresponding fraction, results in proportionally increased reductions in the value of the probability number (the fraction) the closer to 1 that number is. For one, the product, of course, is zero. Below .10 the weighting scheme increases the value assigned to each probability element. Using this approach, probability distributions which are widely dispersed will produce a higher index number or entropy value than distributions in which one or two of the probability values are very large and the rest are relatively small.

Formally this is given by:[26]

$$H(p_1, p_2, \ldots, p_n) = - \sum_{k=1}^{n} p_k \log p_k \quad ,$$

where the entropy $[H(p_k)]$ of the probability distribution $p_1, \ldots, p_n$ is calculated by summing the product of each probability value P_k by its respective logarithm $\log p_k$.

In order to apply this technique to the conditional probabilities used in this analysis, let the forecast scheme be given by

$F = (F_1, \ldots, F_k, \ldots, F_n)$ where P_k represents the
$\quad = (p_1, \ldots, p_,, \ldots, p_n)$
probability of observing forecast F_k and $S = (S_1, \ldots, S_j, \ldots, S_n)$
$= (q_1, \ldots, q_j, \ldots, q_n)$
where q_j is the probability of observing state of nature j based on historical records. Based on the mutual dependence of the schemes, let q_{kj} be the probability that the event S_j of the second scheme; i.e., q_{kj} is simply the conditional probability of observing streamflow S_j given forecast F_k. Next let $\pi_{kj} = p_k q_{kj}$, the joint probability of observing both events S_j and F_k. The entropy of the product of schemes F and S is then given by

$$(8) \qquad -H(FS) = \sum_k \sum_j p_k q_{kj} (\log p_k + \log q_{kj}) \quad .$$

This can be rewritten as $\sum_k p_k \log p_k \sum_j q_{kj} + \sum_k p_k \sum_j q_{kj} \log q_{kj}$.

Since the conditional probability distribution $\sum_j q_{kj}$ is equal to 1 for any forecast F_k and the sum $-\sum_j q_{kj} \log q_{kj}$ can be thought of as the conditional entropy of $H_k(S)$ of the scheme S based on the assumption that the event F_k of the scheme F occurred,[27] then the formulation can be written as:

(9) $$H(FS) = H(F) + \sum_k p_k H_k(S) \quad .$$

Based on the properties of the last term of the above expression, it is possible to represent increased forecast accuracy in terms of a single number. Khinchin states that the value of the conditional entropy of $H_k(S)$ is completely determined by the knowledge of which forecast F_k actually occurred, since it is a random variable in the scheme F. Thus, the term $\sum_k p_k H_k(S)$ is the mathematical expectation of the quantity H(S) in terms of the forecast scheme F.[28] This means that in the context of two mutually dependent schemes, the degree to which knowledge of the first scheme reduces the uncertainty of the second is reflected by the mathematical expectation of the second scheme in terms of the first. Finally, Khinchin states that on the average, knowledge of the results of scheme F can only decrease the uncertainty associated with the scheme S.[29] This technique will be used in the next chapter to show increase in the certainty of the water supply resulting from improved forecasts.

The basic cost, revenue, yield, hydrologic data, specific assumptions, and derivation of the conditional probability distributions necessary for testing the L.P. model are presented in Appendix III. The testing procedure as well as a presentation and analysis of the results are the subject of the next chapter.

FOOTNOTES

[1] Baumol, Economic Theory and Operations Analysis, pp. 75-76.

[2] Thomas A. Miller, "Sufficient Conditions for Exact Aggregation in Linear Programming Models," Agricultural Economic Research, XVIII, No. 2 (1966), pp. 52-57.

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[5] Randolph Barker, "A Derivation of Average Cost Curves by Linear Programming," Agricultural Economic Research, XII, No. 1 (1960), pp. 6-12.

[6] Howard C. Hogg and Arnold B. Larson, "An Iterative Linear Programming Procedure for Estimating Patterns of Agricultural Land Use," Agricultural Economic Research, XX, No. 1 (1968), pp. 17-24.

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[9] Miller, "Sufficient Conditions for Exact Aggregation in Linear Programming Models."

[10] Ibid., p. 52.

[11] Ibid.

[12] Ibid.

[13] Ibid, p. 56.

[14] Jerry A. Sharples, "The Representative Farm Approach to Estimation of Supply Response," American Journal of Agricultural Economics, LI, No. 2 (1969), pp. 353-61.

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[18] Sidney G. Winter, private consultation and course lecture in Economics 754, Linear Economic Models, University of Michigan, Ann Arbor, Mich., April, 1971.

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[20] Day, Economic Analysis: Recursive Programming and Production Response.

[21] Henderson, "The Utilization of Agricultural Land."

[22] Warren A. Hall and Nathan Buras, "Optimum Irrigated Practice under Conditions of Deficient Water Supply," Transactions of the American Society of Agricultural Engineering, IV, No. 1 (1961), pp. 131-134.

[23] Henderson, "The Utilization of Agricultural Land," p. 249.

[24] Ibid., p. 244.

[25] A. I. Khinchin, The Mathematical Foundations of Information Theory, trans. by R. A. Silverman and M. D. Friedman (New York: Dover Publications, Inc., 1957).

[26] Ibid., p. 3.

[27] Ibid., p. 5

[28] Ibid., p. 5-6.

[29] Ibid., p. 6.

CHAPTER VIII

TESTING OF THE MODEL

The purpose of this chapter is to present the results of testing the model developed in Chapter VII and to provide graphical interpretation of the economic significance of those results.

Summary of the Model Structure

Derivation of the structure of the model as well as all supporting data are presented in detail in Appendix III and will be discussed only briefly here. The model is designed to represent the area served by a ditch company with facilities for a maximum of 21,000 acres, the average size of companies in three Colorado basins. Seven crops typically grown under irrigation in Colorado represent the crop portion of the farms operating under the ditch company. The farms are of a family-commercial size with a maximum of 250 acres of land available for each irrigator. It is assumed that each farm has other sources of income such as livestock and poultry. Size of each farm is assumed to be greater than 250 acres. However, no exact specification has been included, since any reasonable size could be used by varying the level of investment in machinery, buildings, and productive improvements on land. (See Appendix III.) For each of the seven crops (alfalfa, barley, dry beans, corn, onions, potatoes, and sugar beets), three different yield levels are used based on specified reductions in per acre water application. Water is drawn from direct flow (surface water), reservoir, and ground water sources. The three yield levels combined with the three sources of water and a provision for crop failure based on inadequate water application produce ten possible activities for each crop.

The states of nature are defined to consist of seven different levels of surface supply and three levels of reservoir water for a total of twenty-one states of nature. In each state of nature a constant pumping capacity is assumed to be available. This capacity does not vary over the states of nature, though the extent of its utilization will.

Details are shown in Appendix III.

To represent forecasts of the expected volume of water to be received during the growing season, the Bayesian formulation is used to establish conditional probability distributions for the twenty-one states of nature. This is accomplished by designating a historical frequency distribution of the twenty-one states of nature for the ditch company and then varying the term in the Bayesian formula that represents historical accuracy of the forecast so as to produce varying conditional distributions. The calculations are shown in Appendix III. Seven different forecast categories are designated (very low, low, below average, average, above average, high, and very high). These categories correspond to specified quantities of water and have a variation in supply comparable to that observed in historical records of several ditch companies in the Arkansas Valley of Colorado (see Appendix III). A crude relationship between surface and reservoir water in the form of a directly proportional relationship between quantity of surface water and quantity of reservoir water is specified; i.e., for years of very low flow, the likelihood of observing reduced reservoir supplies is greater than the likelihood of observing abundant supplies. Calculations and presentation of four different forecast accuracy levels are made in Appendix III where increase in forecast accuracy is represented by a tightening of the conditional distribution for each forecast for each successive increase in accuracy.

Finally, for each crop there is a planting activity with negative payoffs in the objective function equal to planting costs. Acreages planted are restricted by upper and lower bounds based on historical variation in crops planted in Colorado growing areas as well as other factors discussed in detail in Appendix III. The ten possible activities for each crop, seven crops, twenty-one states of nature, and the seven planting activities results in a problem consisting of 1477 activities. For each state of nature there are also ten constraints, three of which represent the three sources of water supply for the given state of nature and seven of which impose the condition that the acreages planted to each crop in the optimization process also be the same for all the states of nature. These seven constraints insure that the program is internally consistent, since planting irreversibly commits the land to certain crops regardless of what the water supply actually turns out to be. The ten constraints for each state of nature, combined with a constraint on total acreage gives 211 rows. The mathematical optimization program used to test the model is discussed briefly in the following section.

Computer Program:
Tests Performed

The program is based on a revised simplex algorithm for linear and separable programming problems developed by the IBM Scientific Research Center. It has been described in Optimization Programs at the University of Michigan by Hall, McWhorter, and Spivey.[1] The program is currently run on the IBM operating system (OS/360) which is run in batch mode several times a week at the University of Michigan computing center. In order to reduce the magnitude of the task, two sub-routines were employed, one for replicating the 70 X 10 matrix of input-output coefficients in each of the twenty-one states of nature; the other for multiplying the elements in the 1 X 70 row vector (representing the objective function in each state of nature) by the conditional probability of observing each of the twenty-one states of nature. This latter operation was performed for each of the seven forecasts and for each of the four levels of accuracy investigated, resulting in twenty-eight different objective functions each consisting of 1470 net returns weighted by the appropriate conditional probabilities plus the seven unweighted negative returns representing the initial cost of planting each of the crops. One run was also made using the historical frequency distribution.

In order to approximate the effect of forecasts under varying water supply conditions, two cases were examined. In Case One, a variable surface water supply is specified with ample supplies of higher cost reservoir and well water available to the irrigator should it be required in the more adverse surface supply situations. In Case Two, the same variable surface supply is used, but the supplies of reservoir and well water are sharply reduced. The purpose of this exercise was not to compare the net regional income between the two supply situations but rather to investigate the effects of increased accuracy as measured against a basic physical constraint situation. A summary of the output from the various computer runs is presented below.

Results and Estimation of Value of Increased Accuracy

Table 15 and Table 17 summarize the results from testing the model for Case One (adequate reservoir and well water) and Case Two (inadequate reservoir and well water). The information shown includes the expected net income associated with each forecast at each accuracy level, crop acreages planted, and the annual expected income accruing under each of the different accuracy levels. Tables 16 and 18 show the variation in income that is possible when the operators plant their fields according to the optimum crop combinations and acreage levels calculated by the model. Table 10 is included so that the reader may have a summary of the more important economic variables which serve to determine the results observed from testing the model. The information contained therein is derived from Appendix III. All cost and price figures have been adjusted to the 1959 price level by means of appropriate indices.

For the interested reader, the derivation of the conditional probabilities used to represent the forecasts are displayed in Appendix III and the range and quantities of water supply for the two cases are listed. Water supply ranges from 32 per cent to 160 per cent of average for surface supplies, 38 per cent to 158 per cent for surface plus reservoir, and 47 per cent to 148 per cent for surface, reservoir and well water in Case One. Case Two has greater overall variation. Turning to the data output from the model, approximately sixty runs were made in order to generate information needed to analyze the value of increased forecast accuracy for the two water supply situations examined. The information generated for each forecast includes total acreage planted, individual crop acreages planted, expected income, source of water application, and level of application in each state of nature for each crop and the degree of utilization of each of the three sources of water in each of the twenty-one states of nature. In addition, the revised simplex procedure used in solving the linear programming problem produces estimates of the incremental values associated with the water and land constraints.

In order to derive the expected income associated with each forecast accuracy level, it is necessary to employ the methodology discussed

TABLE 10

SUMMARY OF COST, REVENUE, LOSS, PRICE, YIELD, WATER APPLICATION AND UPPER AND LOWER PLANTING CONSTRAINTS
(FROM APPENDIX V)

Per-Acre Water Application in acre-feet (in ascending order)	Per-Acre Water Application (in acre-feet)			Per Acre Yield			Gross Revenue minus Cultivating and Harvesting Costs at Three Different Levels of per-acre Water Application			Net Returns per Acre (dollars per acre)			Net Returns per Acre-Foot of Water (dollars per acre-foot)			Planting Cost (dollars)	Per Acre Loss (cultivating plus planting costs--in dollars)	Per Unit Price (dollars)	Specified upper and lower Acreage Bounds
	Level			Level			Level			Level			Level						
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3				
ALFALFA					(tons)														
Sur.	4.7	3.3	2.3	3.4	2.6	1.6	50.82	38.61	23.27	42.28	30.07	14.73	9.00	9.11	6.40	8.54	9.04	21.71/ton	2910 to 7770
Res.	4.7	3.3	2.3				41.18	31.84	18.55	32.64	23.30	10.01	6.94	7.06	4.35				
Well.	3.3	2.4	1.7				31.02	24.21	13.07	22.45	15.67	4.53	6.81	6.52	2.66				
DRY BEANS					(cwt.)														
Sur.	4.2	3.7	3.0	14.8	12.6	9.8	68.51	56.40	40.94	42.83	30.72	15.26	10.20	8.30	5.09	25.60	30.24	5.92/cwt.	1050 to 4200
Res.	4.2	3.7	3.0				59.90	48.81	34.85	34.22	23.13	9.17	8.15	6.25	3.06				
Well.	3.0	2.6	2.1				50.51	40.80	28.34	24.83	15.12	4.53	8.28	5.82	1.60				
FIELD CORN					(bushels)														
Sur.	3.3	2.8	2.3	63	53	36	62.61	50.74	30.49	41.71	29.84	9.59	12.64	10.66	4.17	20.90	28.45	1.32/bu.	2100 to 5250
Res.	3.3	2.8	2.3				55.84	45.00	25.77	34.94	24.10	4.87	10.59	8.61	2.12				
Well.	2.4	2.0	1.7				48.21	38.74	20.29	27.31	17.84	-.61	11.37	8.92	-.36				
ONIONS					(cwt.)														
Sur.	5.3	4.8	4.3	298	248	200	262.33	217.77	174.72	223.75	179.19	136.14	42.22	37.33	31.46	38.50	134.30	2.25/cwt.	0 to 1680
Res.	5.3	4.8	4.3				251.46	207.93	165.90	212.88	169.35	127.32	40.17	35.28	29.61				
Well.	3.8	3.5	3.1				239.53	196.77	156.12	200.95	158.19	117.54	52.88	45.20	37.92				
POTATOES					(cwt.)														
Sur.	4.3	3.5	3.1	171	152	119	155.08	137.48	106.15	70.16	52.56	21.23	16.32	15.02	6.85	84.92	99.59	1.65/cwt.	0 to 2100
Res.	4.3	3.5	3.1				146.26	130.30	99.79	61.34	45.38	14.87	14.27	12.97	4.80				
Well.	3.1	2.5	2.2				136.48	122.48	92.95	51.56	37.56	8.03	16.63	15.02	3.65				
SUGAR BEETS					(tons)														
Sur.	5.3	4.8	4.3	24	12	9	143.06	122.22	90.13	107.66	86.82	54.73	20.31	18.09	12.73	35.40	81.92	23.91/ton 3.00/ton	0 to 3150
Res.	5.3	4.8	4.3	7	tops 6	4	132.19	112.38	81.31	96.79	76.98	45.91	18.26	16.04	10.68				
Well.	3.8	3.5	3.1				120.26	101.22	71.53	84.86	65.82	36.13	22.33	18.81	11.65				
BARLEY					(bushels)														
Sur.	2.7	2.2	1.8	52	44	34	42.46	35.74	26.14	19.58	12.86	3.26	7.25	5.85	1.81	22.88	23.38	0.96/bu.	1680 to 3150
Res.	2.7	2.2	1.8				36.92	31.23	22.45	14.04	8.35	-.43	5.20	3.80	-.24				
Well.	1.8	1.4	1.1				31.06	26.74	18.34	8.18	3.86	-4.54	4.54	2.76	-4.13				

at the end of Chapter II. The method involves determining what the annual expected net regional income is for each level of forecast accuracy. That is, assuming that the irrigators make their planting decisions each year based on the forecasts at a given level of accuracy, the question is what will their annual expected income be at each level of forecast accuracy or in the case in which only climatological information is used. To calculate the annual expected income at each level of accuracy, the expected income for each forecast is weighted by the probability of observing the forecast. These weighted values are summed to determine the annual expected regional income at the given level of accuracy. Expected incomes for each accuracy level are shown in the last line of Tables 15 and 17 in the next two sections.

Frequency of observing each forecast is calculated from the historical accuracy figures presented in Appendix III and are shown below in Table 11 in order to illustrate the change in frequency that occurs as accuracy increases. The table also shows the frequency of observing the various states of nature when only historical records are available.

TABLE 11

FREQUENCY OF OBSERVING VARIOUS FORECASTS AT FOUR LEVELS OF FORECAST ACCURACY

State of Nature or Forecast		Historical Frequency of Observing Each State of Nature	Percentage of Time Each Forecast is Observed at Different Forecast Accuracy Levels			
			Forecast Accuracy Level			
			One	Two	Three	Four
Very Low	(F_1)	10.4	13.9	11.3	9.9	10.3
Low	(F_2)	13.0	15.6	14.2	13.5	13.3
Below Av.	(F_3)	15.5	16.1	15.3	16.1	15.3
Average	(F_4)	24.8	14.0	17.5	20.0	21.9
Above Av.	(F_5)	18.1	14.1	16.9	17.5	17.7
High	(F_6)	10.4	14.1	13.7	13.1	12.3
Very High	(F_7)	7.8	12.2	11.3	10.0	9.3

To provide a meaningful measure of increase in forecast accuracy, the methodology presented at the end of Chapter VII was used to calculate the entropy for each of the forecast probability distributions and historical distributions shown in Appendix III.

TABLE 12

CONDITIONAL ENTROPY ASSOCIATED WITH
STREAMFLOW AT FOUR DIFFERENT
LEVELS OF FORECAST ACCURACY

Forecast	One	Two	Three	Four
Very Low	1.2276	1.1468	1.0980	.8639
Low	1.2273	1.1546	1.1226	.8696
Below Av.	1.2204	1.1443	1.1089	.9236
Average	1.1887	1.0723	1.0282	.7209
Above Av.	1.2098	1.1010	1.0508	.8410
High	1.2204	1.1584	1.1112	.9664
Very High	1.2529	1.1636	1.0910	.9423

Using the frequency information from Table 11, the entropy associated with each forecast accuracy level and the historical frequency distribution is calculated. This information is presented below in Table 13.

TABLE 13

CONDITIONAL ENTROPY ASSOCIATED WITH
FOUR DIFFERENT FORECAST SCHEMES
AND THE HISTORICAL DISTRIBUTION

		Forecast Accuracy Level			
	Historical Frequency	One	Two	Three	Four
Entropy	1.2724	1.2206	1.1327	1.0830	.8593

In order to put the above information in terms of a percentage increase in certainty resulting from the introduction of and improvement in forecasts, let $H(H_f)$ be the entropy for the historical frequency distribution and $H(S_F) = \sum_k p_k H_k(S)$. Reduction in uncertainty relative to the level of uncertainty associated with the historical frequency distribution is then given by $\frac{H(H_f) - H(S_F)}{H(H_f)}$. These values were calculated and are presented below in Table 14.

TABLE 14

PERCENTAGE INCREASE IN CERTAINTY
RESULTING FROM INTRODUCTION
AND IMPROVEMENTS IN
FORECASTS

	Forecast Accuracy Level			
	One	Two	Three	Four
Percentage Increase in Certainty	.04	.11	.15	.33

The results from testing the model for two different water supply situations are discussed below.

Case One--Adequate Reservoir and Well Water

Looking first at Case One, Table 15 presents the estimated acreages and expected income for the situation in which only historical frequency information is available and for the four others that are subject to increasing levels of forecast accuracy. The trends in individual and total crop acreage planted, as forecasts are introduced and improved in accuracy, are shown in figure 9.

Several generalizations relative to changes in crop combinations and total acreage induced by increasing forecast accuracy can be made

TABLE 15

CASE ONE--ADEQUATE RESERVOIR AND WELL WATER SUPPLIES

Individual and Total Acreages Planted and Associated Expected Net Farm Income*

Crops	Historical Frequency	Forecast	Accuracy Levels Accuracy Level One	Accuracy Level Two	Accuracy Level Three	Accuracy Level Four
		F_1				
Alfalfa	3,690		2,940	2,940	2,940	2,940
Beans	1,050		1,050	1,050	1,050	1,050
Field Corn	5,250		2,100	2,100	2,100	2,100
Onions	1,680		1,680	1,680	1,680	1,680
Potatoes	2,100		2,100	2,100	1,952	949
Sugar Beets	3,150		3,150	3,150	3,150	3,150
Barley	1,680		1,680	1,680	1,680	1,680
Total	18,600		14,700	14,700	14,552	13,549
Expected Income	($1,058,000)		($937,000)	($890,000)	($879,000)	($796,000)
		F_2				
Alfalfa			2,940	2,940	2,940	2,940
Beans			1,050	1,050	1,050	1,050
Field Corn			2,420	2,100	2,100	2,100
Onions			1,680	1,680	1,680	1,680
Potatoes			2,100	2,100	2,100	2,100
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			15,020	14,700	14,700	14,119
Expected Income			($950,000)	($931,000)	($933,000)	($870,000)
		F_3				
Alfalfa			2,940	2,940	2,940	2,940
Beans			1,050	1,050	1,050	1,050
Field Corn			3,788	3,788	4,325	4,609
Onions			1,680	1,680	1,680	1,680
Potatoes			2,100	2,100	2,100	2,100
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			16,388	16,388	16,925	17,209
Expected Income			($1,013,000)	($1,025,000)	($1,047,000)	($1,058,000)
		F_4				
Alfalfa			2,940	3,690	3,833	2,940
Beans			1,050	1,050	1,050	1,050
Corn			5,250	5,250	5,250	5,250
Onions			1,680	1,680	1,680	1,680
Potatoes			2,100	2,100	2,100	2,100
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			17,850	18,600	18,742	18,554
Expected Income			($1,095,000)	($1,127,000)	($1,143,000)	($1,173,000)
		F_5				
Alfalfa			4,376	5,196	3,886	2,940
Beans			1,050	1,050	2,259	3,317
Corn			5,250	5,250	5,250	5,250
Onions			1,680	1,680	1,680	1,680
Potatoes			2,100	2,100	2,100	2,100
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			19,287	20,106	20,005	20,117
Expected Income			($1,137,000)	($1,203,000)	($1,206,000)	($1,252,000)

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*Income in 1959 dollars.

TABLE 15--Continued

		F_6				
Alfalfa			5,923	6,090	5,064	3,372
Beans			1,050	1,050	2,076	3,768
Corn			5,250	5,250	5,250	5,250
Onions			1,680	1,680	1,680	1,680
Potatoes			2,100	2,100	2,100	2,100
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			20,834	21,000	21,000	21,000
Expected Income			($1,168,000)	($1,233,000)	($1,257,000)	($1,291,000)
		F_7				
Alfalfa			6,090	5,064	5,064	3,372
Beans			1,050	2,076	2,076	3,768
Field Corn			5,250	5,250	5,250	5,250
Onions			1,680	1,680	1,680	1,680
Potatoes			2,100	2,100	2,100	2,100
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			21,000	21,000	21,000	21,000
Expected Income			($1,176,000)	($1,247,000)	($1,270,000)	($1,307,000)
Expected Income for Each Forecast Accuracy Level	$1,058,000		$1,063,000	$1,100,000	$1,115,000	$1,118,000

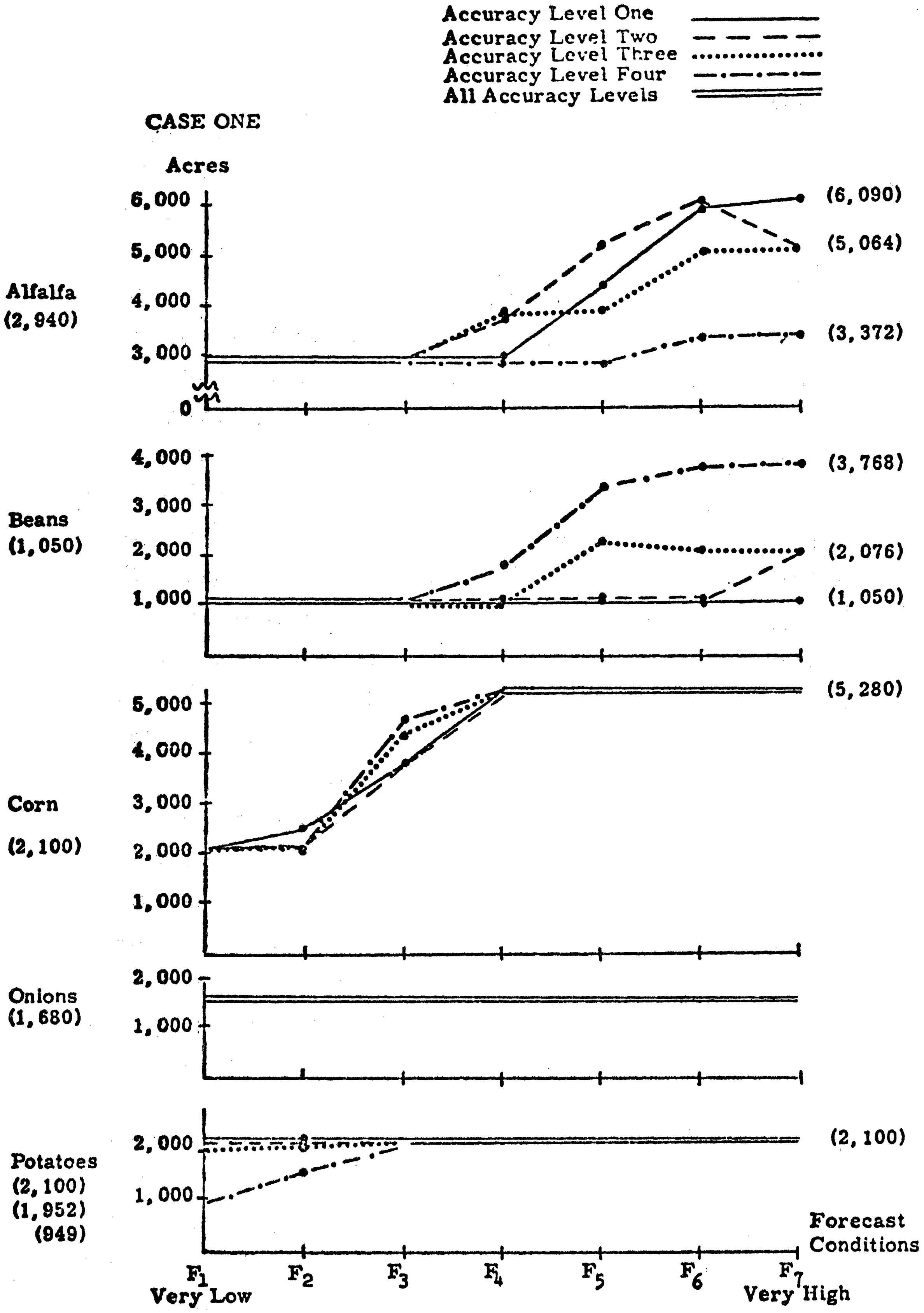
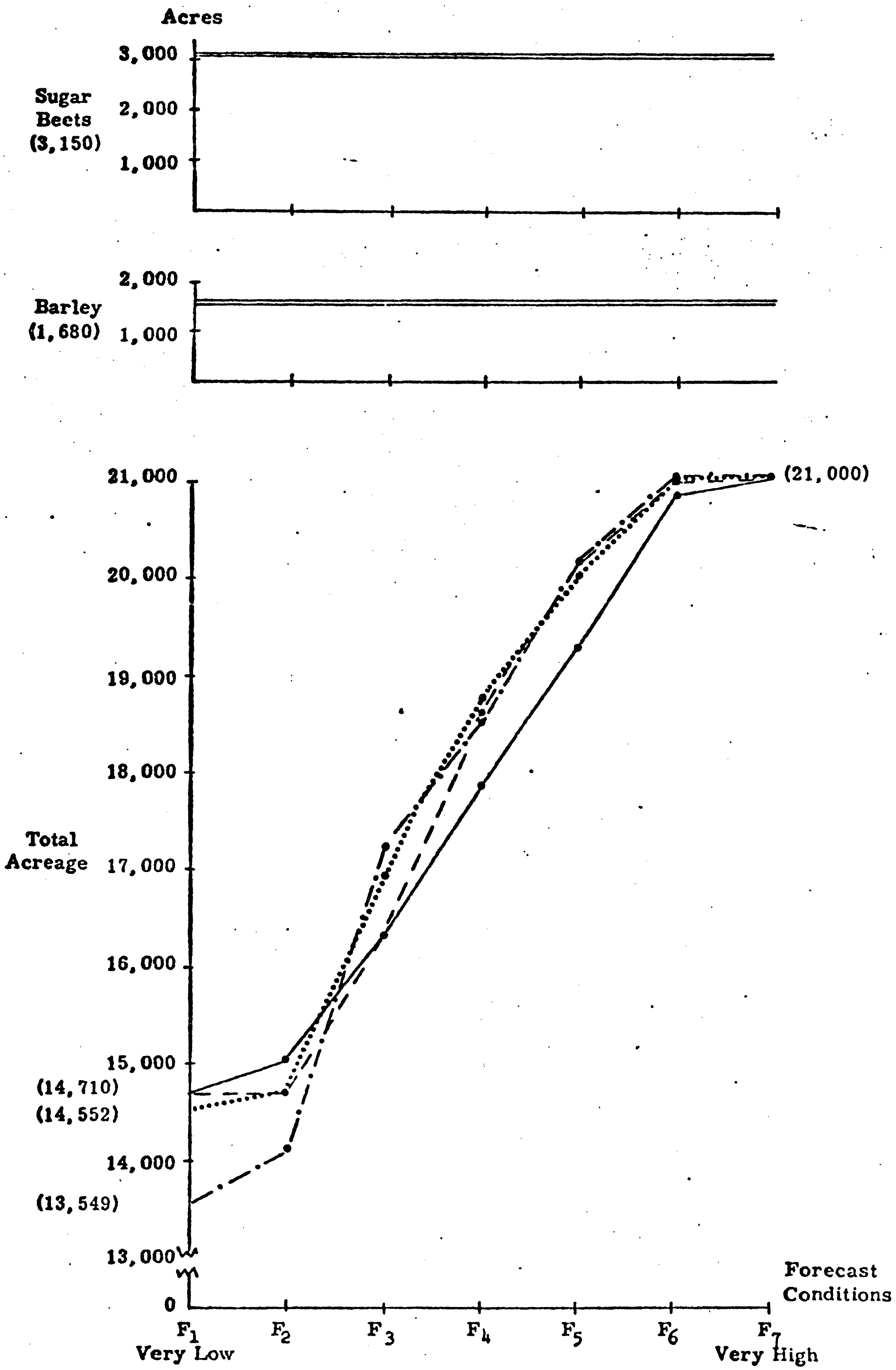


Fig. 9 . Individual and total crop acreages planted given four levels of accuracy of forecast water supply conditions.

Fig. 9. (Continued)



from the trends shown in figure 9. First, introduction of forecasts induces an initial variation in acreage planted ranging from 79 per cent to 133 per cent of that planted, based on climatological information (18,600 acres). Further increases in the accuracy of the forecasts induces a reduction in the acreages planted in the more adverse states of nature to 73 per cent of that planted on the basis of climatological information.

Second, as forecasts increase in accuracy, the following changes in crop composition can be noted. In forecasts of the most adverse state of nature, potatoes are reduced in acreage. From the figures in Table 10, it can be seen that potatoes have the lowest value per acre foot of water of the higher value crops (potatoes, onions, and sugar beets). In addition, potatoes also have the second highest loss per acre ($99.59) if inadequate water is applied. Thus in the adverse states of nature where water is severely limiting, increased accuracy in predicting the occurrence of a bad water year induces a reduction in the acreage of potatoes in the process of obtaining a maximum value of the problem's objective function. Similarly, increased accuracy induces a reduction of the acreage planted to corn initially, but then results in a more rapid expansion of corn acreage for forecasts of below average and average conditions as they increase in accuracy. Finally, increasing forecast accuracy induces first an expansion of alfalfa acreage in the intermediate to abundant supply conditions and then with highly accurate forecasts, a contraction of alfalfa acreage in the forecasts of the better states of nature accompanied by a substitution by beans.

This phenomenon is not as readily explainable from the figures in Table 10 as in the case with potatoes or with corn. Under full water application, the net return per acre foot of water is higher for beans than for alfalfa. However, for levels two and three it is higher for alfalfa. Likewise, net returns per acre of land are higher for beans except for levels two and three of reservoir and well water. The crucial factor in this case is the loss per acre if inadequate water is applied. For alfalfa it is $9.04 per acre whereas for beans it is $30.24. Thus in the situations where forecasts of the intermediate to abundant supply conditions are inaccurate, the benefits of expanding the acreage of beans does not offset the risk of substantial losses should one of the more adverse states of nature obtain. Alfalfa, with its very low per acre loss, serves as a buffer, because in situations of low water supply, losses are minimized. On the other hand, if abundant water is available, a return comparable to other lower value crops (beans, barley) can be attained. As forecasts of the intermediate and abundant states of nature increase in accuracy, the risk involved in planting beans is reduced and a substitution effect with alfalfa is induced by these improvements.

Third, certain patterns of water allocation occur in each run of the model. For each forecast, the model determines how water should be allocated in each state of nature to the acreages which are planted on the basis of the likelihood of occurrence of all the various states of nature. For example, in state of nature A (most adverse supply) in all cases alfalfa, beans, corn, and barley are abandoned in favor of the higher value crops which have been planted. Starting with states of nature C, D, etc. (depending on the total acreages planted), portions of the corn crop are saved by application of reduced levels of reservoir or well water. Proceeding through the states of nature, the general pattern is for corn to be saved first, then barley, beans, and alfalfa, in that order. In all cases, water is applied from reservoir or well sources, except for alfalfa. Likewise, water is applied at less than the level needed to obtain a maximum yield. The level at which these activities enter the optimal basis depends primarily on the value per acre foot of water at the different application levels, the per acre loss incurred when the crop acreage is allocated to the activity in the program which represents abandonment and the opportunity costs incurred when using water on the lower value crops. As would be expected, the general pattern is governed by maximization of returns for all states of nature subject to water availability. In the less abundant states of nature activities entering the optimal solution are determined by maximizing net returns per acre foot of water, though in the most abundant states of nature, water ceases to be the limiting factor, and maximization of returns per acre becomes the controlling influence. Though this type of information is too voluminous to summarize in tabular or graphical form, a copy of a portion of the output for one forecast at one level of accuracy is included in Appendix IV. Using the information contained in all of the computer outputs, it is possible to calculate the income that is associated with the water supply in each state of nature as determined by the acreages planted, on the basis of the probability of observing the states of nature. This is accomplished by multiplying the acreage shown for each activity by the respective net returns per acre. These values are presented on a selected basis in Table 16 below and show, for the historical frequency distribution and for each forecast and each forecast accuracy level, the range of nominal income in each of the twenty-one states of nature. The expected value for each accuracy level and for the historical frequency distribution is also shown. The probability distributions on which the expected values are based are shown in Appendix III.

Comparison of the figures in Table 16 with those for the income range, resulting when planting decisions are based on climatological information, indicate the following patterns as forecasts increase in accuracy. The use of forecasts results in greater income if the forecast conditions obtain and reduction in income if conditions widely divergent from those predicted occur. Likewise, as forecasts increase in accuracy, incomes rise for the general states of nature that were forecast and decrease for states of nature that are widely divergent from them. Introduction and use of forecasts as well as increased accuracy induce changes in the composition and total acreage planted toward those that are better suited to the likely water supply conditions. As a result, higher incomes or reduced losses result if those obtain. If they do not, enough flexibility exists in the planting strategy so that adjustments in level of water application and shifting of water to higher value uses is possible. As forecasts become highly accurate and cropping plans are made accordingly, some of the flexibility is sacrificed in favor of the higher expected income based on the reduction in risk that is a result of the increased accuracy.

While the range of nominal incomes is of practical interest, it is the expected income associated with each accuracy level that is the important indicator of the value of improved forecasts. These figures are shown in the last line of Table 15 and will be discussed in detail

TABLE 16

CASE ONE--RANGE OF POSSIBLE NET INCOMES RESULTING FROM PLANTING DECISIONS BASED ON FORECASTS FOR FOUR DIFFERENT ACCURACY LEVELS AND FOR HISTORICAL FREQUENCY INFORMATION

(In thousands of dollars)

State of Nature	Historical Frequency	Accuracy Level One						
		Forecast						
		F_1	F_2	F_3	F_4	F_5	F_6	F_7
A	339	522	506	437	271	317	269	264
B	522	688	•	•	•	•	•	457
C	655	818	•	•	•	•	•	586
D	657	810	800	744	677	678	631	593
E	806	917	•	•	•	•	•	743
F	936	993	•	•	•	•	•	879
G	954	996	994	984	944	910	873	869
H	1,036	1,054	1,058	1,060	1,050	1,023	990	986
I	1,112	1,071	•	1,116	1,126	1,099	•	1,068
J	1,115	1,090	•	•	1,129	1,102	1,073	1,070
K	1,186	1,103	•	1,150	1,186	1,178	•	1,120
L	1,221	1,114	•	•	1,204	1,228	1,225	1,222
M	1,239	1,134	•	•	1,222	1,240	1,228	1,225
N	1,252	1,135	•	•	•	1,267	1,282	1,282
O	1,265	1,135	•	•	•	•	•	1,319
P	1,283	1,152	1,165	1,245	1,267	•	•	1,333
Q	1,291	•	•	•	•	•	•	1,350
R	1,291	•	•	1,215	1,267	•	•	1,363
S	1,298	•	•	1,223	1,274	•	•	1,352
T	1,298	•	•	•	•	•	•	1,365
U	1,298	1,152	1,165	1,223	1,274	1,321	1,371	1,377
Expected Value	1,058			1,063				

		Accuracy Level Two						
A		522	522	451	339	292	264	242
B		688	•	•	•	•	•	435
C		818	•	•	•	•	•	587
D		810	•	•	•	•	•	551
E		917	•	•	•	•	•	760
F		993	•	•	•	•	•	857
G		996	•	•	•	•	•	847
H		1,054	1,054	1,060	1,036	•	•	964
I		1,071	1,070	1,116	1,112	•	•	1,067
J		1,090	1,090	1,127	1,115	•	•	1,070
K		1,103	•	1,150	1,186	1,163	•	1,146
L		1,114	•	•	1,221	1,228	1,222	1,222
M		1,134	•	•	1,239	1,239	1,225	1,225
N		1,135	•	•	•	•	•	1,287
O		1,135	•	•	•	•	•	1,321
P		1,152	1,152	1,215	•	•	•	1,339
Q		•	•	•	•	•	•	1,353
R		•	•	•	•	•	•	1,366
S		•	•	1,223	•	•	•	1,354
T		•	•	•	•	•	•	1,365
U		1,152	1,152	1,223	1,298	1,347	1,377	1,378
Expected Value				1,100				

• represents values not included for economy of calculation

* Income in 1959 dollars.

TABLE 16--Continued

State of Nature	F_1	F_2	F_3	F_4	F_5	F_6	F_7
				Accuracy Level Three			
A	532	522	409	299	269	-	-
B	694	•	•	•	•	-	-
C	821	•	•	•	•	571	-
D	814	•	•	•	•	•	-
E	916	917	860	•	•	•	761
F	992	993	976	•	•	•	857
G	995	996	970	•	•	•	848
H	1,049	1,054	1,056	1,033	•	•	964
I	1,064	1,071	1,122	1,110	•	•	1,067
J	1,082	1,090	1,133	1,112	•	•	1,070
K	1,095	•	1,165	1,186	1,164	•	1,146
L	1,104	•	•	1,224	1,235	1,222	1,222
M	1,126	•	•	1,239	1,243	1,225	1,225
N	•	•	•	1,287	1,287	1,287	1,287
O	1,126	•	•	•	•	•	1,321
P	1,142	1,152	•	•	•	•	1,339
Q	•	•	•	•	•	•	1,353
R	•	•	•	•	•	•	1,366
S	•	•	1,241	•	•	•	1,354
T	•	•	•	•	•	•	1,365
U	1,142	1,152	1,241	1,303	1,346	1,378	1,378
Expected Value			1,115				
				Accuracy Level Four			
A	585	561	395	-	-	-	-
B	727	•	•	-	-	-	-
C	831	•	•	-	-	-	-
D	833	822	•	-	-	-	-
E	909	913	850	-	-	-	-
F	965	982	969	-	-	-	-
G	976	991	962	913	-	-	-
H	999	1,029	1,054	1,023	-	-	-
I	1,012	1,041	1,125	1,113	1,096	1,040	1,040
J	1,030	1,060	1,133	1,115	•	•	1,034
K	1,043	•	1,172	1,189	1,162	•	1,145
L	1,043	•	•	1,221	1,237	1,221	1,221
M	1,064	1,099	•	1,240	1,241	1,224	1,224
N	-	-	•	•	•	•	1,294
O	•	•	1,223	1,266	•	•	1,326
P	-	-	-	-	•	•	1,344
Q	-	-	-	-	•	•	1,357
R	-	-	-	-	•	•	1,370
S	-	-	-	-	•	•	1,359
T	-	-	-	-	•	•	1,372
U	-	-	-	-	1,351	1,381	1,381
Expected Value			1,118				

• represents values not included for economy of calculation.

† represents zero probability of occurrence based on the forecast.

after the results from testing Case Two (inadequate reservoir and well water supplies) have been presented.

Case Two--Inadequate Reservoir and Well Water

The same information as presented for Case One will be presented and discussed for Case Two in order to provide a basis of comparison for the benefits from increased accuracy in both situations.* Table 17 shows crop acreages and expected income for the situation in which only historical frequency information is available and for the four others that are subject to increasing levels of forecast accuracy. The trends in individual and total crop acreage planted as forecasts are introduced and improved in accuracy are shown in figure 10.

Several generalizations relative to changes in crop combinations and total acreage planted induced by increasing forecast accuracy can be made from the trends shown in figure 10. First, introduction of forecasts induces an initial variation in acreage planted ranging from 92 per cent to 118 per cent of that planted on the basis of climatological information (13, 371). Further increases in the accuracy of the forecasts induce a reduction in the acreages planted in the more adverse states of nature to 74 per cent of that planted on the basis of climatological information and an expansion in the more abundant states of nature to 133 per cent of that planted before introduction of forecasts.

Second, as forecasts increase in accuracy the following changes in crop acreages can be noted. In forecasts of the most adverse states of nature, potatoes are eliminated from the optimal solution. Likewise, with increases in accuracy, sugar beets are cutback drastically. In both cases, these are high value crops with high water requirements and high per acre losses if inadequate water is made available. Increases in accuracy induce a more rapid expansion of potatoes in the intermediate states of nature and a lower level of planting of sugar beets in the more

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*Case Two involves the same surface water supply, but only 500 acre feet of well water in each state of nature and a range of 2,000 to 6,000 acre feet of reservoir water.

TABLE 17

CASE TWO--MINIMAL RESERVOIR AND WELL WATER SUPPLIES

Individual and Total Acreages Planted and Associated Expected Net Farm Income *

Crops	Historical Frequency	Forecast	Accuracy Levels			
			Accuracy Level One	Accuracy Level Two	Accuracy Level Three	Accuracy Level Four
		F_1				
Alfalfa	2,940		2,940	2,940	2,940	2,940
Beans	1,050		1,050	1,050	1,050	1,050
Field Corn	2,100		2,100	2,100	2,100	2,100
Onions	1,680		1,680	1,680	1,680	1,680
Potatoes	771		0	0	0	0
Sugar Beets	3,150		2,876	2,191	1,813	518
Barley	1,680		1,680	1,680	1,680	1,680
Total	13,371		12,326	11,641	11,264	9,968
Expected Income	($795,000)		($629,000	($.566,000	($555,000)	($472,000)
		F_2				
Alfalfa			2,940	2,940	2,940	2,940
Beans			1,050	1,050	1,050	1,050
Field Corn			2,100	2,100	2,100	2,100
Onions			1,680	1,680	1,680	1,680
Potatoes			0	0	0	0
Sugar Beets			2,945	2,499	2,499	1,556
Barley			1,680	1,680	1,680	1,680
Total			12,395	11,949	11,949	11,006
Expected Income			($652,000)	($628,000)	($624,000)	($564,000)
		F_3				
Alfalfa			2,940	2,940	2,940	2,940
Beans			1,050	1,050	1,050	1,050
Field Corn			2,100	2,100	2,100	2,100
Onions			1,680	1,680	1,680	1,680
Potatoes			0	0	0	0
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			12,600	12,600	12,600	12,600
Expected Income			($738,000)	($760,000)	($796,000)	($796,000)
		F_4				
Alfalfa			2,940	2,940	2,940	2,940
Beans			1,050	1,050	1,050	1,050
Corn			2,100	2,100	2,100	2,100
Onions			1,680	1,680	1,680	1,680
Potatoes			630	1,323	1,323	1,788
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			13,230	13,923	13,923	14,388
Expected Income			($827,000)	($890,000)	($909,000)	($948,000)
		F_5				
Alfalfa			2,940	2,940	2,940	2,940
Beans			1,050	1,050	1,050	1,050
Corn			2,100	2,100	2,100	2,253
Onions			1,680	1,680	1,680	1,680
Potatoes			1,788	2,100	2,100	2,100
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			14,388	14,700	14,700	14,853
Expected Income			($901,000)	($995,000)	($1,003,000)	($1,063,000)

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*Income in 1959 dollars.

TABLE 17--continued

		F_6				
Alfalfa			3,403	3,558	2,940	2,940
Beans			1,050	1,050	1,050	1,050
Corn			2,100	2,701	3,837	4,188
Onions			1,680	1,680	1,680	1,680
Potatoes			2,100	2,100	2,100	2,100
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			15,163	15,919	16,537	16,788
Expected Income			($935,000)	($1,026,000)	($1,062,000)	($1,107,000)
		F_7				
Alfalfa			3,851	2,940	2,940	2,940
Beans			1,050	1,050	1,050	1,050
Corn			2,100	3,820	4,131	5,248
Onions			1,680	1,680	1,680	1,680
Potatoes			2,100	2,100	2,100	2,100
Sugar Beets			3,150	3,150	3,150	3,150
Barley			1,680	1,680	1,680	1,680
Total			15,711	16,420	16,731	17,848
Expected Income			($945,000)	($1,042,000)	($1,074,000)	($1,127,000)
Expected Income for Each Forecast Accuracy Level	$795,000		$798,000	$851,000	$872,000	$882,000

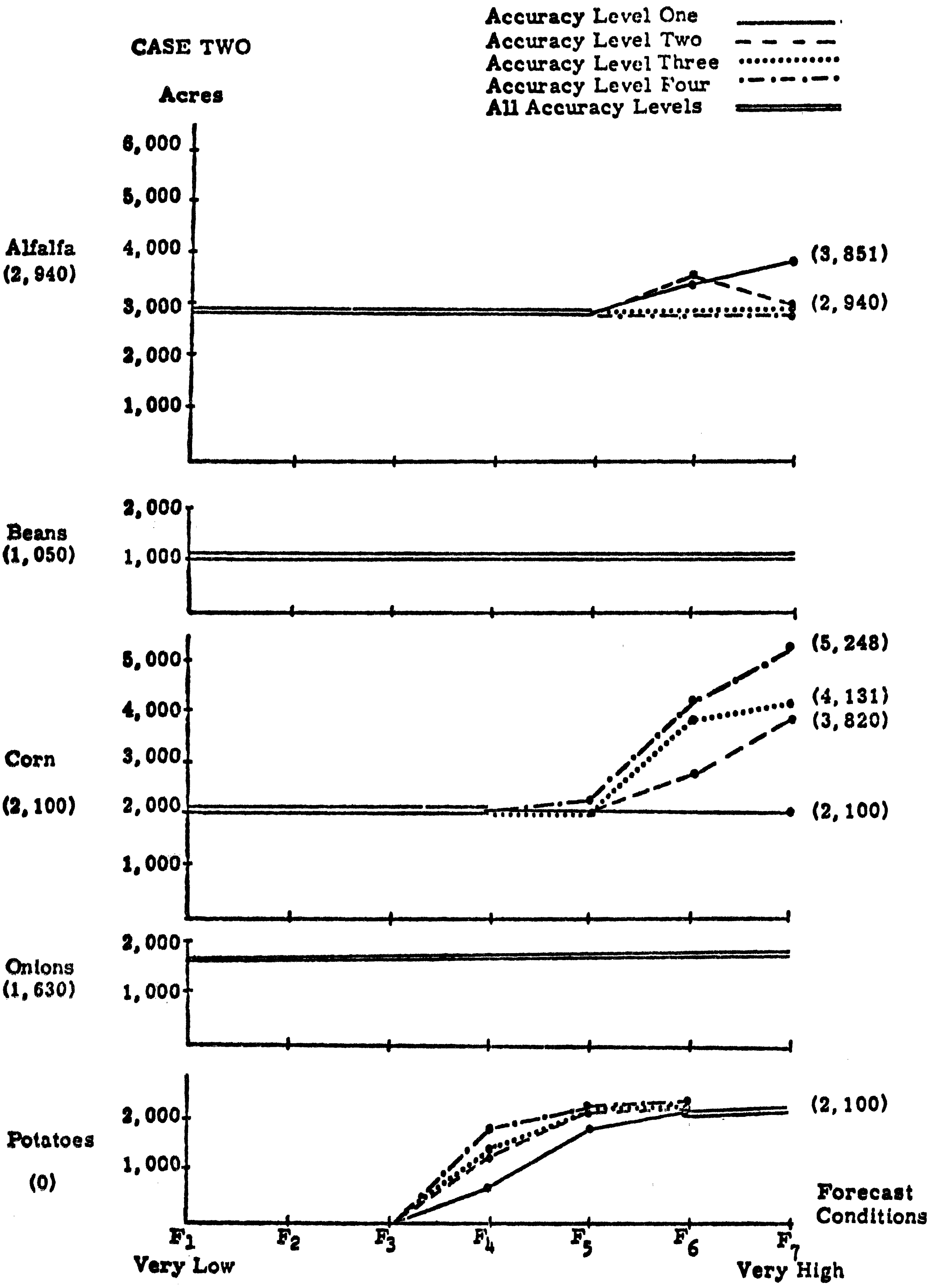

Fig. 10. Individual and total crop acreages planted given four levels of accuracy of forecast water supply conditions.

Fig. 10. (Continued)

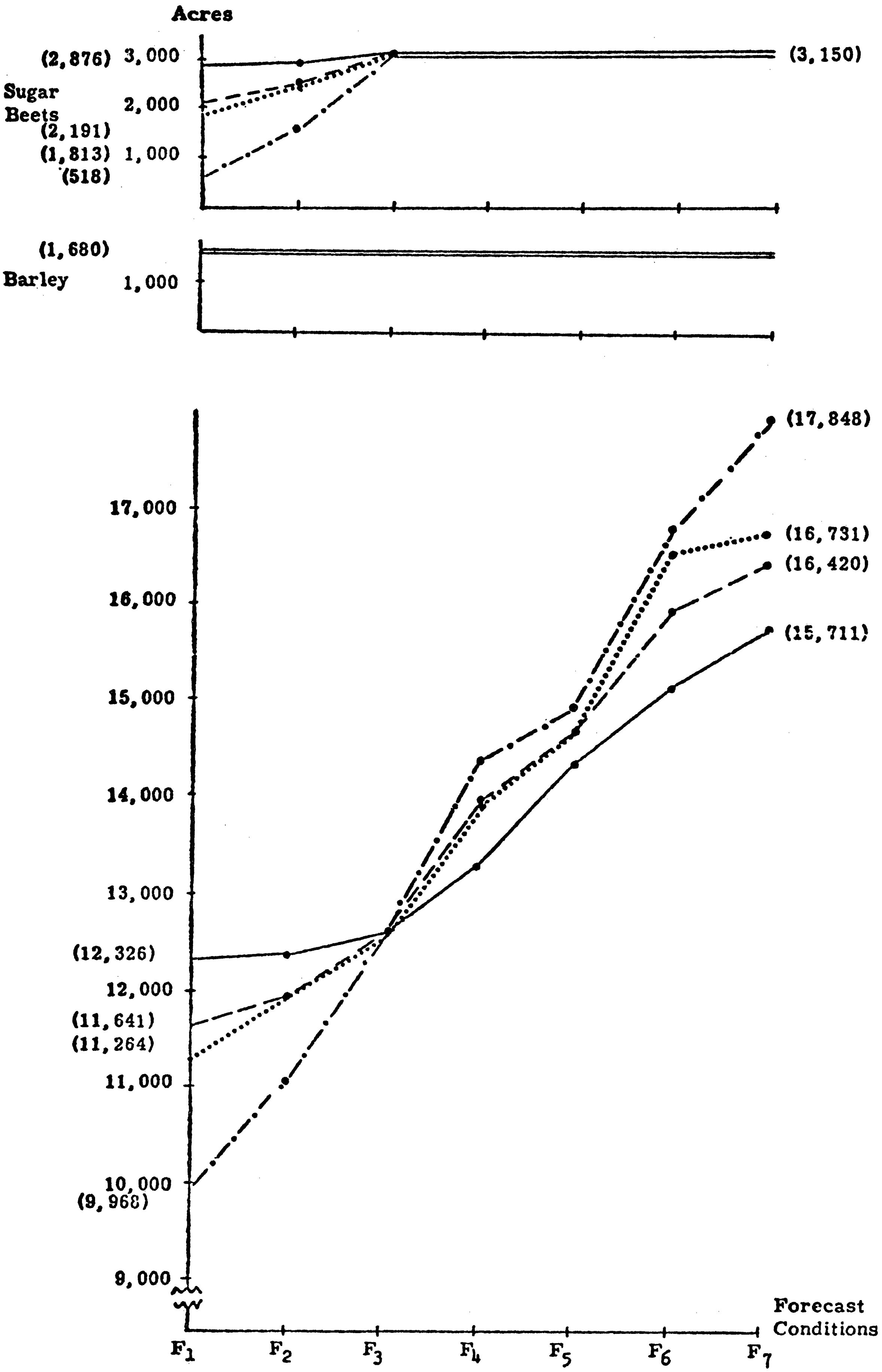

TABLE 18

CASE TWO--RANGE OF POSSIBLE NET INCOMES RESULTING FROM PLANTING DECISIONS BASED ON FORECASTS FOR FOUR DIFFERENT ACCURACY LEVELS AND FOR HISTORICAL FREQUENCY INFORMATION

(in thousands of dollars)

State of Nature	Historical Frequency	Accuracy Level One						
		Forecast						
		F_1	F_2	F_3	F_4	F_5	F_6	F_7
A	-21	92	87	72	-3	-166	-321	-273
B	84	157	•	•	•	•	•	-138
C	149	221	•	•	•	•	•	-36
D	373	452	•	•	•	•	•	259
E	445	517	•	•	•	•	•	323
F	509	567	565	557	519	440	405	388
G	709	737	•	•	•	•	•	619
H	754	774	•	•	•	•	•	676
I	796	807	809	811	799	•	•	726
J	925	884	•	919	924	920	•	892
K	950	932	•	•	949	957	941	928
L	975	946	•	•	975	982	976	966
M	1,052	975	983	1,005	1,045	1,085	1,080	1,070
N	1,054	•	•	•	•	•	•	1,095
O	1,054	•	•	•	•	•	•	1,120
P	1,059	•	•	•	1,049	1,130	1,172	1,188
Q	•	•	•	•	•	•	•	1,190
R	•	•	•	•	•	•	•	1,190
S	•	•	•	•	•	•	•	1,194
T	•	•	•	•	•	•	•	1,194
U	1,059	975	983	1,005	1,049	1,130	1,172	1,194
Expected Value	795			798				
		Accuracy Level Two						
A		143	120	72	-97	-212	-376	-348
B		207	•	•	•	•	•	-203
C		272	•	•	•	•	•	-100
D		492	•	•	•	•	•	203
E		542	•	•	•	•	•	268
F		589	•	•	•	•	•	332
G		685	•	•	•	•	•	563
H		762	771	774	736	•	•	624
I		787	796	811	780	•	•	674
J		877	•	919	928	886	•	856
K		890	•	945	954	951	•	899
L		892	•	•	979	984	959	941
M		902	935	1,005	1,071	1,091	1,073	1,076
N		•	•	•	1,084	1,109	1,098	1,101
O		•	•	•	•	•	•	1,127
P		•	•	•	1,098	1,152	•	1,210
Q		•	•	•	•	•	•	1,217
R		•	•	•	•	•	•	1,217
S		•	•	•	•	•	•	1,224
T		•	•	•	•	•	•	1,224
U		902	935	1,005	1,098	1,152	1,203	1,224
Expected Value					851			

• represents values not included for economy of calculation

* Income in 1959 dollars

TABLE 18--Continued

State of Nature	Accuracy Level Three						
	Forecast						
	F_1	F_2	F_3	F_4	F_5	F_6	F_7
A	171	120	72	-97	-213	-	-
B	208	•	•	•	•	-	-
C	300	•	•	•	-8	-	-
D	505	•	•	•	290	197	-
E	551	•	•	•	•	•	252
F	595	•	•	•	•	•	316
G	725	737	733	•	•	•	548
H	751	771	774	736	•	•	609
I	776	796	811	780	•	•	660
J	854	•	919	928	886	•	844
K	855	•	945	954	951	•	888
L	855	•	•	979	984	938	931
M	861	935	1,005	1,070	1,091	1,076	1,073
N	•	•	•	1,084	1,109	1,101	1,100
O	•	•	•	•	•	•	1,136
P	•	•	•	1,098	1,152	•	1,214
Q	•	•	•	•	•	•	1,226
R	•	•	•	•	•	•	1,228
S	•	•	•	•	•	•	1,235
T	•	•	•	•	•	•	1,235
U	861	935	1,005	1,098	1,152	1,228	1,235
Expected Value				872			
	Accuracy Level Four						
A.	267	190	-	-	-	-	-
B	317		-	-	-	-	-
C	267	-	-	-	-	-	-
D	524	513	432	-	-	-	-
E	557	•	•	-	-	-	-
F	583	597	557	-	-	-	-
G	683	710	733	666	-	-	-
H	696	742	774	716	-	-	-
I	708	769	811	766	746	690	666
J	721	•	919	920	910	•	792
K	•	•	945	957	947	•	843
L	•	•	963	1,002	983	•	890
M	721	833	•	1,085	1,087	1,074	1,048
N	-	-	•	1,099	1,111	1,099	1,085
O	-	-	1,005	1,113	1,125	1,125	1,117
P	-	-	-	-	1,158	•	1,221
Q	-	-	-	-	•	•	1,242
R	-	-	-	-	1,158	•	1,255
S	-	-	-	-	-	-	1,259
T	-	-	-	-	-	•	1,272
U	-	-	-	-	-	1,237	1,274
Expected Value				882			

• represents values not included for economy of calculation

-, represents zero probability of occurrence based on the forecast adverse states of nature. Likewise increase in accuracy induces an earlier and more rapid expansion of corn in the intermediate to abundant states of nature. As accuracy increases, corn acreage is substituted for alfalfa, which is expanded in the more abundant states of nature for the lowest levels of forecast accuracy. As in Case One, alfalfa is expanded initially because of the low level of losses associated with its planting. As forecasts increase in accuracy, the risk of losing corn if it is planted is reduced in terms of the model, thus inducing a substitution of corn for alfalfa.

Water allocation patterns follow those described above for Case One. Generally, the lower value crops are abandoned in the more adverse states of nature or are watered at lower yield levels from the minimal supplemental sources.

Unweighted net income that would be realized in each state of nature should forecasts be used as the basis of planting decisions is presented in Table 18. These values show, for the historical frequency distribution and for each forecast and each forecast accuracy level, the range of nominal income in each of the twenty-one states of nature. The expected value for each accuracy level and for the historical frequency distribution is also shown. The probability distributions, on which the expected values are based, are shown in Appendix III.

Comparison of the figures in Table 18 with those for the income range resulting when planting decisions are based on climatological or historical frequency information indicate the same patterns as discussed under Case One. Qualitative evaluation of the results of testing the two cases is presented in the next section.

Comparison of Case One and Two

As would be expected, the most noticeable differences between the two cases are the levels of expected income, the total acreage planted, and the crop composition shown in Tables 15 and 17. These differences are the controlling factors that underlie the benefits to increased accuracy as measured against the base condition of planting decisions taken on the basis of only climatological information.

In Case One the variable direct flow water is augmented by higher cost supplies of both reservoir and well water. In Case Two the lack of adequate supplemental sources of water results in a cutback in both total acreage and in the acreage of high value crops such as potatoes and sugar beets, even though there is enough water to assure harvest of these crops in the more abundant states of nature. Thus, increased income due to increased accuracy in Case Two results from changes in acreage of the high value crops initially followed by corn or alfalfa. In Case One, high value crops are generally at their upper bound so that changes in acreage come mainly in the lower value crops. The result is greater benefits in Case Two where increased accuracy in forecasts reduces the risk of loss resulting from planting high value crops in years when an adequate water supply appears to be in the offing.

The relationship between increased forecast accuracy (percentage increase in certainty as explained above) and the expected gross annual benefits (Tables 15 and 17) for the two cases can be represented graphically. Benefits are the difference between expected annual income at each level of forecast accuracy and the expected annual income when planting decisions are based on climatological or historical frequency information. The relation between increased accuracy and expected annual benefits is shown below in figure 11.

In comparing these benefit functions, the following observations can be made. First, it can be seen that for initial increases in certainty (reduction in inaccuracy), the benefits in Case One are slightly larger than those in Case Two. When forecasts are initially introduced in Case One, the changes in acreage induced are considerably greater than that induced in Case Two, resulting in slightly higher benefits in Case One. Essentially, the greater flexibility inherent in Case One, because of the availability of supplemental water, results in a greater responsiveness to initial forecasts than is optimal under the conditions applying to Case Two. In Case Two, the risks of loss are highly if overly ambitious planting strategies are pursued and the more adverse states of nature occur. However, beyond a 7 per cent increase in forecast accuracy, the benefits in Case Two exceed those in Case One. The total benefit function for Case Two shows a higher value, with its marginal function decreasing less rapidly than in Case One.

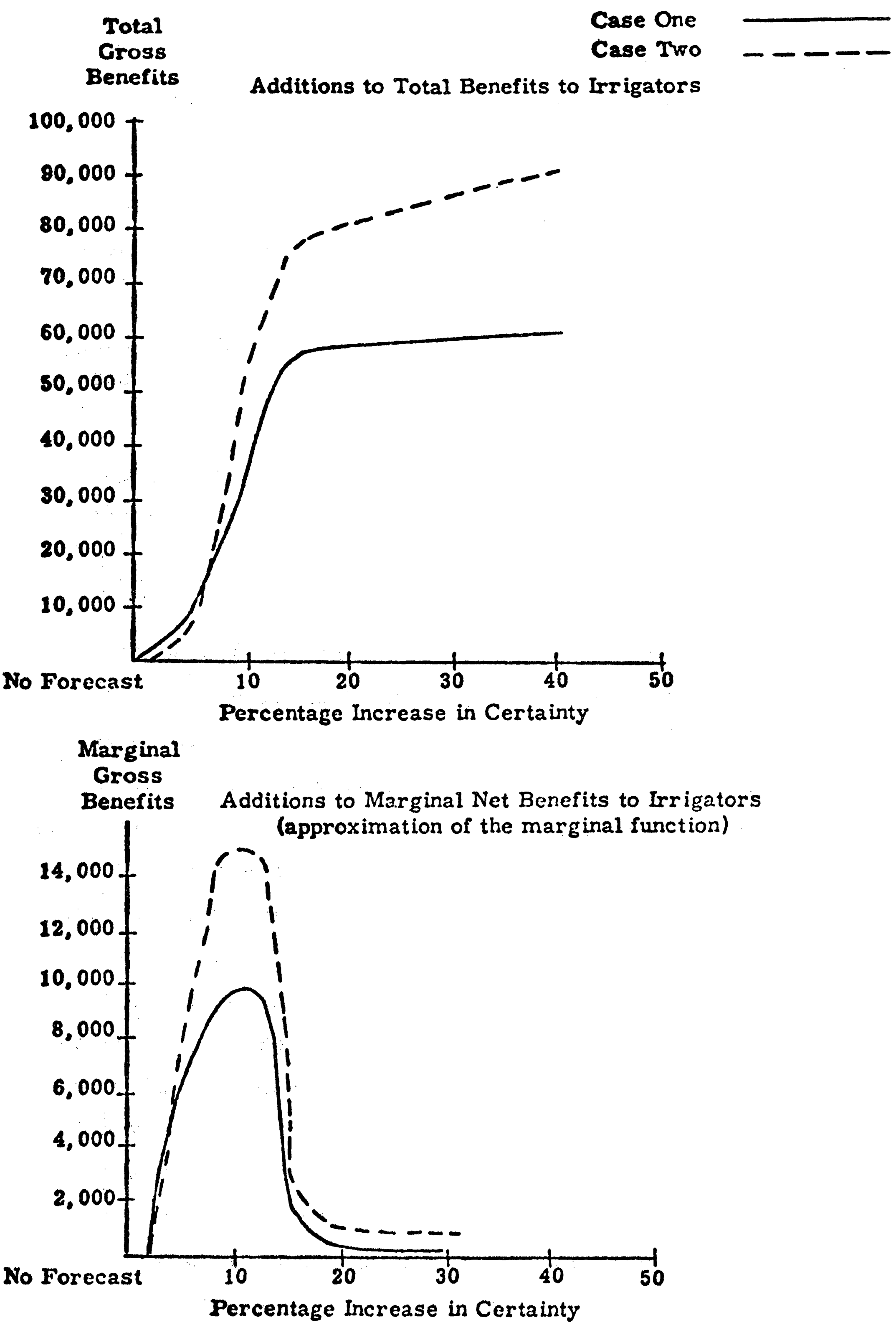

Fig. 11. Comparison of benefits for Case One and Case Two.

Third, though no tests were performed beyond a 33 per cent increase in certainty it is likely that the diminishing marginal returns to increased forecast accuracy observed in both cases beyond the 12 per cent level would continue.

Summary

Table 19 below summarizes the benefits that can be expected based on the assumptions and structure of the model used. Total benefits associated with each increase in certainty are shown in terms of the average acreage planted under each forecast accuracy level. This figure is computed by weighting the acreage planted for each forecast by the probability of observing the forecast.

TABLE 19

SUMMARY OF RESULTS

Case One
(Adequate Reservoir and Well Water)

	Historical Frequency	Forecast Accuracy Level			
		One	Two	Three	Four
Average Acreage Planted	18,600	17,743	18,159	18,250	18,066
Increase in Certainty		4%	11%	15%	33%
Increase in Expected Net Income		$5,000	$42,000	$57,000	$60,000
Per Acre Net Benefits to Irrigators		$0.28	$2.31	$3.12	$3.32

TABLE 19 (continued)

	Case Two (Inadequate Reservoir and Well Water)				
Average Acreage Planted	13,371	13,611	13,897	13,953	13,923
Increase in Certainty		4%	11%	15%	33%
Increase in Expected Net Income		$3,000	$56,000	$77,000	$87,000
Per Acre Net Benefits to Irrigators		$0.22	$4.03	$5.52	$6.25

As can be seen from the above figures, increases in the certainty of water supply resulting from increased forecast accuracy are subject to the law of diminishing returns just as with any other variable input.

It is interesting to note that improved forecasts result in a slight expansion of the average acreage planted in Case Two and produce a slight decrease in Case One. This is due primarily to two factors. First, the crop acreages show greater adjustment to forecasts in Case One, due to the lower value products involved and the greater production flexibility inherent in a situation with abundant reservoir and well water supplies. Second, in Case One more accurate forecasts induce a substitution of beans for alfalfa which results in a slight reduction in total acreage planted. In Case Two the risk of loss on high value crops induces a conservative allocation of acreage under historical information, which is somewhat altered by increasingly accurate forecasts.

The benefit estimates presented here are dependent on both specific structural aspects of the model and on assumptions as to broader economic, technical, and institutional conditions. Consideration of the effects of these factors on benefit estimates is the subject of the next chapter.

FOOTNOTE

[1] William K. Hall, Arthur McWhorter, and W. Allen Spivey, *Optimization Programs at the University of Michigan* (Ann Arbor, Mich.: Bureau of Business Research, Graduate School of Business Administration, The University of Michigan, January, 1971).

CHAPTER IX

AN ANALYSIS OF THE EFFECTS OF VARIOUS MODEL ASSUMPTIONS

As in all models, the formulation developed here necessarily involves simplifying assumptions and abstractions which make theoretical analysis possible. However, it is important to examine the likely effects on the model results from altering these assumptions and to quantify these expected changes, if possible.

Examination of Assumptions as to Upper and Lower Bounds

The ultimately diminishing returns exhibited in the results (as discussed in Chapter VIII are according to expectations in situations in which a variable input (increased accuracy) is applied in increasing amounts to a given bundle of productive resources (land, water, labor, machinery, etc.). However, it is likely that some of the assumptions of the model contribute to the degree of diminishing returns that are observed.

Upper and lower bounds on each crop, in conjunction with net returns per acre foot of water and total water available, limit the amount of substitutions, expansions, and contractions observed in crop acreages and, hence, determine the incremental benefits from increased accuracy. Changes in the assumptions with regard to the upper and lower bounds on crops will also change the estimate of benefits. The value of the dual variable for each of these under various forecasts and levels of accuracy provides useful information for examining this consideration. The value of the dual variable for each crop bound indicates what increase in the value of the objective function would occur if the bound could be expanded by one unit; i.e., the marginal value product of increasing the upper or lower bound for a given crop while holding the total acreage constraint fixed.

Values for the dual variables for activities at the upper and lower crop bounds have been calculated. In addition, the range over which the positive valued activities can be changed without altering the activities in any given optimal solution (final optimal basis) has also been obtained.[1] This information can be used to indicate the sensitivity of the model results to changes in the assumptions governing the crop bounds. Unfortunately, because of its volume, it is impractical to summarize all this information here. Some selected output data are shown in Table 20, however. These figures show the marginal value associated with a one acre expansion of either the upper or lower crop bounds for forecasts of the most adverse (F_1) and most abundant (F_7) conditions at four different accuracy levels. Those values which are negative indicate the reduction in expected net income that would occur if the lower bounds of the given crop were expanded one acre. Similarly, the values which are positive indicate the increase in expected net income that would occur if the upper bound of the given crop were expanded one acre. Values which are zero indicate that for the given forecast, the crop activity is in between the upper and lower bounds and marginal alteration of the bounds would not add or subtract anything from expected net income.

This type of information is sufficient to evaluate the effect on model results from marginal changes in the upper (or lower) bounds of the individual crops. To do this for any given crop, it is necessary to determine the marginal value product (dual value) of expanding the upper bound on the crop for each forecast at a given level of accuracy. These values are weighted by the probability of observing each of the forecasts and then are summed for the given accuracy level. The results of this type of computation are shown below for an expansion of one acre in the upper bound on onions for Cases One and Two. Onions are chosen since they provide the highest net returns and would therefore be the most likely crop acreage to expand, other things remaining equal.

As can be seen from Table 21, as forecasts increase in accuracy, the opportunity cost associated with holding onions at 1680 acres generally rises at a decreasing rate. The table shows that a .06 per cent increase in the upper bound on onions is associated with a .015 per cent increase in the value of the expected net income for Case One and .016 per cent for Case Two (from Tables 15 and 17). Lesser effects

TABLE 20

MARGINAL VALUES ASSOCIATED WITH A ONE ACRE EXPANSION IN THE UPPER AND LOWER BOUNDS FOR SELECTED FORECASTS[a]

	Forecast Accuracy Level							
	Level One		Level Two		Level Three		Level Four	
	F_1	F_7	F_1	F_7	F_1	F_7	F_1	F_7
Case One								
Alfalfa	-.73	0	-6.01	0	-7.54	0	-9.79	0
Barley	-11.91	-9.35	-16.78	-9.10	-18.09	-9.49	-19.76	-11.45
Beans	-6.74	-2.50	-14.10	0	-16.01	0	-18.48	0
Corn	-.90	3.84	-7.88	6.13	-9.73	6.39	-12.65	5.42
Onions	151	162	138	169	134	171	135	173
Potatoes	17.34	20.63	2.67	25.23	0	26.14	0	26.59
Sugar Beets	34.73	46.01	21.71	53.19	18.22	54.88	19.19	56.81
Case Two								
Alfalfa	-10.94	0	-11.96	-.19	-11.92	-.21	-11.53	-.25
Barley	-23.74	-13.22	-24.17	-12.38	-24.37	-12.24	-24.33	-11.87
Beans	-22.98	-7.25	-22.75	-6.33	-23.10	-6.07	-24.11	-5.91
Corn	-17.74	-1.78	-18.75	0	-18.64	0	-18.69	0
Onions	116	142	116	153	116	156	116	156
Potatoes	0	8.72	0	14.30	0	15.81	0	16.24
Sugar Beets	0	33.39	0	38.85	0	39.73	0	40.27

[a] Negative values are associated with a one acre expansion in lower bounds, positive values with a one acre expansion in upper bounds, and zero with crop activities in between bounds.

TABLE 21

INCREMENTAL VALUE ASSOCIATED WITH A ONE-ACRE INCREASE IN THE UPPER BOUND ON ONIONS
(in dollars)

	Historical Frequency	Forecast Accuracy Level			
		One	Two	Three	Four
Case One					
Increase in Expected Net Income	156.00	157.41	159.92	160.94	160.24
Per Cent Increase in Net Income	.015	.015	.015	.014	.014
Case Two					
Increase in Expected Net Income	132.83	129.22	135.12	136.90	137.63
Per Cent Increase in Net Income	.017	.016	.016	.016	.016
Per Cent Increase in the Bound (1,680 acres	.06				

would be associated with expanding the upper bounds of the other high value crops used in the model. Expanding the lower bounds of lower value crops such as barley, alfalfa, and beans would actually reduce expected net income. This results, since losses are increased in the most adverse states of nature, and in the abundant states of nature, opportunities are foregone in other higher value crops.

Since the values presented in Table 21 are only for marginal changes in the bounds, the effect of non-marginal changes on the model results should also be examined. In Case One expansion of the upper bound on onions can be as little as 2 acres and as much as 55 acres without altering the composition of activities in the final optimal solutions, which in turn affect the rate of change in the objective functions associated with expansion of the bound. In Case Two the expansion that can occur without altering the composition of activities in the various optimal solutions ranges from 2 acres to 300 acres, depending on which forecast and accuracy level is involved. In both cases any expansion of the bound which induced a change in the composition of activities in the final optimal solution would reduce the incremental value associated with further expansion of the bound. This would occur as the opportunity cost of shifting water and land from other crops to onions rose. Similar results would hold for the other high value crops.

On the other hand, non-marginal expansion of the lower bounds on the lower value crops would produce an increasing rate of decrease in the various objective functions with each successive increase in the bound. This is due to both the rising opportunity costs associated with withdrawal of land and water from other higher value crops and to the increasing losses incurred in the more adverse states of nature.

From the above example and tables, it is apparent that the level of benefits estimated through the methodology used in this model will be sensitive to the assumptions made as to upper and lower bounds on individual crops. The diminishing returns exhibited by the benefit functions are a product of the present bounds as well as the variable water supply and total land constraint. Though variation of the bounds could be expected to produce a change in the level and shape of the benefit function for both cases, the phenomenon of diminishing returns would not be affected since increasing amounts of a variable input would still be applied to a fixed bundle of productive resources.

Because of this and cost constraints, it is not possible to run several tests of the model with different assumptions as to bounds. Hence, the sensitivity of the results to changes can be discussed and evaluated only in qualitative terms. First, if the total acreage constraint (21,000 acres) were maintained and the upper bounds on the higher value crops were expanded, generally there would be an increase in the net expected income associated with each forecast accuracy level. The effect on the benefit estimates associated with increased forecast accuracy, however, would depend on two factors, the extent of variation in acreage and the variation in types of crops which varied. For example, if the expanded bounds resulted in a situation in which improved forecasts induced little or no change in the optimal acreages planted under each forecast scheme, then the benefits associated with increased accuracy would be lower than under the present set of bounds. On the other hand, if the variation in acreage that did occur was primarily in the higher value crops, it is possible that the benefit estimates associated with improved forecast accuracy would be greater than those estimated using the present set of bounds.

Similarly, if the lower bounds on the lower value crops were decreased, there would be an increase in the net expected income associated with each forecast accuracy level. The impact on the benefit estimates associated with the present set of bounds would again depend on how crop acreage varied with improved forecast accuracy and on what crops varied. If the upper bounds on the higher value crops were held constant, reducing the lower bounds on the lower value crops would probably increase the benefits associated with improved forecast accuracy, at least in Case One. This would result, since it is primarily the acreage of the lower value crops that varies with increased forecast accuracy under the present set of bounds. If the lower bounds were reduced, a wider range of variation would be possible, thus increasing the benefits associated with increased accuracy.

The opposite results would generally hold for decreases in the upper bounds of high value crops and increases in the lower bounds of the lower value crops. In all cases, however, evaluation of the shape of the benefit function such as points of inflection and rate of decrease in the marginal benefits is not possible without complete rerunning of the model with altered bounds.

Since the purpose of the bounds is to represent forms of risk other than that associated with the variable water supply, large differences in the marginal value of expanding bounds for different crops does not necessarily imply that the original bounds are unrealistic. Onions, for example, have the highest unit value associated with expansion of the bounds but they are also a crop with significant production risks other than water supply. Barley is often used as a nursery crop and alfalfa is an important part of rotation sequences. If it were possible to intorduce other forms of risk into the objective function such as price fluctuations and reductions in yield associated with pests and crop disease, the necessity for crop bounds would be considerably reduced. Planting decisions would then be based on the probability of occurrence of several interacting factors which would produce approximately the same effect as use of bounds in the present model, assuming that all important variable conditions could be represented in the form of probability distributions. Since the present range for the various bounds is based on an approximation of the variations in acreage observed in irrigated areas and since the qualitative nature of the sensitivity of benefits to changes in bounds has been discussed, no further refinement will be attempted.

Evaluation of the Results in Terms of Other Model Assumptions

Bounds on crops are not the only aspects of the model that must be evaluated as to their effect on the validity of the benefit estimates. Foremost among the assumptions on which the model rests is that of a two period analysis; i.e., a planting period and a production period in which water is available in fixed quantities according to the existing states of nature. This assumption is a simplification, because timing of application of water is a critical factor to successful irrigation. Therefore, the model overlooks certain production subtleties that could increase the importance of improvement in forecasts of the availability of early and late season water. Small grains, for example, may often be planted to take advantage of early season water because of their relatively short growing season. Likewise, indication as to the availability of late season water would facilitate decisions on whether or not to plant high value, long growing season crops such as sugar beets or potatoes.

The bias introduced by this assumption results in an overstatement of benefits in the case of high value crops and an understatement in the case of crops that mature early, such as small grains. Because the model uses a volume of water per season to crop yield relationship, planting of high value, long season crops on the basis of predicted total volume only exposes the decision-maker to the risk of inadequate water towards the end of the growing season, when its availability is often crucial. On the other hand, because the net returns per acre foot of water allocated to small grains such as barley is low, no consideration of this factor is possible in a model based on a volume-yield criterion. Thus benefits from planting early season crops are omitted entirely.

It is doubtful, however, that these overestimates and underestimates offset each other to any significant degree, particularly in Case Two, where forecast benefits are obtained through expansion and contraction of some of the higher value crops. In defense of the approach used in the model, it can be said that in cases where physical control exists in the form of reservoirs or well water, the simple volume-yield assumption is fairly realistic. Also, since water rights are usually stated in terms of rates of flow and ditch companies often have decrees of varying priorities, some translation of volume into the likely flow pattern is possible. If the company has some reservoir or well water to fall back on, the relationship of volume-yield may serve as an adequate first approximation to the problem in lieu of a multiple period analysis. It would also be possible to frame the forecast in terms of "effective" or economically useable water so that ditches with flood rights only would not fall into a category receiving useable water. On balance, the two period framework introduces a moderate overestimate of benefits.

Another assumption is that of a high degree of precision in water management by the irrigator and a well defined and moderately uniform water requirement for similar crops. Irrigation management is seldom as precise as the model would presume nor are water requirements as uniform in practice as they are in the model. However, the issue in this case is less one of methodology and more one of what degree and level of management one wishes to employ in representing the production relationships. Since the trend in an economic sector severely pressed by rising costs and stable or declining price is likely to be towards greater efficiency in resource utilization, benefit estimates based on use of efficient practices should become more realistic over time. Bias introduced by assumptions as to precision is difficult to assess, though it also would likely be on the positive side.

A final major assumption underlying the framework of the model is that forecasts are directed at specific ditch companies. This is not realistic since present streamflow forecasts are for river basins or specific reaches of a basin. However, translations of basin forecasts into water supply forecasts for specific ditch companies are undertaken by the better managed companies as was discussed in Chapter VI. This assumption essentially presumes a technology that is not formally applied in most cases since printed streamflow forecasts do not specify conditions for individual ditch companies. To this extent, the methodology will overestimate benefits. On the other hand, subjective translation of the forecasts into predictions of supply conditions tailored to individual production situations can be assumed. Also, as is discussed in the concluding chapter, one possible improvement in forecasts would be more detailed predictions. To this extent, the benefit estimates would be representative of what could be expected under situations of more specific forecasts. The benefit estimates thus presume one level of improvement to begin with and then reflect benefits to increased accuracy starting from that initial level of improvement. To what extent this produces an upward bias in the estimates is difficult to determine, though some overestimation is probably unavoidable.

Economic Factors Affecting Benefit Estimates

Since the analysis focused on those benefits that would accrue to a small region, the impact on quantities and prices over a broad region such as the West were by necessity ignored. Increased accuracy in forecasts most likely would be the result of substantial research and investment affecting all regions to some extent. Thus the partial equilibrium results of the model must be qualified in a qualitative sense by general equilibrium considerations, including the effect of price supports for several farm products and the subsidies implicit in Bureau of Reclamation projects. Likewise, the methodology employed involves an "instantaneous" improvement which is assumed to apply over several years of hydrology and which is compared with other levels of forecast accuracy of the same hydrologic period. Since agricultural technology, farm size, and farm management practices have changed considerably in the last several decades and these and similar changes will continue to affect the structure of irrigated agriculture, a methodology which produces an annual benefit estimate that remains constant in the face of changing production conditions will likely be biased. Dynamic considerations on the demand side will also affect benefit estimates as population growth and rising per capita income shift demand for agricultural products outward. Thus considerations of general equilibrium and dynamic aspects such as growing demand and structural change in agriculture will affect the benefits estimates based on the methodology used in this study.

General Equilibrium Considerations

Price Effects

Use of substantially improved forecasts are likely to result in a more efficient irrigation operation since planting and water allocation decisions can be adjusted more closely to the probable water supply. These adjustments in turn result in an increase in output of certain crops through expansion of acreage when abundant water supply is predicted and reductions in the incidence of abandonment in the opposite case. This effect can be seen in the figures presented in Chapter VIII in Tables 15, 16, 17, and 18, which show acreage planted and nominal income in each state of nature. From Tables 15 and 17 it can be seen that increased accuracy induces changes in the acreages planted to various crops and from Tables 16 and 18 it can be seen that increases in accuracy raise the nominal value of regional income. This increase in income is the direct result of changes in cropping patterns which tailor the acreage planted more precisely to the probable water supply conditions. These adjustments in turn produce an overall expansion of the output of crops. If improvements in forecast accuracy affect most irrigated areas, the existence of better forecasts could be expected to have non-marginal effects on the output of various crops. Because the demand for most of the products under consideration is highly inelastic, expansion of total supply due to use of improved forecasts would have some effect on product prices. Estimation of the extent of such price effects is beyond the scope of this work, though the nature of the complexities of the issues involved should at least be mentioned.

First, the effect of expansion of output on price will depend on the percentage of supply which is involved and the price elasticity of demand for the products. For crops whose markets are more local in nature, price effects are likely to be significant. On the other hand, crops whose markets are national or international in scope and for which output from Western states is not a significant percentage, are less likely to exhibit any significant changes in prices directly attributable to increased forecast accuracy. Second, substitution and expansion and contraction of crop acreage in each area will depend on a host of factors such as soil, climate, and dependability of existing water supply. Thus, increase, in average output of certain crops in one irrigated area will not necessarily imply the same types of changes in other areas. It is likely, however, that for crops for which irrigators expect substantive price changes, the overall effect of improved forecasts would be a more conservative pattern of crop planting. This would mean that lower estimates of benefits attributable to increases in forecast accuracy would be more appropriate.

Finally, abundant supply conditions in one geographic area are not always positively associated with similar abundant supply conditions in other areas. There may even be a negative relationship due to long-term weather patterns. The extent to which price effects occur will thus be further masked in any given year if the nature of adjustments differ among regions.

The general conclusion which can be drawn is that expectations of lower prices in response to higher yields from improved forecasts will induce more conservative crop planting patterns. This in turn will mean that the above benefit estimates which were based on constant prices have a built-in upward bias.

Effects of Subsidized Water Costs

At present the price of irrigation water supplied through Bureau of Reclamation projects is subsidized in part from power revenues so that irrigators do not pay the full amortization and associated costs of Federal project water.[2] In addition, water prices are based on zero interest charge for capital. Because of these subsidies, reservoir water is employed beyond the point at which its marginal social cost equals its marginal value product. Benefit estimates of improved forecasts will thus be understated to the extent that full cost pricing of reservoir water would enhance the value of more accurate knowledge of the available surface supply.

Effects of Government Farm Programs

Since the marginal social valuation, as determined by the laws of market supply and demand, is often altered by national farm price and income support programs, private and social benefits attributable to increased forecast accuracy will not necessarily coincide. For example, the 1970 voluntary feed grain program included corn, grain sorghum, and barley and provided for a specified minimum rate of diversion to qualify for price support payments and loans.[3] A similar program was in effect for wheat. If supplies of certain crops are in such abundance that policies are necessary to bolster prices for political and equity considerations, then increase in the output of these crops will have a lower real economic value than that indicated by the artificial support price. Thus real economic benefits attributable to increased forecast accuracy will be less than those indicated by the model in cases where planting adjustments occur primarily in price supported crops. As in the case of price effects due to expanded output, the effect of private marginal valuation exceeding social marginal valuation will be to produce an upward bias in the benefit estimates. This latter factor may be offset over time, however, as is discussed below.

Dynamic Considerations

Growing Demand

With growing world population and rising per capita incomes, demand for agricultural products in general can be expected to shift outward over time. Several crops which are in surplus today may not be so in the future, hence private benefits associated with increased forecast accuracy could be expected to approximate social benefits more closely with the passage of time. The extent to which expansion in irrigated acreage will occur in basins in which streamflow forecasts are important is debatable. Studies indicate that with full cost pricing of water, water resource developments in the subhumid East represent an economical substitute to expansion of submarginal irrigation in several Western basins where competing uses of the water would have a higher marginal value.[4] On the other hand improved forecasts in conjunction with other types of developments may, in some cases, offer lower cost alternatives to reservoir construction regardless of the region and thus represent more economical means of obtaining marginal increases in outputs of certain commodities.

Structural Change in Agriculture

A phenomenon observed over the last several decades and likely to continue in the future has been substantial technical change affecting many areas of the agricultural sector. In turn, this has resulted in increasing farm size, greater efficiency in resource use and increased agricultural output. This trend has certain implications for the nature of the benefit function associated with increased forecast accuracy, since the assumption of a more or less constant production technology over the period of analysis (length of hydrologic record) is unrealistic. Increasing farm size, improvements in the efficiency of farm equipment, better management practices, and improved marketing and transportation facilities can be expected to both shift the demand for more precise production information as well as create the conditions under which improved forecasts of prices, weather, or streamflow can be better utilized by the decision-maker. As farming operations increase in size and complexity, the need for more precise planning and management also increases, which in turn creates greater demand for sound advisory information. At the same time, it could be argued that increased farm size, improved management and greater access to financial markets and credit tend to introduce greater operational flexibility which in turn reduces the critical nature of year to year fluctuations in agricultural conditions so important to the small operator. With greater flexibility in production decisions, the feasibility of adjusting to highly accurate forecasts of water supply conditions increases since the critical nature of an unlikely poor decision is more easily borne by a corporate type farm than by a small family operation with definite minimum income requirements.

To the extent that the above points are valid, these trends will have the tendency of increasing the actual benefits that can be attributed to increased accuracy of streamflow forecasts. This does not imply, however, that the net benefits estimated previously are overstated, since the model assumed a profit maximizing decision-maker with no aversion or preference to risk. Hence the methodology used in the model already assumes the implied improvements in management techniques. One aspect subject to variation relates to the bounds placed on crops. With better information about other factors that introduce risk into the decision process, it is conceivable that increased forecast accuracy would permit greater variation in crop acreage for certain years than is represented in the model in its present form. To this extent, the benefits estimated by the model may be understated.

Application of Institutional and Water Resources Management Innovations

Often there are institutional changes and innovations in management techniques which may serve to increase the present efficiency of water utilization in given basins. The nature of these changes in turn can serve to increase the value that would be associated with improvements in forecast accuracy. Institutional changes revolve around individual state water laws which are based on the doctrine of prior appropriation. Some of the issues were briefly discussed in the introduction, but the various arrangements are too varied and numerous to deal with here. One example, however, centers on altering the geographic point of diversion so that upstream users, regardless of priority, would divert first, as long as downstream flow was adequate to meet senior rights. The purpose of this arrangement would be to increase reuse of the river through the utilization of return flow. Implementation of this general type of reorganization in conjunction with better forecasts of streamflow could be very beneficial to those ditch companies who normally receive water only after downstream senior rights have been satisfied. Quality considerations arise under this scheme due to the increase in total dissolved solids in the return water from irrigation fields. This fact often makes acceptance of the proposal difficult, particularly from the point of view of those with downstream senior water rights who stand to suffer a loss in the quality of their irrigation water.

Institutional and legal changes which increase the effectiveness of the rental market for water also will serve to enhance the benefits associated with increased accuracy. As was discussed in the introduction, in many cases changes are needed just to establish mechanisms for the transfer of water during the irrigation season. By improving the opportunity to purchase water from lower value or surplus users, the more efficient irrigators are given added incentive to intensify their operations. With increased accuracy in forecasts, judgment as to the likely availability of rental water would be facilitated, resulting in increased farm income.

The area of management innovations involving a minimum of structural features was also discussed in Chapter I. For example, there is need in several basins for policies designed to promote the conjunctive use of ground and surface waters.[4] Implementation of greater coordination in the combined use of surface and ground water should enhance the benefits that would be associated with greater accuracy in streamflow forecasts, since these types of changes generate the greatest benefit when it can be determined that heavy pumping will be offset by recharge at a later date.

The effect of these broader types of developments will tend to alter the decision level at which increases in accuracy will have the greatest impact. Smoothing of the annual variation of water supply through increased management coordination tends to reduce the risk inherent in planting decisions, which in turn will tend to reduce the direct operational importance to the individual decision-maker from highly accurate forecasts. On the other hand, to the extent that greater management coordination is achieved through improved forecasts of probable runoff from mountain watersheds, monetary benefits to irrigated agriculture may be equivalent or greater than in the case where decision-makers adjust production plans on the basis of forecasts of a variable input. This last consideration overlaps with the points discussed below.

Benefits Due to Improved System Operation

Some improvement in system operation would result from the creation of more accurate information concerning probable inflows to specific water systems. These in turn would facilitate longer term decisions that have effects on several water uses including hydroelectric power production, municipal water supply, recreational use, and, of course, irrigation supply. Though no new supplies of water are created in this process, the ability to make allocational decisions well in advance, with a high degree of confidence in the outcome of the factors that underlie the decision, would serve to reduce some of the losses and inefficiencies often associated with situations where it is necessary to take management decisions on a short notice or contingency basis. In conjunction with application of more comprehensive basin management techniques in which greater coordination between ground and surface water is achieved, it would seem likely that highly accurate forecasts could play an important role. On the one hand, improvements in water supply information would serve to enhance the operational efficiency of water supply systems. On the other hand, production decision-making in adjusting to unavoidable variations in the supply would be facilitated. It was this latter area that the work in the preceding chapters attempted to analyze.

In areas where complex systems of water storage and delivery have been developed, increased forecast accuracy will provide benefits to the irrigator both in terms of adjusting his own planting decisions to the variations in supply that do occur as well as improving the efficiency of the system and thus the dependability of the irrigators supply. In situations where water management and storage systems are less extensively developed, benefits associated with increased forecast accuracy will be more nearly comparable to those depicted by the model. To some extent the differentiation in water supply conditions presented in Chapter VIII indicates the lower level of benefits directly attributable by the irrigator to improved forecasts in situations where other sources of water are available at a higher price to offset deficient direct flow supplies in bad years. However, the model does not reflect the benefits that might result from application of improved forecasts to water systems management.

From the discussion in this chapter, it appears that the general methodology used tends to produce somewhat upward biased estimates of the benefits. With this consideration in mind, in the next chapter the model will be used to evaluate two important subjects; namely, comparison of additions to water supply with increased accuracy and the feasibility of expanding acreage on the basis of improved forecasts.

FOOTNOTES

[1] Hall, McWhorter, and Spivey, Optimization Programs at the University of Michigan, p. 19.

[2] Ruttan, The Economic Demand for Irrigated Acreage, p. 29.

[3] U. S., Department of Agriculture, Agricultural Stabilization and Conservation Service, The 1970 Voluntary Feed Grain and Wheat Programs, January, 1970.

[4] Ruttan, Ibid., p. vi.

CHAPTER X

UTILIZATION OF THE MODEL FOR COMPARING INCREASED ACCURACY WITH OTHER ALTERNATIVES

The model provides an easy method by which to examine the difference in benefits between increased forecast accuracy and additions to the reservoir water supply. Also the feasibility of expanding the acreage under cultivation on the basis of increased accuracy can be examined.

Comparison of Additional Reservoir Water With Increased Forecast Accuracy

An important issue in contemporary debates over western water resources utilization is the tendency to see structural measures as the only means by which desired benefits can be secured. Other alternative measures are hardly ever considered. As the preceding discussion has shown, increased accuracy in streamflow forecasts could be one alternative for increasing regional agricultural income. The economic question then becomes how the net benefits from expenditure of public or private resources on additional reservoir development compare with the expected net benefits from increased accuracy of forecasts of the available supply. It is not possible to determine net benefits from the model output since information about the costs of increased forecast accuracy as well as about costs of reservoir development would be required. However, comparison of gross benefits is possible, if the benefits of incremental increases in accuracy and reservoir supply can be couched in comparable units of measure.

Evaluation of increases in reservoir supplies is a difficult process, since the marginal values are not independent of the level of forecast accuracy. To calculate the marginal value product of an acre-foot of reservoir water, the marginal value products for each forecast at a given level of accuracy are weighted by the probability of observing each of the forecasts and these results are then summed. For example, if irrigators follow forecasts at accuracy level four, the marginal value product of reservoir water would be $9.57 in Case One and $14.38 in Case Two. In contrast, these values are $10.72 and $15.51, respectively, when irrigators only have historical information on which to base their planting decisions.

To avoid the problem of which accuracy level to use in evaluating increases in reservoir supplies, it was assumed that the choice is between introducing forecasts to a situation where none existed previously or adding to the reservoir capacity. To accomplish this, the historical frequency distribution was used and four succe-sive increments of 2000 acre feet were added to the minimum reservoir capacity available in all states of nature. It was assumed that the water would be secured through new reservoir capacity designed to redistirbute water from other time periods or from other geographic points. The results for Case One and Case Two are presented below in Table 22.

Looking first at the results for Case One, it can be seen that the increase in expected value is approximately linearly related to the increase in the volume of reservoir water. The increase in expected value is achieved through expansion of the acreage of alfalfa and reduction in crop losses in the more adverse states of nature through application of reservoir water, except for the last increment where alfalfa is expanded at a more rapid rate. In this case, the possibilities for reduction in crop losses have been exhausted by the preceding increments to reservoir supply so that the next best alternative becomes more rapid expansion of alfalfa. The linear relationship between increments of water and increase in expected value is due to the hundreds of substitution possibilities in the linear program which results in the marginal value of an acre-foot of water ($10.72) remaining constant except for the last increment to supply (differences in net value are due primarily to rounding).

In Case Two, the increase in expected value is accomplished primarily be expansion in acreage of potatoes for the first three increments to reservoir supply and by reduction in losses on lower value crops for the fourth increment. The increase in expected value is linearly related to additions to reservoir supplies for the first three increments but the marginal returns decrease slightly for the fourth increment. This is caused by exhaustion of the higher return alternatives by the first three

TABLE 22

CROP ACREAGE AND EXPECTED INCOME FOR FOUR SUCCESSIVE 2,000 ACRE FOOT INCREMENTS TO RESERVOIR WATER WHEN PLANTING DECISIONS ARE BASED ON HISTORICAL FREQUENCY INFORMATION

Case One					
Crop	**Hist. Freq.**	**Plus 2000 A.F.**	**Plus 4000 A.F.**	**Plus 6000 A.F.**	**Plus 8000 A.F.**
Crop Acreages Planted					
Alfalfa	3,690	4,115	4,541	4,966	5,711
Beans	1,050	1,050	1,050	1,050	1,050
Corn	5,250	5,250	5,250	5,250	5,250
Onions	1,680	1,680	1,680	1,680	1,680
Potatoes	2,100	2,100	2,100	2,100	2,100
Sugar Beets	3,150	3,150	3,150	3,150	3,150
Barley	1,680	1,680	1,680	1,680	1,680
Total	18,600	19,025	19,451	19,876	20,621
Expected Total Net Income (1,000's of dollars)	($1,058)	($1,080)	($1,101)	($1,122)	($1,141)
Incremental Net Income (1,000's of dollars)		22	21	21	19
Case Two					
Crop Acreages Planted					
Alfalfa	2,940	2,940	2,940	2,940	2,940
Beans	1,050	1,050	1,050	1,050	1,050
Corn	2,100	2,100	2,100	2,100	2,100
Onion	1,680	1,680	1,680	1,680	1,680
Potatoes	771	1,296	1,867	2,100	2,100
Sugar Beets	3,150	3,150	3,150	3,150	3,150
Barley	1,680	1,680	1,680	1,680	1,680
Total	12,371	13,896	14,467	14,700	14,700
Expected Total Net Income (1,000's of dollars)	($795)	($826)	($857)	($888)	($916)
Incremental Net Income (1,000's of dollars)		31	31	31	28

increments, so that the fourth increment of water serves merely to reduce losses on some of the lower value crops and to bring potatoes to their full level of watering in the more adverse states of nature. No expansion takes place in the acreage of the lower value crops because the expected value of reducing losses or increasing return on the existing acreage exceeds the expected value associated with expansion of lower value crops.

Since cost figures on increased accuracy and reservoir development were not available, the only comparison which is useful is to find the level of additions to reservoir capacity needed to provide equal benefits to the specified level of accuracy improvement. This is easily done based on the approximately linear relationship between increments to reservoir capacity and increase in expected net income. Table 23 below shows the increase in reservoir capacity needed in Cases One and Two to just equal the benefits associated with a 33 per cent increase in accuracy.

In order to obtain comparable monetary benefits for Cases I and II, only a 12 per cent increase in forecast accuracy is required in Case II. This increase would yield $60,000 annual expected net income and would be equivalent to a 4,138 acre foot expansion in reservoir capacity. As would be expected, benefits associated with both increased accuracy and expansion of reservoir capacity are greater in Case Two, where supplemental sources of water are inadequate. The benefit functions derived from the

TABLE 23

COMPARISON OF BENEFITS ASSOCIATED WITH INCREASED ACCURACY AND EXPANDED RESERVOIR CAPACITY

	Annual Benefits from a 33 per cent Increase in Forecast Accuracy (in dollars)	Expansion in Reservoir Capacity Needed to just Equal Benefits Associated with Increased Forecast Accuracy (in acre feet)
Case One	60,000	5619
Case Two	87,000	5613

model output permit the types of comparison shown above. Lack of cost data, however, limits the extent to which these figures can be meaningfully used.

Feasibility of Acreage Expansion Using Increased Forecast Accuracy

One of the possible consequences of improved accuracy would be an increase in the total acreage planted. In examining this question, several factors must be considered, both in terms of the model and in terms of the actual situation. The economic feasibility of expanding acreage through substitution of highly accurate forecasts for increased physical control of the water obtained through additional reservoirs or wells depends on four factors. These are (1) the expected net value of incremental expansion of acreage under cultivation, which in turn is directly related to the types of crops that will be grown; (2) the investment costs associated with developing the land for cultivation which may range from minimal clearing and preparation to major expenditures on new equipment and irrigation facilities; (3) the percentage of time that predicted abundant supply conditions will obtain; and (4) the reliability of the forecasts.

Though the dual variable values from the model indicate what an additional acre would add to the value of the objective function, these values are predetermined by the scheme of upper and lower bounds on individual crop acreages. Major changes in the bounds, in situations of predicted abundant water supply conditions, could be investigated and the difference between the associated expected income and the expected income with the original bounds could be computed. Alternatively, the information describing the range over which bounds could be altered without altering the composition of activities in the final solutions could be used to compute small expansions in the bounds of various crops as well as in the associated expected income. Looking at only those crops in Case One for which expansion in bounds is associated with positive increases in expected income, the following table can be constructed. In Case Two, the total acreage constraint is never reached so that the issue of acreage expansion is not important.

TABLE 24

INCREASE IN EXPECTED INCOME ASSOCIATED WITH SMALL INCREASES IN THE UPPER BOUNDS OF SELECTED CROPS UNDER HIGHLY ACCURATE FORECASTS OF THE MOST ABUNDANT SUPPLY CONDITIONS

CASE ONE

Crop	Expansion of Bounds which do not Alter the Composition of Activities in the Various Final Solutions (in acres)	Increase in Expected Income per acre	
Corn	10	$5.42	
Onions	6	$172.90	
Potatoes	7	$26.59	
Sugar Beets	6	$56.81	
Total	29	Total Expected Income	$1614.81

Percentage of Time Total Acreage Constraint is Tight	21.6 %
Average Expected Value of Acreage Expansion	$348.80

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[a] Total expected income for the situation where water supply conditions are forecast to be so abundant that individual crop acreage constraints are binding.

To determine the economic feasibility of this type of expansion, components of fixed costs from Table 39 in Appendix III must be examined. For example, if the expansion required additions to equipment, buildings and land improvements averaging $32.50 per acre per annum, the total annual fixed costs of $942.50 would exceed the expected return. However, since the level of fixed costs on land which on the average is used only one out of every five years would not be the same as fixed costs on fully productive land, the discrepancy between fixed costs and net expected returns would not be as large as shown by the above figures. On the other hand, it is also unlikely that fixed costs on fully productive land and land used only 20 per cent of the time would be different enough to allow the necessary investment to break even, not to mention a return to management and capital.

In terms of the model, expansion of acreage of the higher value crops based on highly accurate forecasts would only be economically feasible if there were under utilization of many of the fixed cost items. If, for example, items such as buildings, machinery, and irrigation structures are underutilized, additional land potentially could be brought into production without incurring major additional costs. Also, certain types of equipment could be rented. On the other hand, if a single high return crop such as onions were involved or if there were alternative dry land activities to defray some of the fixed costs in years of inadequate water, there could be justification for carrying the fixed costs of equipment for land that would only be productive in one year out of five.

Though the results presented in this chapter are only suggestive, they do provide examples of how the general methodology developed in this study can be used to evaluate some water resource problems. The concluding chapter of this section provides a summary and recommendations for further research.

CHAPTER XI

SUMMARY AND AREAS FOR FURTHER RESEARCH

Summary

A brief summary of the methodology employed is useful at this point as a basis for proposing areas for further research. The model presented here combines the concepts of Bayesian decision strategy with a sequential probabilistic model using the optimization process of linear programming. Forecasts of volume water supply are represented by the conditional probability distribution of observing various water supply levels, derived by using the Bayesian formula and hypothetical water supply data. Changes in accuracy are represented by altering the term in the formula for historical accuracy of the forecast.

The sequential decision model is a two period analysis representing a planting period followed by an instantaneous production period. The sequential character of the decision process is represented by using the water supply levels as the states of nature for which the probabilistic forecasts give the decision-maker added information. Each water supply level is set up as one of the constraints on the productive activities, representing the net returns per acre for different crops. The same activities appear for each water level constraint. To make the problem a sequential one, the net returns for each level are weighted by the probabilities generated by the particular forecast and accuracy level under consideration. To tie the two periods together, activities representing crop planting are included and are assigned negative payoffs equal to planting costs. Since the planting activities are not weighted by any probability, but the net returns are, the model depicts a situation in which the decision-maker plants his crops based on the likelihood of receipt of various quantities of water. The likelihood or probability of receiving different supplies will be determined by the particular forecast and its accuracy level. Data for testing the model were drawn from a variety of sources though the primary production cost figures were taken from a single study and much of the other information was derived from agricultural data for various portions of Colorado irrigated areas.

Testing of the model involved the use of an IBM computer program available at the University of Michigan. For various assumptions as to supplemental water supply, the model showed a net benefit to irrigators of up to $6.00 per acre for a 33 per cent increase in forecast accuracy.

As in any first approximation of a problem, there are several areas which could be investigated in greater detail in future studies. These are discussed briefly in the paragraphs below.

Areas for Further Research

Elaboration of the Model

More realistic results could be obtained if the model were expanded and refined as follows. First, it is important to irrigators to have some idea of what their late season supply will be when planting decisions are taken. Although present volume forecasts are not couched in these terms, some forecasts give a qualitative assessment of the likelihood of late season water. Other techniques are employed to predict the approximate date of low flow and to predict residual flows after the early melting has taken place. A model which incorporated a representation of planting, early season, and late season periods would more accurately depict the real world decision problems.

A second area that would improve the realism of the results would be a more accurate representation of the hydrologic relationships between surface and ground water. This would require a simulation approach, however.

Finally, since all input costs except those for reservoir and well water are netted out of gross returns, the model assumes a perfectly elastic supply of all of these inputs and no competition among crop activities for the various inputs other than water. Often the timing of a crop's requirements for labor, production credit, and various types of machinery can be very important to planting decisions, since crops may compete for these inputs at about the same time during the planting and production period. Also, supplies of these inputs may be fairly elastic over certain ranges but certainty would be subject to rising price in situations where major changes in planting of some crops occurred. Thus a more realistic model would involve explicit consideration of constraints on other inputs as well as the price elasticity of such inputs. Also there is often a limited substitutability between inputs such as water and labor. For example, in cases of great abundance, water may be managed extensively to reduce the need for labor. Inclusion of these considerations in a more refined model would involve use of purchasing activities associated with each of the inputs. Rising input cost could be approximated by different classes of supply each with a successively higher price. All of the above considerations pose formidable data requirements.

Data

If it were deemed worthwhile to pursue some of the refinements discussed above, present data availability would probably prove to be inadequate. Even for the present level of analysis, difficulty was encountered in obtaining consistent comprehensive data and information for one geographic area. It was necessary to employ data from a variety of sources and make adjustment where possible in order to fit the data as closely as possible to a single production situation.

A primary concern of any further study should be a broad based empirical investigation and sampling of one geographic area in order to obtain internally consistent data. Ideally this information would include all production costs, prices, yields, accurate hydrologic information, and approximations of the timing and competitive nature of various crops for productive inputs. Likewise, approximations of crop yield and timing of stress, some of which already exist, would be required for a multi-period analysis.

Development of a Model for System Benefits

The model presented here represents only one facet of the total benefit function that would be associated with increased forecast accuracy. In order to approximate the nature of the benefits that would accrue in complex water resources systems, a broad based general model incorporating approximations of the benefit functions to major users of the forecasts could prove to be useful. Such an undertaking would prove to be very difficult, though specification of at least a general case of the economic and major technical features involved would be worthwhile.

Recommendations and Conclusion

Though research efforts to improve the present accuracy of forecasts should vary depending on the geographic area and characteristics of the particular basin, three broad recommendations can be made that would produce significant benefits regardless of differences in individual basins or institutions. First, efforts should be made to further develop techniques for estimating water supply to individual decision units such as the major ditch companies. Second, and directly related to the first point, continuing efforts should be made to refine and develop techniques for predicting the approximate time of occurrence of low flow and for forecasting residual flows. Third, and of greatest significance both regionally and nationally, would be development of the ability to accurately predict long-range temperature and precipitation patterns on a reasonably precise geographic basis. Though the analysis in the model was based on the assumption that inability to predict longer range weather patterns placed an upper limit on possible increases in accuracy, it is unlikely that the final level of accuracy portrayed in the model could be achieved without some improvements in longer range weather prediction as well.

Of necessity, the results obtained from the methodology and model developed in the preceding chapters are only suggestive. As in all models, various assumptions have been employed in order to reduce the size and complexity of the problem. In spite of these qualifications, the model provides a rigorous framework within which increases in certainty of water supply produced by improved streamflow forecasts can be evaluated. Areas which are incomplete or are covered by restrictive assumptions should provide fruitful ground for further research and elaboration of the methodology presented here.

APPENDIX I

PRODUCTION FLEXIBILITY

This appendix reviews briefly the nature of the production alternatives open to the irrigator and the present practices used in conjunction with streamflow forecasts.

A review of the available literature reveals a few references to changes in cropping patterns as a result of snow surveys. Israelson and Hansen state in terms of general strategy:

> In years of limited water supply, cropping and irrigation plans may be modified, less land may be irrigated, crops that use less water may be planted and early maturing crops may be substituted for those requiring a longer season. When water supplies are above normal, additional lands may be brought under irrigation or more intensive farming may be practiced.[1]

With reference to specifc crops grown in Carson Velley in Nevada, where irrigation depends entirely on water from snow runoff and from springs, Johnson makes the following observations.

> The entire planting season plans are regulated by the flow of water predicted to runoff during the growing season. Grain is planted when the forecast shows water sufficient to mature the crop. Oats are seeded for a hay crop when it is not certain whether water will be sufficient to mature the crop. Seeding is in early March, gambling on the danger of an early frost, if the forecast shows a low supply of water after June 1. Alfalfa is never seeded unless growers are certain that there will be an ample supply for the entire growing season.[2]

With reference to Colorado conditions, Washichek, Stockwell, and Evans make the following observations.

> Demands for irrigation water exceed water supplies over much of the irrigated area of Colorado. Agricultural water users may adjust to water available by changing total areas to be irrigated, acreage of crops having high water requirements as related to acreage of grains and grasses, and by use of groundwater as a supplemental supply. . . . A typical irrigation operation balances acreages of such crops as sugar beets, potatoes and alfalfa against those of grain, pasture or fallow. When water supply is short, the acreage of grain and

> pasture or land left idle is increased. In years of below normal runoff, water is diverted from late season irrigation of alfalfa to sugar beets. Corn, sorghum, and dry beans are popular "buffer crops," since they may be planted and matured late if there is an improvement in water supply during the spring months.[3]

They indicate that, in basins where there is little or no reservoir storage and water is abundant early in the season, that alfalfa, wheat, and oats may be produced, since each of these crops requires large amounts of early season water. Also canning peas may be matured before a water shortage begins. Alfalfa will continue to grow throughout the late summer months, provided water is available. On the other hand, sugar beets, potatoes, and corn require less water early in the season, but during the end of the season, these crops require large amounts of water.[4]

A series of informal interviews with several irrigators in the Arkansas Valley of Colorado, conducted by the author, reveal the following general responses to forecasts of low water supply.

Generally, the snow surveys are used to some extent by the more efficient operators, as well as by some of the ditch companies in their management operations. Specifically, the following actions may be taken.

1) Operators may hedge against expected late season, low flow by planting maize or milo instead of corn, dry beans instead of sugar beets, or spring grains instead of sugar beets. Dry beans and spring grains are planted to take advantage of early season water and to avoid the potential economic losses that may occur if crops are planted which mature late in a low water year.

2) If a low water year is forecast or appears likely, those operators with wells may plant their cash crops in the fields closest to the wells.

3) If the snow report points to a bad water year, some farmers may decide to put their prorated number of acres in soil bank programs. The water that is thus freed is then used on the remaining acreage.

4) For farms on ditches with good water rights, cropping patterns do not change appreciably because of variability in river flow or because of forecasts of that flow.

5) In the operations of ditch companies with reservoir storage or with options on reservoir water, if a low snow pack is forecast, these ditch companies may contract for available reservoir water.

6) In general, if reservoirs are low and the forecast shows a low snowpack, the more efficient operators may plant crops less sensitive to water deficiencies.

7) Planting of alfalfa may serve as a primary hedge against uncertainties of water availability, particularly for farms under less secure water rights, since alfalfa can suffer water shortage and still produce a yield.

Finally, a series of articles in Soil Conservation Magazine describes the following sets of actions that may be taken in conjunction with forecasts relative to various basins. Work indicates that, in years when low flow is forecast, more extensive acreages of early season crops are planted to take advantage of early runoff. Likewise, the acreage of heavy water using late season crops is restricted.[5]

Irving and Nelson indicate that in the Twin Falls Soil Conservation District in Idaho, irrigators have responded to low flow forecasts by cutting acreages of irrigated crops so that the water that is available can be utilized to bring to maturity those crops that are planted.[6] Use of the forecasts results in reduction of losses in low water years from not preparing, pre-irrigating and seeding acreage. Water thus saved can then be diverted to the crops that are planted.

FOOTNOTES

[1] Israelsen and Hansen, Irrigation Principles and Practices, pp. 15-16.

[2] William Johnson, "Benefits of Forecasting Data of Low Snow to Water Users of the Carson River," p. 82.

[3] U.S., Department of Agriculture, Snow Surveys in Colorado, p. 32.

[4] Israelsen and Hansen, Ibid., p. 268.

[5] R. A. Work, "Snow Water," Soil Conservation, U. S. Department of Agriculture, Soil Conservation Service, April, 1963, pp. 212-213.

[6] R. N. Irving and Morlan W. Nelson, "Snow Surveys Made by and for the Water Users," Soil Conservation, U. S., Department of Agriculture, Soil Conservation Service, March, 1956, p. 182.

APPENDIX II

RESERVOIR AND WELL WATER DEVELOPMENT IN SELECTED WESTERN STATES

This appendix includes selected tables which provide a general representation of the water supply situation in various western states.

Table 25 from the Bureau of Reclamation 1968 Crop Reports presents estimates of irrigated acreage under various classes of water service in eleven western states. Acreage is classified as follows:

Full Irrigation Supply--generally an adequate water supply solely from project facilities.

Supplemental Water Service--generally an inadequate water supply from non-project sources. The supply of both project and non-project water generally constitutes an adequate supply.

Temporary Water Service--generally there is a wide fluctuation from year to year on these areas due to availability of water.

Comparison of estimated total irrigated acreage in the selected states with acreage under Bureau of Reclamation projects is presented in Table 26.

The information in Tables 25 and 26 indicate roughly the extent of physical control gained through Bureau of Reclamation projects. As shown in Table 25 gross value per irrigated acre varies widely among states, due to the diversity of environments and the differences in types of crops grown. It is interesting to note that in six of the eleven states in Table 25, average gross income in areas with supplemental service is greater than for areas with full service. Possibly, supplemental service provides the necessary timing of delivery in areas already developed but unable to realize the full productivity of the land because of maldistribution in timing of the supply. Figures from the 1959 Irrigation Maps on areas irrigated from surface and ground water sources are presented below in Table 27.

Estimations in volume in acre feet are presented in Table 28.

TABLE 25

IRRIGATED ACREAGE UNDER BUREAU OF RECLAMATION PROJECTS IN ELEVEN WESTERN STATES, 1968[a]

State	Full Service			Supplemental			Temporary			Total		
	Irrigable Area for Service	Irrigated Area	Gross Crop Value per Irr. Acre (in dollars)	Irrigable Area for Service	Irrigated Area	Gross Crop Value per Irr. Acre (in dollars)	Irrigable Area for Service	Irrigated Area	Gross Crop Value per Irr. Acre (in dollars)	Irrigable Area for Service	Irrigated Area	Gross Crop Value per Irr. Acre (in dollars)
Arizona	406,571	276,750	378.70	95,854	—	300.81	—	—	—	502,425	—	361.92
Calif.	775,258	637,816	409.99	1,985,165	1,488,554	409.89	66,239	63,181	346.20	2,826,662	2,189,551	408.08
Colorado	109,928	92,282	144.44	866,466	845,380	129.41	—	—	—	976,394	937,662	130.89
Idaho	493,626	439,758	129.31	1,129,948	1,070,470	131.00	371	371	112.70	1,623,945	1,510,599	130.50
Montana	362,620	309,889	63.66	28,004	27,090	40.51	—	—	—	390,624	336,979	61.80
Nevada	73,002	61,697	70.04	68,598	48,684	85.63	—	—	—	141,600	110,381	76.91
New Mex.	267,957	204,013	204.53	—	—	—	625	415	66.69	268,582	204,428	201.25
Oregon	362,235	323,971	129.54	133,263	118,068	132.84	1,022	328	68.63	496,520	442,367	130.37
Utah	17,270	15,258	102.19	389,528	318,221	92.52	—	—	—	406,798	333,479	92.96
Wash.	813,738	714,947	233.25	181,811	152,078	282.37	160	138	214.21	995,729	867,163	241.86
Wyoming	245,448	299,136	88.57	110,728	96,338	109.76	—	—	—	356,176	325,474	94.84
Total	3,927,653	3,375,517	—	4,989,385	4,240,868	—	68,417	64,433	—	8,985,455	7,610,820	—

[a] Source: U. S., Department of Interior, Bureau of Reclamation, Division of Water and Land Operations, Federal Reclamation Projects, 1968 Crop Report and Related Data, Table 1.

TABLE 26

TOTAL ACREAGE IRRIGATED AND ACREAGE UNDER FEDERAL RECLAMATION PROJECTS, 1964[a]

State	Total Acreage Irrigated (1,000)	Federal Total (1,000)	Reclamation Percent
Arizona	1,125	349	31
California	7,599	1,731	23
Colorado	2,690	925	34
Idaho	2,802	1,512	54
Montana	1,893	274	15
Nevada	824	109	13
New Mexico	813	202	25
Oregon	1,608	432	27
Utah	1,092	301	28
Washington	1,150	786	68
Wyoming	1,571	274	17
Total	23,167	6,895	30

[a] Source: U. S., Department of Interior, Bureau of Reclamation, Federal Reclamation Projects, Crop Reports.

TABLE 27

ESTIMATED ACREAGES SERVED BY SURFACE AND GROUND WATER IN ELEVEN WESTERN STATES IN 1959[a]

State	Acres by Surface Water	Acres by Ground Water	Total	Percentage by Ground Water
Arizona	380,000	772,000	1,152,000	67
California	3,403,000	3,993,000	7,396,000	54
Colorado	2,185,000	500,000	2,685,000	19
Idaho	2,124,000	453,000	2,577,000	18
Montana	1,841,000	34,000	1,875,000	2
Nevada	440,000	103,000	543,000	19
New Mexico	286,000	446,000	732,000	61
Oregon	1,185,000	199,000	1,384,000	14
Utah	904,000	158,000	1,062,000	15
Washington	873,000	134,000	1,007,000	13
Wyoming	1,436,000	34,000	1,470,000	2
Total	15,057,000	6,826,000	21,883,000	31

[a] Source: U. S., Department of Commerce, Bureau of the Census, 1959 Irrigated Land Maps.

TABLE 28

ESTIMATED VOLUMES OF WATER IN MILLION ACRE FEET USED BY IRRIGATION IN ELEVEN WESTERN STATES IN 1960[a]

State	Total Surface and Ground Diversions	Conveyance Loss	Surface Applied	Total Consumed	Ground Water Withdrawals
Arizona	(Total water use 7 MAF, approximately two thirds from wells)				
California	21.7	-	-	-	-
Colorado	-	-	-	-	2.13
Idaho	12.2	5	9.6	4.5-5.5	2.6
Montana	7.6	1.9	5.7	2.4	.038
Nevada	2	.425	1.2	1.1	.400
New Mexico	2.8	.640	1	1.5	1
Oregon	-	1.7	5.1	-	.270
Utah	-	.840	3.4	-	.390
Washington	-	1.1	3.7	-	.470
Wyoming	5.064	1.5	3.5	2.5	.064

[a] Source: U. S., Department of Interior, Geological Survey, The Role of Ground Water in the National Water Situation, by C. L. McGuinness, Geological Survey Water Supply Paper 1800.

APPENDIX III

DATA AND STRUCTURE FOR TESTING THE LINEAR PROGRAMMING MODEL

This appendix presents the basic data and structure to be used in testing the linear programming model. Items covered include: (1) justification for the total acreage constraint; (2) specification of crops to be included in the model; (3) specification of upper and lower bounds for each crop and justification of the ranges used; (4) crop water requirements; (5) water costs; (6) water-crop yield estimates; (7) estimates of yields, prices, and variable and fixed costs; (8) specifications of the water supply characteristics for the hypothetical ditch company; and (9) determination of the hypothetical conditional probability distributions and specification of a range of improvements, represented by a decrease in the error dispersion for each forecast distribution.

The above information is combined to establish the specific structure for the program. While the purpose of this study is to explore a generalized methodology, data used in testing the model are drawn primarily from studies and statistics covering Colorado irrigated agriculture, in particular the Arkansas and South Platte Basins and Western Slope area. Variable cost estimates are derived primarily from a study of the Columbia Basin by McKains, Franklin, and Jensen.[1] Estimates of typical per acre yields under varying quantities of water, prices, and general background are based on a study by L. M. Hartman and Norman Whittelsey.[2]

Total Acreage Constraint

Table 29 below gives the minimum, maximum, and average acreages for ditch companies in three Colorado basins.[3]

TABLE 29

MINIMUM, MAXIMUM, AND AVERAGE ACREAGES UNDER DITCH COMPANIES IN THREE COLORADO BASINS

Basin	Arkansas	Rio Grande	South Platte
Acreage Minimum	4,321	6,280	6,500
Acreage Maximum	92,000	115,685	60,000
Acreage Average	25,721	23,859	19,242
Number of Companies	11	12	38

The weighted average for the three basins is 21,319 acres, and this figure, rounded to the nearest thousand, is used as the acreage under the hypothetical ditch company. It will be assumed that the 21,000 acres represents the maximum irrigable area that can be serviced by the ditch company.

Crops

Crops included in the program are those typically grown under irrigation in the Arkansas and South Platte Basins and Western Slope area of Colorado. Among these are alfalfa, barley, beans, corn grain, corn silage, onions, potatoes, sorghum, sorghum, sugar beets, and wheat.[4] For all of these crops except alfalfa and wheat, Colorado ranked in the top ten producing states in 1967. The list of crops precludes several that are also grown, but for purposes of the analysis, only the more important crops will be considered. In terms of the model, the crops to be selected will be chosen from those above, based on the availability of data from previous published studies of irrigated agriculture in Colorado and other areas, primarily the Columbia Basin in Washington.

Upper and Lower Bounds

Determination of upper and lower bounds to be placed on the acreage of each crop in the program is necessarily a somewhat arbitrary exercise. The importance of these constraints, however, cannot be de-emphasized by the lack of precise information on which to base them. As Day points out:

> The lower the elasticity of demand for a given crop (ceteris paribus) or, alternatively, the greater the crop's yield variability due to weather (ceteris paribus), the more cautious we should expect to find farmers in changing output patterns.
>
> These hypotheses suggest that the flexibility constraints are structurally meaningful and are not more artificial rigging. They provide a simple and highly plausible means of describing the effects of uncertainty on farmers' plans to change existing cropping patterns.[5]

Two sources are employed here for specifying the flexibility range of the crops in the model. One is the observed percentage variation of acres planted to various crops in counties in the Arkansas, South Platte, and West Slope areas of Colorado from 1959 to 1968. The other is based on assumptions used by Hartman and Whittelsey in their investigation.[6]

The observed variations are derived from the Colorado Agricultural Statistics. Since the data available are for total acres planted, both irrigated and non-irrigated, they do not precisely reflect the variation of irrigated acres planted. In most cases, however, the majority of the crops are cultivated under irrigation. A second problem arises due to both the effects of longer term structural changes, which are reflected over time in the composition of crops planted in a given area, and to the effect of government farm programs on various crop acreages planted.

Crop composition varies from area to area, as seen by the data in Table 30. To arrive at some reasonably consistent means of specifying upper and lower bounds, however, the average variability is calculated and presented in Table 31.

TABLE 30

PERCENTAGE RANGE OF VARIATION FOR COLORADO CROP ACREAGES

Crop	Arkansas Valley	Weld Co.	Larimer Co.	Montrose Co.	Delta Co.
Winter Wheat	12.5-22.1	27.2-37.1	16.1-33.8	1.8- 2.5	.2- 2.5
Corn	8.3-12.5	13.5-21.7	16.3-19.4	10.0-15.3	13.3-19.4
Barley	1.2- 4.7	6.8-15.7	9.9-17.9	11.9-21.0	11.1-15.3
Sorghum for Grain	20.4-32.0	6.3-13.7	--	.2- 1.0	--
Dry Beans	6.3-13.7	3.6- 7.6	2.4- 3.6	10.5-15.9	4.5- 7.2
Sugar Beets	1.6- 5.4	7.9-13.2	5.5- 9.3	2.1- 7.2	1.7- 5.7
Oats	.9- 3.4	2.5- 5.0	2.1- 5.8	7.2-13.2	6.7-10.1
Alfalfa	24.0-29.0	16.3-17.5	24.1-33.9	37.7-49.0	50.5-57.5
Potatoes	--	1.2- 2.1	--	.4- 1.3	--

[a] Source: Various issues of Colorado Agricultural Statistics

[b] Includes Bent, Crowley, Otero, and Pueblo Counties

TABLE 31

AVERAGE PERCENTAGE VARIABILITY IN ACREAGES OF TYPICAL COLORADO CROPS[a]

Crop	Minimum	Maximum
Winter Wheat	11.6	19.6
Corn	12.3	17.7
Sorghum	9.0	15.6
Dry Beans	5.5	9.6
Sugar Beets	3.8	8.2
Oats	3.9	7.5
Alfalfa	30.5	36.6
Potatoes	.8	1.7
Onions	--	--

[a] Source: Colorado Agricultural Statistics

Hartman and Whittlesey place quotas on various crops included in their model. For example, at the time (1959), sugar beets and wheat were under acreage control programs by the government. Based on a farm of 160 acres, they assumed that government planting allotments would limit wheat to 15 acres and sugar beets to 10 acres. They also assumed that risk of planting crops such as potatoes, onions, and beans would limit these crops to 10, 8, and 40 acres, respectively.[7] At another point, they state that small grains and alfalfa are widely grown in the irrigated valleys due to the advantages of crop rotation schemes.[8] In analyzing the value of late season water, they assume that alfalfa is kept at a minimum of 22 acres "for rotational purposes and that some acreage of barley is desirable for better utilization of labor throughout the season and also for rotation purposes, that is, for new seeding of alfalfa and so on."[9] Table 32 below gives their acreages estimates as a per cent of total land in the farm (160 acres).

TABLE 32

PERCENTAGE OF 160 ACRE IRRIGATED FARM THAT CAN BE ALLOCATED TO VARIOUS CROPS

Acres	Crop	Per Cent
(max.) 15	wheat	9.4
(max.) 10	sugar beets	6.3
(max.) 10	potatoes	6.3
(max.) 8	onions	5
(max.) 40	beans	25
(min.) 22	alfalfa	13.8

Planting various irrigated crops involves risk as to prices, pests, disease, and the effects of weather on yields, as well as the risk involved in receiving adequate water supplies. The upper and lower bounds will be assumed to reflect compensations for the latter forms of risk (prices, etc.) and, therefore, a liberal range of variation will be employed. This procedure is used, since the risk inherent in water supply is reflected in the L. P. model by the weighting scheme derived from the conditional probabilities. The ranges involved, however, are established by rounding and liberalizing the averages from Table 31. In some cases, the figures will be modified by the assumptions Hartmand and Whittelsey employ. The assumed upper and lower bounds are presented in Table 33.

The figures listed in Table 33 are necessarily somewhat arbitrary; however, the sensitivity of the model could be tested for changes in the various assumptions as to upper and lower bounds.

Crop Water Requirements

The amount of delivered water necessary to mature a given irrigated crop depends on four factors. These are the crop's consumptive use (measured on a per acre basis), the efficiency with which water is de-

TABLE 33

ASSUMED UPPER AND LOWER BOUNDS FOR CROPS TO BE USED IN THE PROGRAM

Crops	Minimum	Maximum
Alfalfa[i]	14 %[a]	37 %[b]
Barley	8 %[c]	15 %[c]
Beans	5 %[c]	20 %[d,f]
Corn	10 %[d]	25 %[d]
Onions	0 %[e]	8 %[a]
Potatoes	0 %[g]	10 %[a]
Sugar Beets	0 %[g]	15 %[d,h]
Winter Wheat[i]	10 %[d]	20 %[d]

[a] Assumption from Table 32.

[b] Average maximum Table 31.

[c] Averages--Table 31.

[d] Liberalized figure from Table 31.

[e] A zero minimum is assumed, due to the nature of heavy water requirements.

[f] Reduced maximum from Table 32.

[g] Zero possibility included, due to the heavy water requirements, long growing season, and large cost involved.

[h] Liberalized figure from Table 32.

[i] Inclusion of both of these crops in a model, which assumes crop planting to occur at approximately the same time, is problematic. Winter wheat is planted in the fall, so that its acreage is already determined at the time of spring planting. Alfalfa can be planted in the fall or spring, but is grown over more than one season, or can be. It would be possible to include these crops in the model as fixed acreages, drop them entirely, or include one or both on the same basis as the other crops, but sacrifice some realism in the model. In the case of winter wheat, this acreage will not be included in the final combination of crops to be used. Alfalfa, on the other hand, will be included, due to its importance in rotation schemes as well as the fact that it is often planted in the spring, with yields being attained over the first season. Anderson, in discussing a simulation program for establishing optimum crop patterns on irrigated farms based on preseason estimates of water, uses alfalfa as one of the crops subject to the decision process.[10] Likewise, rotation plans involving only one season of alfalfa are discussed in Heady and Jensen.[11]

livered to the crop, and the effective precipitation which occurs during the growing season. Consumptive use is defined as the quantity of water transpired during plant growth plus the quantity of water evaporated from the plant leaves and from the surrounding soil. Irrigation efficiency is the quantity of water actually made available to meet plant consumptive use from the amount that is diverted. Effective precipitation is the depth of water provided from summer rainfall which is capable of satisfying a part of the consumptive use. The theoretical quantity of water per acre to be delivered for irrigation of a given crop would then be the consumptive use divided by the irrigation efficiency minus effective precipitation.

There are several procedures for estimating crop consumptive use, either by techniques of direct measurement or by climatic observations as an index to consumptive use. Israelson and Hansen provide a comprehensive presentation of the details of these various techniques in Irrigation Principles and Practices.[13]
Sutter and Correy summarize the techniques as follows:

> Consumptive use can be estimated by using water balance, Micrometeorological, evaporimeter, and empirical methods. Water balance methods involve basin hydrology, soil moisture studies, and lysimeters; micrometeorological methods involve the measurement of water vapor concentrations at and above the ground surface; evaporimeter methods relate consumptive use to the amount of evaporation from a free water surface.[14]

They indicate that empirical formulas used to estimate consumptive use usually include only climatic and plant variables. For example:

> The climatic factors most often used are temperature, humidity, and solar radiation. Plant factors usually represent the crop type and, less frequently, the stage of crop growth. Climatic and crop factors can be chosen to represent varying periods of water consumption. Some methods can be used only for an entire growing season and others give inaccurate results for periods of less than one month. As the length of the period over which consumptive use is to be estimated decreases, the accuracy of the measurement of the climatic factor or factors becomes more important and, also, more difficult to obtain. At present, there is no universally accepted empirical method for estimating consumptive use.[15]

Israelsen and Hansen indicate that several researchers have studied the effect of temperature, humidity, wind velocity, vapor pressure, and solar radiation on plant consumptive use. For example, "Penman, in England, has made the most complete analysis using several climatic variables, whereas temperature has been used as the principal variable to obtain an index to consumptive use by Thornwaite in the humid eastern United States, by Lowry and Johnson, and by Blaney and Criddle in the arid western United States."[16]

The Blaney and Criddle method is widely recognized throughout the West for its accuracy and the revised Blaney-Criddle method is likewise known for its modest data requirements relative to information output.[17] Estimates of water requirements will be drawn from studies using the Blaney-Criddle and revised Blaney Criddle methods. Estimated consumptive use figures from five different studies for selected crops are presented in Table 34.

To arrive at the per acre water requirement, it is necessary to divide the consumptive use figure by the approximate irrigation efficiency. Efficiencies will vary depending on soil type, means of conveyance, means of water application, and the crop type. As Miles points out, efficiencies are generally higher on alfalfa, corn, and grain sorghum than on small grain, vegetables, and sugar beets. With reference to the Arkansas Valley, field irrigation efficiencies "may range from 20 to 90 per cent, but will average higher than in most areas of Colorado."[18] For purposes of this study, a 50 per cent irrigation efficiency, from the point of division to the soil root zone, will be assumed for surface and reservoir water. This figure is used in other studies of irrigation systems.[19,20] Israelsen and Hansen state:

> ...in normal irrigation practice, surface irrigation efficiencies of application are in the range of 60 per cent, whereas well-designed sprinkler irrigation systems are generally considered to be approximately 75 per cent efficient.[21]

Application of pumped ground water through surface distribution facilities may also exhibit a higher efficiency, since the distance transported is generally less than for surface or reservoir water and better distribution facilities may be used. For example, in the Arkansas Valley, irrigation efficiency for well water has been estimated at about 80 per cent by the U. S. Geological Survey.[22] While the model can be tested for its sensitivity to variations in well water application efficiency, the more

TABLE 34

CONSUMPTIVE USE ESTIMATES (INCHES) FROM FIVE STUDIES FOR SELECTED CROPS GROWN UNDER IRRIGATION ON THE HIGH PLAINS AND INTER-MOUNTAIN WEST

	Sutter and Corey[a]	Israelsen and Hansen[b] (growing season) in days		Hartman and Whittelsey[c]	Anderson and Maass[d]	Water Budget of Northern High Plains[e]
		180-210	150-180			
Alfalfa	23.8	36.0	30.0	28.0	27.5	34.1
Barley	16.9	16.0	16.0	16.0	11.5	--
Beans	17.9	14.0	14.0	25.0	15.5	13.8
Corn Silage	17.7	--	--	20.0	--	22.2
Corn Grain	21.7	26.0	24.0	20.0	19.5	21.3
Onions	--	--	--	32.0	--	--
Potatoes	21.2	21.0	20.0	26.0	21.5	--
Sugar Beets	24.3	30.0	26.0	32	23.5	27.1
Wheat-spring	16.9	16.0	16.0	16.0	11.5	--
Wheat-winter	23.8	--	--	--	--	16.5
Sorghum grain	--	16.0	14.0	--	20.5	16.9

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[a] Agricultural Experiment Station, University of Idaho, College of Agriculture, Consumptive Irrigation Requirements for Crops in Idaho, by R. S. Sutter and G. L. Corey.

[b] Israelsen and Hansen, Irrigation Principles and Practices, Table 11.15, p. 263, entitled "Total Consumptive Use and Peak Daily Use, Western United States, Inter-mountain, Desert, and Western High Plains (after Woodward)

[c] Colorado State University Experiment Station, A Linear Programming Analysis of Farm Adjustments to Changes in Water Supply, by L. M. Hartman and Norman Whittelsey, Table v., p. 28.

[d] Anderson and Maass, A Simulation of Irrigation Systems.

[e] Colorado State University Experiment Station, "Monthly Consumptive Use by Irrigated Crops in the Western United States, by H. F. Blaney, H. R. Haise, and M. E. Jensen.

conservative figure of 70 per cent will be used.

Representation of the effect of warm weather precipitation on crop water requirements is included in the model by the following assumption. It is assumed that water supplied through warm weather precipitation contributes to streamflow and is thus delivered to the crops in the form of surface water. Although this is unrealistic from the point of view of calculation of crop irrigation water requirements, it does allow for summer precipitation to be included in the various states of nature. Since the upper bounds on increase in accuracy of the forecast is set by the unpredictable nature of longer range weather and its effect on both streamflow and crop water requirements, to keep focus on the problem under examination in the model, it is assumed that, rather than reducing crop water requirements, summer precipitation adds to available water supply. Since warm season weather is one of the factors contributing to the stochastic nature of runoff from mountain watersheds, this assumption is fairly plausible. Sutter and Corey, in estimating consumptive irrigation requirements (consumptive use minus effective precipitation), use historical frequency distributions of occurrence of summer precipitation at designated weather stations to estimate a range of crop consumptive irrigation requirements. Thus for a given crop at a given location, consumption irrigation will not exceed y inches x% of the time.[23] Elaboration of the linear programming model to include this additional information is beyond the scope of this work but would be a possibility for future research.

The per acre water requirements used will be those based on the Hartman-Whittelsey study, since their yield data is also employed. These figures are presented in Table 36.

Water Costs

As discussed in Chapter IX, water costs will be considered a part of fixed costs for surface supplies and a part of variable costs for reservoir and well water. Since the purpose of this work is to present a methodology for evaluating increased accuracy of forecasts, no exhaustive study of water costs will be attempted. Cost figures used will fall within the ranges estimated from other studies.

Looking first at well-water costs, estimates relating to the South Platte Basin (Colorado) indicate that costs vary from about $1.00 to $10.00 per acre foot. Variation in cost depends upon pump lift, pump efficiency, type of fuel used, and volume pumped each year. The average is estimated at about $3.50 to $4.00 per acre foot pumped.[24] Estimates from other parts of the country include $8.00 to $10.00 per acre foot in Kern County, California.[25] Hirschleifer et al. estimate a cost ranging between $4.00 and $30.00 per acre foot for western irrigation wells,[26] depending on variations in capital and operating costs. Studies of the San Joaquin area in California show typical per acre foot pumping costs ranging from $3.95 per acre foot to $9.11 per acre foot, with an average cost of $6.39.[27] For purposes of the cost figures to be added to per acre variable production costs, the figure of $6.00 per acre foot will be used. This figure falls within the range of all of the various cost estimates, though it does not correspond to the average for the South Platte Basin. It is chosen based on the fact that it is the minimum cost at which the value of the marginal product of well water falls below the marginal value of surface water for the lower value crops.

As in the case of well water, per acre foot costs of reservoir vary widely throughout the west, depending on reservoir size and other features. For example, in the South Platte Basin, assessments to irrigators for water delivered from reservoir storage (privately owned) average $2.05 per acre foot and vary from 21 cents to $6.49 per acre foot delivered annually.[28] Hirschleifer et al. indicate that average per acre foot cost of storage capacity has varied from about $5.00 for very large reservoirs to $20.00 for smaller reservoirs.[29] In another study of the Utah area, average annual unit costs of reservoir storage capacity were estimated to range from $1.07 per acre foot to $8.05 per acre foot with the larger values for smaller reservoirs.[30] Though a wide range of costs could be used, the estimated average for the South Platte Basin of $2.05 per acre foot will be used to represent unit cost of reservoir water. As with well water costs, this, too, could be varied to test the sensitivity of the results.

Surface water costs are part of the fixed costs facing the individual irrigator, since he is generally assessed his portion of the ditch company's costs, and not charged on the basis of the quantity of water which he actually receives. It is of interest to note that according to Anderson, assessment charges in the South Platte Basin, to companies supplying up to 1 foot per acre, serve over 15,000 acres at an average cost of $1.14 per acre foot. Companies delivering over 3 feet per acre have service areas of around 2,500 acres and charge an average of 34 cents per acre foot.[31] Inclusion of water costs will be discussed further under the heading, "Variable Costs, Yields, and Revenues."

Water-Crop Yield Response

The production function relating a crop's marketable yield to the timing and quantities of water application is necessarily highly complex. Although there is considerable general understanding of the relationships involved and a great deal of work has been accomplished on estimating the relationships, specific information is not widely available. In the extreme, if soil moisture content is inadequate (or conversely soil moisture stress is high) to meet the minimum daily plant evapotranspiration requirements for a long enough period, permanent wilting takes place and crop loss results. On the other hand, excessive application of water may result in a negative marginal product for water, thus depressing average per acre yields.

The ultimate ability to attain optimum crop yields depends on the ability to measure soil moisture content, knowledge of the relation between timing of water application and yields, and the extent to which irrigators can control timing of their water supply. In this context, Young and Martin propose a model describing the yield response function of water in irrigation.[32] In the course of their review of the literature and based on evidence gathered in an experiment with Arizona crops, they list the following properties of the yield response function.[33]

a) The rate of change of yield is not always maximized when soil moisture stress is at low levels (when soil moisture content is high).

b) The various characteristics of plant growth, such as fresh weight, dry weight, height, leaf area, fruit weight, chemical constituents and others will not always respond identically to changes in soil moisture stress. It is the yield of marketable product that is of interest for purposes of determining optimum allocation of irrigation water.

c) Observations indicate that for some crops the effect of moisture stress on yield varies as to the stage of growth of the plant. For specific plants, the response to moisture will eventually become low as the crop matures.

d) Likewise, observations suggest that the effects of moisture stress during certain stages of growth may carry over the later periods, even though water may be abundant enough to otherwise not inhibit growth.

The authors postulate a relationship between the quantity of water applied at the ith irrigation and the corresponding contribution to output. While the nature of this relationship would suggest that the most profitable application would be less than the quantity of water that maximized the value of the yield, if the two points are close, the assumption of returning the root zone to field capacity is the practical approach for most situations.[34]

Application of their model to data gathered by Erie for four seasons on grain sorghum produced interesting results in support of their hypothesis regarding stage of growth and soil moisture tension.[35]

Anderson and Maass cite a number of studies of crop yields under soil moisture stress. The authors state: "These studies show generally the reduction in potential yield of a crop from varying degrees of soil moisture stress at different stages of the growth cycle."[36] They go on to state:

> Since potential growth and potential yield are directly associated, it follows that harvestable yield will be reduced as a result of moisture stress. The amount of reduction in growth and yield will depend on the duration and severity of the stress period and the time of occurrence during the growth cycle. If the stress period occurs when plant growth would normally be most rapid and water demands high, or when reproductive processes are critical, the reduction will be greater than during periods of similar length, when growth and development are slow--such as near maturity.[37]

Since the objective of this study is to evaluate forecasts of volume, the relationship between timing of water application and crop yield will not be dealt with directly. As discussed on page 160, forecasts pertaining to specific ditch companies could be in the form of "effective water," or volume which may exclude peak amounts early in the season, whose marginal value product, without storage facilities, is zero or negative. Thus, specified reductions in per acre water application (in terms of volume) will be related to specified reductions in yield, on the assumption that where reduction in yield occurs, one or more irrigation periods for the given crop have been missed. To represent this, the activity for crop failure in the objective function of the model will involve only a fraction of the water per acre necessary to mature the crop.

Yields, Prices, and Costs

Yields and Product Prices

Crop yields in a given region will vary due to soil fertility, water availability, and the intensity of management (field preparation, fertilizer application, weed and pest control, and water application techniques). This analysis will focus only on yield variations attributed to variation in the quantity of water application, though the objective function of the model could conceivably be modified to represent different soil fertilities or management levels. Average yield estimates by Hartman and Whittelsey for three levels of water application for typical Colorado growing areas (1959) are reproduced below.[38]

The estimated average yields under normal water supply conditions are based on the Census of Agriculture (1955) and a 1959 survey of the Bureau of Reclamation Uncompahgre Project in Western Colorado. The yields are number 1 to 3, where 1 is average yield with normal water application, and 2 and 3 represent approximately 20 per cent reductions in water use levels. The yield reduction estimates were made from various publications pertaining to estimates of water-crop yield response for specific crops.[39]

TABLE 35

PRICES AND PER ACRE YIELDS WITH VARYING PER ACRE WATER APPLICATION FOR SELECTED COLORADO CROPS

Crop	Yield per acre 1	2	3	Price
Wheat (bu.)	39	34	29	$ 1.88
Alfalfa (ton)	3.4	2.6	1.6	21.71
Clover, hay (ton)	.9	.8	.8	21.71
Clover, seed (cwt.)	2.7	2.2	1.5	27.00
Corn, grain (bu.)	63	53	36	1.32
Corn silage (ton)	12.6	11.3	8.2	7.85
Beans (cwt.)	14.8	12.6	9.8	5.92
Sugar beets (ton)	14	12	9	13.91
Sugar beets, tops (ton)	7	6	4	3.00
Potatoes (cwt.)	171	152	119	1.65
Barley (bu.)	51	44	34	.96
Onions (cwt.)	298	248	200	2.25

Prices are based on the 1954-1958 average of prices Colorado farmers received for their crops, as computed by Hartman and Whittelsey from various issues of the Colorado Agricultural Statistics. These average prices are presented in Table 35, along with the estimates of crop yield.

Costs

Because of the problem under consideration, only variable costs of production will be used to calculate net per acre revenue for each crop. Since fixed costs, such as interest payments on land, machinery, buildings or structures, water costs, most forms of insurance, and property taxes are incurred whether the irrigator plants or not, it is the maximization of expected returns on variable costs of production that will determine the annual crop pattern, within the constraints of available machinery, previous investments in facilities, and other factors. These latter would include labor supply, marketing and distribution facilities, and government farm programs. Since no adequate set of data was found which relates precisely to one geographic area and point of time, it is necessary to draw cost data from several sources. Because there are broad ranges in management abilities among individual farmers, variation in their individual income objectives, and variations in soils and climate among regions, and variation in the other factors that affect production costs, this approach is less than ideal. Without an extensive empirical study of a specific region, however, this method offers the only practical means of estimating typical production costs.

Variable Costs

Variable production costs for each crop are divided into three categories representing the planting costs, tending or cultivating costs, and harvest costs. Negative returns are assigned to the payoff coefficients for planting equal to the planting costs, whereas the net payoff for each of the various crop activities will be equal to the total per acre revenue minus tending plus harvesting costs. The activity for failure for each crop is set equal to the tending costs.

Depending on the crop, planting costs will generally consist of those of plowing, harrowing and disking, floating, ditching, seeding, and fertilizer applied at the time of planting.

Tending costs will generally include cultivating, weeding and hoeing, and spraying, depending on the crop.

Harvest costs will depend on the crop, its yield, and whether the irrigator harvests himself or pays for a custom harvest.

Cost estimates for selected crops are presented in Table 36 on the following pages. These figures are based primarily on a study of production costs by McKains, Franklin, and Jensen in the Columbia River Basin of Washington.[40] These cost estimates are supplemented by information from other sources.[41] and are adjusted to 1959 price levels in order to be consistent with the Hartman-Whittelsey information on yields and prices received. In using the McKains data, a number of assumptions were made. These are listed below.

1) McKains et al. indicate that most of the labor time for each crop would be performed by the operator, on the assumption of family size farms. That assumption is also made for this study.

The only exception pertains to weeding and hoeing the various crops and to cutting and treating seed. Thus no imputation for the costs of operator supplied labor are included; likewise, all fixed costs are excluded, including charges for surface water.

2) Average managerial intensity is assumed in that there is no variation in planting costs (seed bed preparation, fertilizer application, and the amount of seed). Inclusion of different planting costs for each crop poses no significant change in the programming format but does pose data requirements beyond the scope of this work. Therefore, no attempt has been made to include other than average management. Thus, variation in net revenue is due to the reduced yield corresponding to reduced per acre water application, added costs of reservoir and well water, and the reductions in harvesting and tending costs due to decreased yield (where such approximations can be made from the data). Price expectations are assumed to be based on an average of prices prior to 1959.
3) Certain components of basic production costs (wages, seed, fertilizer, and motor supplies) have been adjusted by the price indexes contained in The Farm Cost Situation.[42] The figures for inflating (or deflating) the various components of production cost are: fertilizer, .97; seed, .87; motor supplies, 1.06; and wage rates, 1.18. Costs are adjusted from the 1955 to the 1959 to the 1959 levels.
4) In formulating the reduction in specific cost components corresponding to reduced yields, the following procedure was employed. Other than adjustments for the price level, the only change in costs between the data from the McKains study and the costs associated with the maximum yields from the Hartman-Whittelsey work will be those where per unit costs based on yield are specified.

Arbitrary reductions were made in tending costs in some categories on the assumption that receipt of a lower quantity of water during the course of the growing season than had been anticipated would result in shifting of labor to more intensive management of crops that were to be watered at their full per acre requirements. Reduction in costs in this category was in proportion to the reductions in yield associated with reduced per acre water application.

All computations except adjustment by the appropriate indeces are included in the following pages of Table 36. The format for production costs follows that of McKains et al. Costs are for type I-W land, defined as land with comparatively few limitations for agricultural use, with smooth slopes of less than 5 per cent. The itemized costs associated with the yield level used in the McKains study are shown in the first column for each crop. Costs associated with the yield levels used in the Hartman-Whittelsey study are presented in the last three columns. All calculations are on a "per acre" basis.

TABLE 36

VARIABLE COSTS OF PRODUCTION AND NET REVENUE FOR SELECTED COLORADO IRRIGATED CROPS UNDER VARYING LEVELS OF WATER APPLICATION AND SOURCES OF WATER SUPPLY

(in dollars per acre)

Crop: ALFALFA HAY (in tons per acre)

	Yield Levels			
	McKains Study	Hartman-Whittelsey Study 1	2	3
	5.5	3.4	2.6	1.6
Cash costs, Materials, etc. [a]				
(Irrigation water)	(7.21)	--	--	--
Irrigation Dist. Charges	(1.05)	--	--	--
Fertilizer 100 # 44% P_2O_6	4.00	3.88	3.88	3.88 [f]
Seed 70¢ @ 10 # [b]	1.75	1.52	1.52	1.52 [f]
Inoculants	.05	.05	.05	.05
Gas & Oil-Farm Mach. @ 50¢ an hr. 4.3 hrs.	2.15	2.28	1.90	1.44 [g]
Gas & Oil--Auto-truck [c]	1.00	1.06	1.06	1.06 [f]
Baling @ $4.50 a ton	24.75	15.30	11.70	7.20
Repairs to Machinery @ 60 ¢ an hr. 10.9 hrs.	6.55	6.94	5.77	4.36 [b]
Small tools [d]	.50	.50	.50	.50
Insurance and Licenses	(1.40)	--	--	--
Total cash cost/acre	50.41	31.53	26.38	20.01 [i]
			Percent of yield one	
			76	47

Labor					
Spring Work (hours)					
Weed burning & clean ditches	.5 hrs				
Plowing [c]	--				
Harrowing	--				
Corrugating	.4				
Applying Fertilizer	.4	1.3 hrs.			
Planting	--				
Floating	--				
Renovating	.5				
Summer Work (hours)					
Irrigating	6.5		1.59	1.21	.75

(1) gas & oil: car & truck
planting
$\frac{1.3}{4.3} \times 1.06 = .32$
Harvest = (total expenses - .32
.74

(2) gas & oil: Farm Mach.
planting
(total expense $\times \frac{1.3}{4.3} = .69$
harvest (total expense-.69)
X% reduction in yield

Alfalfa Hay

Item		McKains Study	Hartman-Whittelsey Study		
			1	2	3
Harvest (hours			(3) Repairs to Machinery planting $\frac{1.3}{4.3}$×total expense =20 harvest (total expenses-2.08×% reduc in yield)		
Mowing	1.5	3.0hrs			
Raking	1.5				
Hauling & stacking	5.5				
Overhead labor	2.0				
Total hrs labor	18.8				
Value of labor $1.00/hr		18.80	4.86	3.69	2.28
Total cash cost/acre		50.41			
Total		69.21			
Surface water requirements (acre ft)			4.7	3.3	2.3
(50 % efficiency)					
Planting costs			8.54	8.54	8.54
Tending costs			.50	.50	.50
Harvesting costs			22.49	17.34	10.97
Total			31.53	26.38	20.01
Net revenue/acre		9.04			
Reservoir water requirements (acre ft)			4.7	3.3	2.3
(50% efficiency)					
Planting costs			same	same	same
Tending and Harvesting costs			32.63	24.61	16.19
Total			41.17	33.5	24.73
Net revenue/acre			32.64	23.30	10.01
Well water requirements (acre ft.)			3.3	2.4	1.7
(70% efficiency)					
Planting costs			same	same	same
Tending and harvesting costs			42.79	32.24	21.67
Total			51.33	40.78	30.21
Net revenue/acre			22.48	15.67	4.53
Gross revenue ($21.71/ton)			73.81	56.45	34.74
Total reservoir water costs ($2.05/ac ft)			9.64	6.77	4.72
Total well water costs ($6.00/ac ft)			19.80	14.40	10.20

Alfalfa

a) Taxes, interest and depreciation are not included.

b) Seed cost in year seeded is $1.00, inoculation 10¢ cost shown here is average over 4 years life of stand.

c) Car 70¢ , truck 30¢ --Hauling to stack.

d) Includes shovels, siphon tubes, wrenches, hoes, canvas dams, etc.

e) Usually seeded with a nurse crop such as grain or peas. If seeded alone, 4.0 hrs. would be required for seed bed preparation and drilling.

f) Significant price variations for labor, seed, fertilizer, and motor supplies have been made using indexes from the farm cost situation. Motor supplies: 1.06; Fertilizer: .97; Seed: .86; wage rates 1.18.

g) h) Calculated by adjusting the original cost by the proper index, subtracting planting costs, reducing the remainder in proportion to the reduction in yield and then summing estimated planting and harvesting costs.

i) Excludes surface water costs, Irrigation District charges, and license and fees.

Crop: DRY BEANS (in cwt per acre)

Item	McKains Study	Hartman-Whittelsey Study 1	2	3
Cash Costs: Materials, etc.	28	14.8	12.6	9.8
Irrigation Water	(7.21)	--	--	--
Irrigation Dist. Charges	(1.05)	--	--	--
Fertilizer[b] 125# NH_3	12.38	12.00	12.00	12.00
Seed 80 #	9.60	8.35	8.35	8.35[f]
Inoculants 1#	.50	.50	.50	.50
Gas & Oil-Farm Machinery @ 50¢ an hour 6.1 hrs.	3.05	3.24	3.03	2.76[g]
Gas & Oil--Auto Truck[c]	1.00	1.06	1.06	1.06[f]
Combine	12.00	12.00	12.00	12.00
Repairs to Machinery @ 60¢ an hr. 6.6 hrs.	3.95	4.19	3.92	3.58[h]
Small tools[d]	.50	.50	.50	.50
Weeding and hoeing	2.50	2.95	2.51	1.95[i]
Licenses & Insurance[e]	(1.40)	--	--	--
Total cash costs per acre	55.14	44.79	43.87	42.70[j]
			Percent of yield one	
			86	66

Labor

Spring Work (hours)		
Pre-irrigating	1.0	
Weed burning and clean ditches	.5 hrs.	
Plowing	1.0	
Disking	.5	
Harrowing	.5	3.5hrs.
Corrugating	.5	
Applying Fertilizer	.5	
Planting	.5	
Summer Work (hours)		
Irrigating	4.0 hrs.	
Cultivating	.8	
Harvest (hours)		
Cutting	1.0 hrs.	
Raking	.8	

(1) gas & oil: Auto-truck

planting

(57) $\frac{3.5}{6.1}\times 1.06 = .60$

harvesting

(.30) $\frac{1.8}{6.1}\times 1.06 = .32$

tending

(.13 $\frac{.8}{.1}\times 1.06 = .14$

(2) gas & oil: Farm Machinery

planting

$.57\times 3.23 = 1.84$

harvesting (total expense-planting)×

$\frac{.30}{.43}\times$ % reduction in yield

.97 .82 .64

tending (total exp., plant, harv.)

.43 .39 .28

Dry Beans	McKains Study	Hartman-Whittelsey Study 1	2	3
(3) Repairs to Machinery				
planting (total expenseX.57) 4.19X.57=2.39				
harvesting (total expense-planting)X.70X % reduction in yield		1.26	1.07	.83
tending (total expense-plantingX.30)X % reduction in yield		.54	.46	.36
Hauling				
Overhead labor (hours)	2.0			
Total hours of labor	14.1			
Value of labor /acre @ $1.00/hour	14.10			
Total cash cost/acre	55.14			
Total	$69.24			
Surface Water requirements (acre ft) (50% efficiency)		4.2	3.7	3.0
Planting costs		25.68	25.68	25.68
Tending costs		4.56	3.98	3.23
Harvesting costs		14.55	14.21	13.79
Total		$44.79	$43.87	$42.70
Net revenue per acre		$42.83	$30.72	$15.26
Max. cost of crop failure	$30.24			
Reservoir water requirements (acre ft) (50% efficiency)		4.2	3.7	3.0
Planting costs		same	same	same
Tending and harvesting costs		27.72	25.78	23.17
Total		53.40	51.46	48.85
Net revenue per acre		34.22	23.13	9.17
Well water requirements (acre-ft) (70% efficiency		3.0	2.6	2.1

Dry Beans

		Yields	
	1	2	3
Planting costs	same	same	same
Tending and harvesting costs	37.11	33.79	29.62
Total	62.79	59.47	55.30
Net revenue per acre	24.83	15.12	2.72
Gross revenue ($.592/cwt.)	87.62	74.59	58.02
Total reservoir water costs ($2.05/ac ft)	8.61	7.59	6.15
Total well water costs ($6.00/ac ft)	18.00	15.60	12.60

a) Taxes, interest, and depreciation are not included.

b) 8# zinc should be added to land that has not received zinc.

c) Auto @ 70¢ ; truck approximately 3.7¢ per mile.

d) Includes shovels, siphon tubes, wrenches, hose, canvas dams, etc.

e) Farm share--auto $20.00; truck $78; Farm liability $12.

f) Adjusted by the appropriate index.

g) Calculated by adjusting the original cost by the appropriate index,
h) subtracting estimated planting costs (total expenses times the proportion of machine time), calculating the proportion of the remainde that is allocated to tending and harvesting costs (respective proportions of machine time) reducing these in proportion to the reductions in yield and then summing the components.

Calculated by adjusting the original cost by the appropriate index and then reducing costs for 2 and 3 in proportion to the reductions in yield.

j) Excludes surface water costs, irrigation district charges, and licenses and fees.

Crop: FIELD CORN (in bushels per acre)

Item	McKains Study	Hartman-Whittelsey Study 1	2	3
Cash Costs; Materials, etc.$^{a)}$	80	63	53	36
Irrigation Water	(7.21)	--	--	--
Irrigation Dist. Charges	(1.05)	--	--	--
Fertilizer 150 # NH_3	14.25	13.82	13.82	13.82$^{l)}$
Seed @ 21¢ a lb. 12 #	2.52	2.19	2.19	2.19$^{l)}$
Dusting & spraying$^{b)}$	2.00	2.00	2.00	2.00
Gas & Oil-Farm Machinery @ 50¢ an hour 5.1 hr.	2.55	2.70	2.55	2.30$^{g)}$
Gas & Oil-Auto-truck$^{e)}$	1.00	1.06	1.06	1.06$^{l)}$
Corn Picking	8.00	9.44	9.44	9.44
Drying - 200/ton$^{d)}$	4.50	3.56	2.97	2.03
Repairs to Machinery @ 60¢ an hour 6.1 hrs.	3.60	3.82	3.61	3.23$^{i)}$
Small tools$^{e)}$	.50	.50	.50	.50
Weeding & Hoeing$^{f)}$	2.00	2.36	1.98	1.35$^{j)}$
Insurance and Licenses	(1.40)	--	--	--
Total Cash Cost per acre	50.58	41.45	40.12	37.93$^{k)}$
Percent of yield one			84	36

Labor

Spring Work (hours)		
Pre-irrigating	1.0	
Weed burning and clean ditches	.5	
Plowing	1.0	3.1 hrs.
Disking	.4	
Harrowing	.4	
Corrugating	.3	
Applying Fertilizer	.5	
Planting	.5	
Summer Work (hours)		
Irrigating	3.8	
Cultivating	2.0	
Harvest		
Hauling	1.0	

(1) Gas and Oil: Auto-Truck

(.61) planting $\frac{3.1}{5.1}$×1.06=.65

(.39) tending $\frac{2.0}{5.1}$×1.06=.41

(2) Gas and Oil-Farm Machinery

planting (total expense×.65)=1.76

tending (total expense-planting×% reduction in yield)

.94 .79 .54

(3) Repairs to Machinery

planting (total expense×.65)=2.49

tending (total expense-planting)× % reduction in yield

1.34 1.13 .76

Field Corn	McKains Study	Hartman-Whittelsey Study		
		1	2	3
Overhead labor (hours)	2.0			
Total hours labor	13.4			
Value of labor per acre @ $1.00 per hour	$13.40			
Total cash cost per acre	50.58			
Total	$63.98			
Surface Water Requirements (acre/ft) (50% efficiency)		3.3	2.8	2.3
Planting costs		20.90	20.90	20.90
Tending costs		7.55	6.81	5.56
Harvesting costs		13.00	12.41	11.47
Total		41.45	40.12	37.93
Net revenue/acre		41.71	29.84	9.59
Maximum cost of crop failure	$28.45			
Reservoir Water Requirements (acre ft) (50% efficiency)		3.3	2.8	2.3
Planting costs		same	same	same
Tending and harvesting cost		27.32	24.96	21.75
Total		48.22	45.86	42.65
Net revenue/acre		34.94	24.10	4.87
Well Water Requirements (acre ft) (70% efficiency)		2.4	2.0	1.7
Planting costs		same	same	same
Tending and harvesting costs		34.95	31.22	27.23
Total		55.85	52.12	48.13
Net revenue/acre		27.31	17.84	-.61
Gross revenue ($1.32/bu.)		83.16	69.96	47.52
Total reservoir water costs ($2.05/ac ft)		6.77	5.74	4.72
Total well water costs ($6.00/ac ft)		14.40	12.00	10.20

Field Corn

a) Taxes, interest, and depreciation not included.

b) Airplane dusting @ $2.00.

c) Car @ 70¢ ; truck ¢ 30¢ .

d) Corn drying charge varies by moisture content from 18¢ /ton to $4.25. Average = $2.00/ton.

e) Includes shovels, siphon tubes, wrenches, hoes, canvas dams, etc.

f) Picking, thinning, sacking, topping, etc.

g) Calculated by adjusting the original cost by the appropriate index
h) subtracting estimated planting costs, estimating the proportion
i) of the remainder attributed to harvesting and tending, reducing these in proportion to the reductions in yield and then summing the components.

j) Calculated by adjusting the original cost by the appropriate index and then reducing costs for 2 and 3 in proportion to the reductions in yield.

k) Excludes surface water costs, irrigation district charges, and licenses and fees.

l) Adjusted by the appropriate index.

Crop: ONIONS (in cwt per acre)

Item	McKains Study	Hartman-Whittelsey Study 1	2	3
		Yields		
Cash Costs; Materials, etc.	200	298	248	200
Irrigation Water	(7.21)	--	--	--
Irrigation Dist. Charges	(1.05)	--	--	--
Fertilizer 95/ton 600# mixed	28.50	27.65	27.65	27.65 L)
Seed	1.00	.87	.87	.87 L)
Dusting & Spraying	3.00	3.00	3.00	3.00
Gas & Oil-Farm Machinery @ 50¢ an hr. 9.0 hrs.	4.50	4.77	4.55	4.34 f)
Gas & Oil-Auto-Truck b)	3.10	3.23	3.29	3.29 L)
Repairs to Machinery	5.40	5.72	5.46	5.21 f)
Small Tools c)	.50	.50	.50	.50
Sacks, Wire, Twine d) 75¢ 6T	15.00	22.35	18.60	15.00 g)
Weeding & Hoeing	75.00	88.50	73.46	59.30 h)
Top & Sack e) $7.50/T	150.00	263.73	219.48	177.00 i)
Loading Trucks .75¢ /T	15.00	26.37	21.95	17.70 j)
Insurance & Licenses	(1.40	--	--	--
Total cash cost per acre	310.66	446.75	378.81	313.86 k)
		Percent of yield one		
			83	67

Labor

Item	Hours	
Spring Work (hours)		
Weed Burning and clean ditches	.5	
Plowing	1.1	
Disking	.6	
Harrowing	.9	
Corrugating	.4	6.6 hrs.
Applying Fertilizer	1.0	
Planting	.8	
Floating	1.0	
Lifting	.8	
Summer Work (hours)		
Irrigating	7.2	
Cultivating 3x	2.4	
Harvest (hours)		
Hauling	1.0	

(1) Gas & Oil: Auto-Truck

(.73) planting $\frac{6.6}{9.0} \times 3.29 = 2.40$

(.27) tending $\frac{2.4}{9.0} \times 3.29 = .89$

(2) Gas & Oil: Farm Machinery
planting (total exp.× .73)=3.48
tending (total exp.-planting)×% reduction in yield

1	2	3
1.29	1.07	.86

(3) Repairs to Machinery
planting (total expense× .73)=4.18
tending (total expense-planting)

1	2	3
1.54	1.28	1.03

Crop: Onions	McKains Study	Hartman-Whittelsey Study 1	2	3
Item				
<u>Overhead</u> <u>Labor</u> (hours)	2.0			
Total hours of labor	19.7			
Value of labor/acre @ $1.00/hour	19.70			
Total cash cost/acre	310.66			
Total	$330.00			
<u>Surface</u> <u>Water</u> <u>Requirements</u> (acre ft.)		5.3	4.8	4.3
(50% efficiency)				
Planting costs		38.58	38.58	38.58
Tending costs		95.72	80.20	65.58
Harvesting costs		312.45	260.03	209.70
Total		$446.75	$378.81	$313.86
Net revenue/ acre		223.75	179.19	136.14
Maximum cost of crop failure $134.30				
<u>Reservoir</u> <u>Water</u> <u>Requirements</u> (ac ft)		5.3	4.8	4.3
(50% efficiency)				
Planting costs		same	same	same
Tending and harvesting costs		419.04	350.07	284.10
Total		$457.72	$388.65	$322.68
Net revenue per acre		212.88	169.35	127.32
<u>Well</u> <u>Water</u> <u>Requirements</u> (acre ft)		3.8	3.5	3.1
(70% efficiency)				
Planting costs		same	same	same
Tending and harvesting costs		430.97	361.23	293.88
Total		469.55	399.81	332.46
Net revenue/acre		200.95	158.19	117.54
Gross Revenue $2.25/cwt		670.50	558.00	450.00
Total reservoir water costs ($2.05/cwt)		10.87	9.84	8.82
Total well water costs ($6.00/ac ft)		22.80	21.00	18.60

a) Taxes, interest, and depreciation not included.

b) Auto @ 70¢ ; truck @ 30¢ .

c) Includes shovels, siphon, tubes, wrenches, hoes, canvas dams, etc.

d) Cost of sacks figured at .0225¢ /sack, .60¢ /sack or 75¢ for sack/tons.

e) Picking, thinning, sacking, topping, cleaning, etc.

f) Calculated by adjusting the original cost by the appropriate index,
g) subtracting estimated planting costs, estimating the proportion of the remainder attributed to harvesting and tending, reducing these costs in proportion to the reduction in yield and then summing the components.

h) Calculated by adjusting the original cost by the appropriate index
i) and then reducing costs for 2 and 3 in proportion to the reductions
j) in yield.

k) Excludes surface water costs, irrigation district charges, and licenses and fees.

l) Adjusted by the appropriate index.

Crop: POTATOES (in tons per acre)

		Yields		
Cash Costs; Materials, etc.	McKains Study 180	Hartman-Whittelsey Study 1 171	2 152	3 119
Irrigation Water	(7.21)	--	--	--
Irrigation Dist. charges	(1.05)	--	--	--
Fertilizer 100 # NH_3 300 # 16-20	22.10	21.44	21.44	21.44[K]
Seed @ \$90 a ton .7T	63.00	54.81	54.81	54.81[K]
Dusting and spraying	2.00	2.00	2.00	2.00
Gas & Oil-Farm Mach. @ 50¢/hr. 9.5 hrs.*	4.75	5.04	4.75	4.24f)
Rental NH_3 Applicator	.50	.50	.50	.50
Repairs to Machinery @ 60¢/hr. 14.5 hrs.	8.70	9.22	8.44	7.75g)
Small tools c)	.50	.50	.50	.50
Weeding & hoeing	2.50	2.95	2.63	2.07h)
Cutting & treating seed d)	9.00	10.09	8.92	7.01i)
Insurance & Licenses	(1.40)	--	--	--
Total cash cost per acre	125.66	109.68	107.12	103.45j)
			Percent of yield one	
			89	70

Labor

Spring Work (hours)		
Pre-irrigating	1.0	
Weed burning and clean ditches	.5	
Plowing	1.0	
Disking	.4	
Harrowing	.4	4.0 hrs.
Corrugating	.3	
Applying Fertilizer	.8	
Planting	1.1	
Summer Work (hours)		
Irrigating	6.0	hrs.
Cultivating	4.5	
Harvest (hours) e)		

(1) Gas & Oil-Auto-Truck

(.47) Planting $\frac{4.0}{8.5}\times 3.13=1.47$

(.53) Tending $\frac{4.5}{8.5}\times 3.13=1.65$

(2) Gas & Oil-Farm Machinery

Planting (tot. exp. & .47) = 2.37

Tending (tot. exp.-planting)X % reduction in yield)

2.67 2.38 1.87

(3) Repairs to Machinery

planting (total expenseX.47)=4.33

tending (tot. exp.-planting)X% reduction in yield)

4.89 4.11 3.42

(* discrepancy between total machine hours and sum of spring and summer work)

Crop: Potatoes	McKains Study	Hartman-Whittelsey Study		
		1	2	3
Item				
Digging, staking, and elevating (hours)	4.0			
Hauling	5.0			
Overhead Labor (hours)	2.0			
Total hours of labor	27.0			
Value of labor/acre @ $1.00/hr	27.0			
Total cash costs/ac	125.66			
Total	$152.66			
Surface Water Requirements (acre-ft) (50% efficiency)		4.3	3.5	3.1
Planting costs		34.92	84.92	84.92
Tending costs		14.67	13.28	11.52
Harvesting costs		*(10.09)	(8.92)	(7.01)
Total		109.68	107.12	103.45
		**(211.99)	(198.24)	(175.12)
Maximum cost of crop failure $99.59				
Net revenue per acre		70.16	52.56	21.23
Reservoir Water Requirements (ac-ft) (50% efficiency)		4.3	3.5	3.1
Planting costs		same	same	same
Tending and harvesting costs		135.89	120.50	96.56
Total		220.81	205.42	181.48
Net revenue per acre		61.34	45.38	14.87
Well Water Requirements (70% efficiency)		3.1	2.5	2.2
Planting costs		same	same	same
Tending and harvesting		145.67	128.32	103.40
Total		230.59	213.24	188.32
Net revenue/acre		51.56	37.56	8.03
Gross revenue ($1.65/cwt)		282.15	250.80	196.35
Total Reservoir water costs ($2.05/ac ft)		8.82	7.18	6.36
Total well water costs ($6.00/ac)		18.60	15.00	13.20

* Harvest costs	112.40	100.04	78.68
** Total costs	211.99	198.24	175.12

*** Harvest costs are based on figures from study by Anderson and Maass[41]

a) Taxes, interest, and depreciation are not included.

b) Car @ 70¢ ; truck @ 30¢

c) Includes shovels, siphon tubes, wrenches, hoes, dams, etc.

d) Picking, thinning, sacking, topping, cleaning, etc.

e) Harvest costs do not include charge for washing, grading, sacking, and warehousing.

h) Calculated by adjusting the original cost by the appropriate index
i) and then reducing costs for 2 and 3 in proportion to the reductions in yield.

j) Excludes surface water costs, irrigation district charges, and licenses and fees.

k) Adjusted by the appropriate index.

Crop: SUGAR BEETS (in tons per acre)

Item		Yields McKains Study	Hartman-Whittelsey Study		
Beets			14	12	9
Tops			7	6	4
Total		28	21	18	13
Cash Costs, Materials, etc.					
Irrigation Water		(7.21)	--	--	--
Irrigation Dist. Charges		(1.05)	--	--	--
Fertilizer 100 # NH_3 300 # 16-20		24.50	23.77	23.77	23.77 i)
Seed @ 45¢ a lb. 5#		2.25	1.96	1.96	1.96 i)
Gas & Oil-Farm Mach. @ 50¢ /hr.	8.8hr.	4.40	4.73	4.39	3.86 e)
Gas & Oil-Auto-Truck[b]		3.70	3.92	3.92	3.92
Rental NH_3 Applicator		.50	.50	.50	.50
Repairs to Machinery @ 60¢ /hr.	15.8hr.	9.50	10.07	9.35	8.01 f)
Small tools c)		.50	.50	.50	.50
Weeding & hoeing d)		10.00	11.80	10.15	7.55 g)
Insurance & Licenses		(1.40)	--	--	--
Total cash cost per acre		65.01	57.25	54.54	50.07 k)
			Percent of yield one	86	64

Labor

Spring Work (hours)

Weed burning and clean ditches	.5 hrs.
Plowing	1.0
Disking	.4
Harrowing	.4
Corrugating	.3
Applying Fertilizer	.5
Planting	.6
Floating	.5
Mech. thinning	.6

Summer Work (hours)

Irrigating	8.0
Cultivating	2.0

(1) Gas & Oil: Auto truck (dollars)

planting $\frac{4.3}{8.8} \times 3.92 = 1.92$

tending $\frac{2.0}{8.8} \times 3.92 = .90$

harvesting $\frac{2.5}{8.8} \times 3.92 = 1.10$

(2) Gas & Oil-Farm Mach. (dollars)

planting (tot. exp. &. 49)=2.32

tending (tot. exp.-planting) $\frac{2.0}{4.5}$ X %redu in yield

1.35   1.16   .86

(3) Repairs to Machinery (dollars)

planting (tot. exp. X. 49)=4.93

tending (tot. exp.-planting)X. 44)X % reduct in yield

2.26   1.94   1.49

harvesting (tot. exp.-planting-harvest X % reduction in yield

2.88   2.48   1.59

Crop: Sugar Beets		Hartman-Whittelsey Study 1	2	3
To truck	2.5 hrs.			
Hauling	7.0			
Overhead Labor (hrs.)	2.0			
Total hrs. of labor	26.3			
Value of labor/acre @ $1.00/hr.	$26.30			
Total cash cost/acre	65.01			
Total	$91.3			
Surface Water Requirements (acre-ft) (50% efficiency)		5.3	4.8	4.3
Planting costs		35.40	35.40	35.40
Tending costs		16.52	14.40	11.12
Harvesting costs		5.33	(4.74)	(3.55)
Total		(57.25)	(54.54)	(50.07)
Maximum cost of crop failure	$51.92	108.02*	98.10*	32.46*
Net revenue/acre		107.66	86.82	54.73
Reservoir Water Requirements (ac-ft) (50% efficiency)		5.3	4.8	4.3
Planting costs		same	same	same
Tending and harvesting costs		83.55	72.54	55.88
Total		118.95	107.94	91.28
Net revenue per acre		96.79	76.98	45.91
Well Water Requirements (acre-ft) (70% efficiency)		3.8	3.5	3.1
Planting costs		same	same	same
Tending and harvesting costs		95.48	83.70	65.66
Total		130.88	119.10	101.06
Net revenue per acre	84	84.86	65.82	36.18

Total net revenue for sugar beets consists of $13.91/ton for the beets and $3.00/ton for tops[44]

Sugar beets	14	12	9
tops	7	6	4

Data on harvest costs taken from study by Anderson and Maass[44]

	56.16	48.30	35.94

a) Taxes, interest, and depreciation are not included.

b) Car @ 70¢ ; truck @ 30¢ .

c) Includes shovels, siphon tubes, wrenches, canvas dams, etc.

d) Picking, thinning, sacking, topping, etc.

e) Calculated by adjusting the original cost by the appropriate index,
f) subtracting estimated planting costs, estimating the proportions of the remainder attributed to harvesting and tending, reducing these costs in proportion to the reduction in yield and then summing the components.

g) Calculated by adjusting the original cost by the appropriate index and then reducing costs for 2 and 3 in proportion to the reductions in yield.

h) Excludes surface water costs, irrigation district charges, and licenses and fees.

i) Adjusted by the appropriate index.

Crop: WHEAT (other small grains, including barley) (in bushels per acre)

		Yields			
		McKains Study	Hartman-Whittelsey Study 1	2	3
Cash Costs, Materials, etc.[a]		55	54	44	34
Irrigation Water		(7.21)	--	--	--
Irrigation Dist. Charges		(1.05)	--	--	--
Fertilizer 90 # N		13.50	13.50	13.50	13.50 [c]
Seed 100 #		5.75	5.00	5.00	5.00 [g]
Gas & Oil-Farm Machinery @ 50¢ an hr.	2.5hrs	1.25	1.33	1.33	1.33[d]
Gas & Oil-Auto Truck		1.00	1.06	1.06	1.06[c]
Combine		6.00	6.00	6.00	6.00
Repairs to Machinery		2.25	2.39	2.39	2.39[e]
Small tools[b]		.50	.50	.50	.50
Insurance and Licenses		(1.40)	--	--	--
Total Cash cost per acre		39.91	29.38	29.38	29.38[f]
				Percent of yield	
				81	63

Labor			
Spring Work (hours)			
Weed burning & clean ditches	.5		
Plowing			
Disking 2x	.6	2.5 hrs	
Harrowing 2x	.6		
Corrugating	.4		
Applying Fertilizer	.5		
Planting	.4		
Summer Work (hours)			
Irrigating	3.0		
Harvest (hours)			
Hauling	.6		
Overhead Labor (hours)	2.0		
Total hours labor	8.6		
Value of labor per acre @ $1.00 per hour			$8.60
Total Cash cost per acre			39.91
Total			$48.51

Crop: WHEAT (other small grains)--BARLEY

	Hartman-Whittelsey Study		
Item	1	2	3
Surface Water Requirements (acre-ft) (50% efficiency)	2.7	2.2	1.8
Planting costs	22.88	22.88	22.88
Tending costs	.50	.50	.50
Harvesting costs	6.00	6.00	6.00
Total	29.38	29.38	29.38
Net return per acre	19.58	12.86	3.26
Maximum cost of crop failure 23.38			
Reservoir Water Requirements (acre-ft) (50% efficiency)	2.7	2.2	1.8
Planting costs	same	same	same
Tending and harvesting costs	12.04	11.01	14.30
Total	34.92	33.89	33.07
Net return per acre	14.04	8.35	-0.43
Well Water Requirements (acre-ft.) (70% efficiency)	1.8	1.4	1.1
Planting costs	same	same	same
Tending and harvesting costs	17.90	15.50	14.30
Total	40.78	38.38	37.18
Net return per acre	8.18	3.86	-4.54
Gross revenue ($0.96/bu.)	48.96	42.24	32.64
Total reservoir water costs ($2.05/ac. ft.)	5.54	4.51	3.69
Total well water costs ($6.00/ac. ft.)	11.40	9.00	7.80

a) Taxes, interest, and depreciation not included.

b) Includes shovels, siphon tubes, wrenches, hoes, canvas dams, etc.

c), d), e) Adjusted by the appropriate index.

TABLE 37

GROSS REVENUE MINUS TENDING AND HARVESTING COSTS
(in dollars per acre)

ALFALFA			
Sur.	50.82	38.61	23.27
Res.	41.18	31.84	18.55
Well.	31.02	24.21	13.07
DRY BEANS			
Sur.	68.51	56.40	40.94
Res.	59.90	48.81	34.85
FIELD CORN			
Sur.	62.61	50.74	30.49
Res.	55.84	45.00	25.77
Well.	48.21	38.74	20.29
ONIONS			
Sur.	262.33	217.77	174.72
Res.	251.46	207.93	165.90
Well.	239.53	196.77	156.12
POTATOES			
Sur.	155.08	137.48	106.15
Res.	146.26	130.30	99.79
Well	136.48	122.48	92.95
SUGAR BEETS			
Sur.	143.06	122.22	90.13
Res.	132.19	112.38	81.31
Well.	120.26	101.22	71.53
BARLEY			
Sur.	42.46	35.74	26.14
Res.	36.92	31.23	22.45
Well.	31.06	26.74	18.34

Production Credit Costs

Conceptually, costs of borrowing on production loans would be included in the category of variable costs. These costs would be allocated to the crop for which they were incurred and would be part of the information on which the decision to plant would be based.

Production cost data from the McKains study does not provide estimates of production credit costs nor were any other sources for this information located. To further complicate the problem, a typical financial plan for current farm operations calls for a budgeted loan. As Heady and Jensen state:

> Such loans are planned at the beginning of the year; credit is advanced as needed; principal and interest payments are made as products are sold; and interest is paid for the periods only when capital is actually in use.[46]

The farmer also can meet seasonal production needs for financing by building up large idle cash reservers; or he may be in a position where he must borrow all his production financing. Repayment of loans may be from other farm enterprises, such as a feed lot or livestock operation, so that allocating costs to specific crops is difficult.

In the Arkansas Valley, for example, the customers of the Production Credit Administration generally borrow all of their short-term production finances.[47] The duration of these loans is usually for one year, with refinancing subject to the continuing credit worthiness of the productive enterprise.

The variable costs of production associated with the different acreages planted in the model range from about 1.4 to 1.7 million dollars for Case One and 1.1 to 1.5 million dollars for Case Two. Various assumptions could be made as to the interest rate, proportion of total variable costs borrowed, and the duration of the loan. For example, if half the production costs were borrowed at an interest rate of 5 per cent for an average period of six months, production credit costs would vary from about \$16,000 to \$23,000 seasonally, depending on the forecast conditions and the case. Changing the length of the loan, interest rate or proportion of finances borrowed would alter the estimate of seasonal production credit costs that could reasonably be associated with the variable cost estimates used in the model. Since it is not possible to incorporate production credit costs into the decision framework, the total seasonal credit costs should be deducted from net regional income generated for each forecast and accuracy level. The method used to estimate the benefits from increased forecast accuracy, however, involves differencing expected values at successive accuracy levels. Because the differences in variable costs of production are slight for comparable forecasts at different accuracy levels and because the expected income figures are rounded to the thousands place, no inclusion of these costs will be attempted, even though some imprecision is thereby introduced.

Fixed Costs

While fixed costs do not enter into the optimization calculations of the model directly, they are important in the assessment of the value of increased accuracy and in assessing the realism of the results. The rate of return on investment, including return to management, must be sufficient to assure the long-run feasibility of the operation.

Information source for fixed costs is from McKains, Franklin, and Jensen[48] and from various Colorado Agricultural Experiment Station farm budget studies of the Arkansas Valley.[49] Since fixed costs can be expected to vary widely among farms and regions, these figures are only suggestive of actual fixed costs. Short of a detailed empirical study of one region, this approach provides the only feasible alternative, while still maintaining realistic cost data. In discussing fixed costs, the same general categories used by McKains et al. are followed.[50] These figures are adjusted from the 1955 price level to the 1959, to be consistent with the variable costs of production.[51]

Case One

Depreciation of Machinery.--The calculations presented by McKains are for an 80 acre farm, which is smaller than that envisioned in the model. In order to adjust for this, new cost of additional machinery is included in calculation of depreciation figures. Additional machinery includes an onion lifter, one-half-interest potato planter, and a one-quarter-interest, two-row potato planter, and a one-quarter-interest, two-row potato harvester and a swather. Total irrigated acres under the typical farm in the model is assumed to be 250. This figure is slightly less than those observed in the 1964 Census of Agriculture for various sections of Colorado. Table 38 below is adapted from McKains to include the additional machinery. Converting the annual depreciation to a per-acre basis gives $6.38. Adjusting this by the proper index (factor of 1.19) gives a per-acre cost for depreciation of machinery of $7.59 per acre.

Interest on investment in machinery.--McKains et al. calculate interest on machinery as follows:

> In long-time farming operations, the acreage investment in machinery would be approximately half the price of new equipment. Ordinarily, old machines can be traded or otherwise disposed of at 10 per cent of their purchase price. Thus, interest on investment in machinery is calculated on 55 per cent of the cost when new.[55]

Fifty-five per cent of $15,283.00 is $7,305.65 and at five per cent interest is $345.28. On a per-acre basis, this would be $1.46, and adjusting for increases in interest rates (factor of 1.08) gives $1.58.

Depreciation of buildings, fences, and irrigation structures.--Items in this category include the farm house, machine and tool shed, irrigation structures, fences, domestic water system, and land. Of the improvements, a portion of the domestic water system is assumed used in productive livestock enterprises, whereas the house is considered a non-productive improvement. For purposes of calculating depreciation on the productive improvements, half the cost of the domestic water system and the total cost for the machine and tool shed, irrigation structures, and fences are used.[56] McKains indicates that depreciation on frame buildings and well-constructed irrigation structures is about 3 per cent, while depreciation on fences is more rapid. Figures from Table 18 of the McKains study are presented below, adapted to the larger size farm and adjusted for different land costs.[57]

TABLE 38

NEW COST, RATE OF DEPRECIATION, AND CALCULATION OF ANNUAL DEPRECIATION OF MACHINERY FOR A 250 ACRE FARM

Item	Rate of Depreciation (in per cents)	New Cost	Annual Depreciation
Tractor[a]	15	$2,530	$380.00
Truck	15	2,800	420.00
Plow	10	500	50.00
Disc	10	360	36.00
Harrow	10	85	8.50
Float	10	45	4.50
Corn Planter	10	180	18.00
Drill	10	640	64.00
Fertilizer Spreader	10	300	30.00
Corrugator and Ditcher	10	150	15.00
Mower	10	380	38.00
Rake	10	510	51.00
Bean Lifter	10	240	24.00
Cultivator	10	280	28.00
½ interest Sugar Beet Harvester	10	1,350	135.00
Onion Lifter	10	65	6.50
Potato Planter (½ interest)	10	700	70.00
Two Row Potato Harvester (1/3 interest)	10	2,133	213.30
Swather	10	35	3.50
Totals		$13,283.00	$1,595.30

[a] In using the above machinery costs for a 250-acre farm, it is important to assure that the tractor size corresponds to the operational requirements, particularly if the operation requires an all-purpose tractor.[52] Jones indicates that for small farms or for large farms with small fields, the smaller or two-row tractor is generally well-suited. Heady and Jensen indicate that for a 250-acre farm, a three- or two-plow tractor can be utilized at approximately the optimum point of operation on a per-acre cost basis.[53] The approximate inflation adjusted cost of the tractor in the McKains study would be typical of 21 to 26 drawbar horsepower tractor capable of handling three plows.[54] Based on these approximations, no adjustment will be made in tractor size.

TABLE 39

ESTIMATED LAND AND BUILDING VALUES
FOR A 250-ACRE FARM
(in dollars)

Item	Value
House	8,000
Machine and Tool Shed	3,000
Irrigation Structure	1,550
Fences	620
Domestic Water System	2,000
Productive Improvements	6,170
Land--250 @ $233/acre	58,250
Production Improvement and Land	64,420

Using 3 per cent depreciation on the value of productive improvements gives an annual cost of $185.10, or $0.74 per acre. Adjusting this by the proper index (1.11) gives $0.82 per acre.

Interest on investment in land and buildings--Land values will depend on productivity and the alternatives uses to which land can be put. In the McKains study, land values are shown with a range from $75.00 per acre to $350.00 per acre, where land values include costs of land clearing, land leveling, and irrigation facilities.[58] For purposes of this study, figures from budget studies conducted in the Arkansas Valley of Colorado in the mid-sixties will be used.[59] These studies show a range in interest cost on land ranging from $12.00 to $24.00 per acre. Using the upper range of these estimates to represent interest in Case One (good but variable supply) and adjusting for price changes (1966 to 1955--factor of .49) gives $11.76 per acre in 1955. To determine the total value of the land, the per-acre interest payment is multiplied by 250 and capitalized at a 5 per cent rate of interest. This gives a total investment in land of $58,800 per farm. Adding to this the value of productive improvements from Table 39 gives $64,970. Five per cent of this figure divided by 250 and adjusted by the proper index gives $14.03 per acre.

State and county taxes.--Annual charges for direct flow deliveries by mutual ditch companies is highly variable, depending on the seniority of the company's water rights and the level of investment in facilities. Costs on one farm in the Arkansas Valley average about $1.41 per acre,[60] while in the South Platte estimates showed a cost from $1.00 to $1.14 per acre.[61] In order to present a somewhat conservative estimate of costs, the higher figure from the Arkansas Valley will be used.

Other.--Under this category come such costs as licenses and insurance, estimated in the McKains study at $1.40 per acre. Although this figure might vary with the acreage planted, no method for determining this was established, and these costs will be allocated to the fixed cost category.

Per acre costs are presented in Table 40, and the total fixed costs for the hypothetical region are calculated for Case One (abundant reservoir and well water, with variable surface supply) and Case Two (limited reservoir and well supplies and variable surface flow). In Case Two, lower land costs are assumed, based on a lower level of productive improvements and a slightly less capital intensive operation, due to the more variable and restirctive nature of the water supply. Adjustments in fixed costs for Case Two are discussed below.

Case Two

Depreciation of machinery.--Adjustments in this category include the following: one-third interest in a sugar beet harvester ($900.00); one-half interest in a potato planter ($350.00); and one-sixth interest in a potato harvester ($1,067.00). Total depreciation is now $1,442.00, or $5.77 on a per-acre basis. Adjusting for price changes gives $6.87 per acre depreciation costs.

Interest on investment in machinery.--Total new investment in machinery is now $11,417.00. Fifty-five per cent of this figure is $6,279.35, and five per cent of that is $3,397. On a per-acre basis, this is $1.26 and adjusted for price changes would be $1.36.

Depreciation of buildings, fences, and irrigation structures.--This category of costs is left unaltered, since the size of the farm is assumed to remain constant at 250 acres.

Interest on investment in land and buildings.--This category is altered in order to reflect the poorer nature of the farming operation,

TABLE 40

FIXED COSTS OF PRODUCTION

	Case One--21,000 acres fully developed	
Item	Per Acre Cost	Total Cost
Depreciation of Machinery	$ 7.59	$159,390.00
Interest on Investment in Machinery	1.58	33,180.00
Depreciation of Buildings, Fences, and Irrigation Structures	0.82	17,220.00
Interest on Investment in Land and Buildings	14.03	294,630.00
State and County Taxes	5.67	119,070.00
Surface Water Assessment	1.41	29,610.00
Other	1.40	29,400.00
Total Fixed Costs	$32.50	$682,500.00

	Case Two--21,000 acres available but slightly less capital intensive with lower land values and taxes	
Item	Per Acre Costs	Total Cost
Depreciation of Machinery	$ 6.87	$144,270.00
Interest on Investment in Machinery	1.36	28,560.00
Depreciation of Buildings, Fences and Irrigation Structures	0.82	17,220.00
Interest in Investment in Land and Buildings	10.85	227,850.00
State and County Taxes	4.88	102,480.00
Surface Water Assessment	1.41	29,610.00
Other	1.40	29,400.00
Total Fixed Costs	$27.59	$379,390.00

due to more erratic water supply. Taking the median value from the farm budget studies conducted in the Arkansas Valley ($18,00) and adjusting for changes in interest costs (1966 to 1955--factor = .49) gives $8.82 per acre in 1955. To determine the total value of the land, the per acre interest payment is multiplied by 250 and capitalized at a 5 per cent rate of interest, giving a total investment in land of $44,100. Adding to this the value of productive improvements from Table 39 gives $50,270. Five per cent of this figure divided by 250 and adjusted by the proper index gives $10.85 per acre.

State and county taxes.--Using the lower range from the farm budget studies in the Arkansas Valley and adjusting for price changes gives a figure of $4.88 per acre.

Surface water assessment.--This charge is assumed to remain the same.

Other.--These costs are assumed to remain the same.

Water Supply and Conditional Probabilities

It will be assumed that seasonal water supply consists of:

(1) a maximum surface quantity of 70,000 acre feet, if 100 per cent of the hypothetical ditch company's water rights are fulfilled throughout the entire season;

(2) a maximum of 20,000 acre feet of reservoir water, determined by storage rights in Federal reservoirs and storage capacity in private facilities assumed owned by the ditch company; and

(3) a maximum quantity from ground water of 10,000 AF per season, determined by aquifer characteristics and the extent of well development.

The irrigators under the ditch company are assumed to face twenty-one possible states of nature, consisting of the twenty-one possible combinations of quantities from surface flow and from reservoir water, plus the maximum quantity available from groundwater. The seven possible quantities from surface flow are assumed to consist of percentages of the maximum (70,000 ac. ft.), starting with 20 per cent and increasing by increments of 15 per cent. Average supply from surface water is assumed to be about 65 per cent of full decreed rights. The three quantities possible from reservoir water consist of a low average and high where low equals 40 per cent of the maximum, average equals 70 per cent of maximum, and high equals 100 per cent of maximum.

Because many reservoir systems have enough capacity to store water between seasons, a minimum reservoir supply of 40 per cent of capacity is assumed available to the ditch company. The possible combinations of reservoir and surface water are presented in Table 41 in the form of constraints. No particular significance can be attached to the water supply composition chosen, and these components could be altered to test the sensitivity of the results.

As shown below in Table 41, each state of nature consists of one of seven possible surface supply conditions, one of three possible reservoir supply conditions, and one maximum available ground water supply. The states of nature are rated from most adverse (A) to most abundant (U).

In order to approximate the typical variation in water supply that ditch companies are subject to, figures on minimum, maximum, and average annual deliveries for several ditches in the Arkansas Valley of Colorado were obtained.[62] These figures, along with their respective percentage variations from average, are presented in Table 42. The assumed variations for the model are presented in Table 43. These figures show the minimum, maximum, and average seasonal water supply for the hypothetical ditch company used in the model.

Derivation of the Conditional Probabilities

Derivation of the conditional probabilities that are assumed to arise from streamflow forecasts is at best an arbitrary exercise. The initial probabilities are based on three assumptions:

(1) Quantity forecasts are divided into seven classes corresponding to the categories facing the ditch company (i.e., very low, low, etc.). Again, no significance can be attached to picking seven categories, since 10 to 20 could be used with corresponding appropriate conditional probabilities being attached to observing the 21 assumed states of nature faced by the ditch company.

(2) The initial probability distribution for each forecast is assumed to be widely dispersed for any given forecast, with forecasts showing a skewed distribution away from the quantity predicted (i.e.,

TABLE 41

CONSTRAINTS FOR EACH STATE OF NATURE

Water Supply	States of Nature		
	(A)	(B)	(C)
Surface	$\leq$ 14,000	$\leq$ 14,000	$\leq$ 14,000
Res.	$\leq$ 8,000	$\leq$ 14,000	$\leq$ 20,000
Ground	$\leq$ 10,000	$\leq$ 10,000	$\leq$ 10,000
	(D)	(E)	(F)
Surface	$\leq$ 24,500	$\leq$ 24,500	$\leq$ 24,500
Res.	$\leq$ 8,000	$\leq$ 14,000	$\leq$ 20,000
Ground	$\leq$ 10,000	$\leq$ 10,000	$\leq$ 10,000
	(G)	(H)	(I)
Surface	$\leq$ 35,000	$\leq$ 35,000	$\leq$ 35,000
Res.	$\leq$ 8,000	$\leq$ 14,000	$\leq$ 20,000
Ground	$\leq$ 10,000	$\leq$ 10,000	$\leq$ 10,000
	(J)	(K)	(L)
Surface	$\leq$ 45,500	$\leq$ 45,500	$\leq$ 45,500
Res.	$\leq$ 8,000	$\leq$ 14,000	$\leq$ 20,000
Ground	$\leq$ 10,000	$\leq$ 10,000	$\leq$ 10,000
	(M)	(N)	(O)
Surface	$\leq$ 56,000	$\leq$ 56,000	$\leq$ 56,000
Res.	$\leq$ 8,000	$\leq$ 14,000	$\leq$ 20,000
Ground	$\leq$ 10,000	$\leq$ 10,000	$\leq$ 10,000
	(P)	(Q)	(R)
Surface	$\leq$ 66,500	$\leq$ 66,500	$\leq$ 66,500
Res.	$\leq$ 8,000	$\leq$ 14,000	$\leq$ 20,000
Ground	$\leq$ 10,000	$\leq$ 10,000	$\leq$ 10,000
	(S)	(T)	(U)
Surface	$\leq$ 70,000	$\leq$ 70,000	$\leq$ 70,000
Res.	$\leq$ 8,000	$\leq$ 14,000	$\leq$ 20,000
Ground	$\leq$ 10,000	$\leq$ 10,000	$\leq$ 10,000

TABLE 42

ANNUAL DIVERSIONS BY MAJOR DITCH COMPANY IN UPPER ARKANSAS VALLEY (in acre feet)

Ditch	Minimum	Maximum	Average	% of Average
Bessemer	41,100	84,607	60,752	68 to 139
Colorado	4,700	154,600	80,428	6 to 192
Rocky Ford Highline	45,900	117,400	72,380	63 to 162
Ford	11,500	35,800	23,775	48 to 151
Otero	500	20,200	8,502	6 to 238
Catlin	38,100	112,100	80,635	
Holbrook	6,900	80,600	34,935	47 to 231
Rocky Ford	38,900	55,400	47,622	82 to 116
Las Animas	13,200	40,800	23,925	55 to 171
Fort Lyon	95,000	393,500	216,673	44 to 182
Fort Bent	5,453	24,700	16,164	34 to 153
Amity	15,234	126,800	21,005	19 to 157
Lamar	15,761	48,400	34,355	46 to 141
Buffalo	7,600	20,700	14,505	52 to 143

---

[a] Source: Water Legislation Investigations for the Arkansas River Basin in Colorado, Volume II, Comprehensive Report, W. W. Wheeler and Associates and Woodward-Clyde and Associates, Consulting Engineers (Denver, Colo.: September, 1968).

TABLE 43

ASSUMED VARIATION IN WATER SUPPLY OF HYPOTHETICAL DITCH COMPANY

(in acre feet)

	Minimum	Maximum	Average	% of Average
Case One				
Surface	14,000	70,000	43,862	32 to 160
Surface and Reservoir	22,000	90,000	57,622	38 to 156
Surface, Reservoir, and Well	32,000	100,000	67,622	74 to 148
Case Two				
Surface	14,000	70,000	43,862	32 to 160
Surface and Reservoir	16,000	76,000	47,696	34 to 159
Surface, Reservoir, and Well	16,500	76,500	48,196	34 to 159

for a forecast of "very low," the conditional probability of observing states of nature close by would be greater than observing those more distant). Improvements in accuracy will be reflected by changing the distributions in the following ways:

(a) Forecasts become accurate enough so that extreme values have a zero probability of being observed.

(b) increase in accuracy reflected by an increase in probability of observing both the quantity predicted and the quantities close to the quantity predicted.

(c) The relationship between surface flow and water in storage will be assumed to be a direct one; i.e., a forecast of a very high surface supply will also imply that water in reservoir storage will be abundant. Thus, if the forecast is for a very high water season, the conditional probability of observing state of nature U (very high surface-high reservoir) is assumed to be greater than observing state of nature T, S, or R; however, the conditional probabilities of observing the row S, T, and U and the column U, R, O, L, I, F, and C exceed those of the other rows and columns. This can be seen by inspection of the assumed conditional probabilities to be used in the initial run of the model, presented in Table 44.

In order to calculate the conditional probabilities, two sets of information are necessary. First, an historical frequency distribution for the state of nature must be either empirically derived or, if that is not possible, established based on reasonable assumptions. Likewise, the historical accuracy levels of present forecasts and the assumed accuracy levels of improved forecasts must be approximated. With this information, it is thus possible to calculate the conditional probabilities of observing the various states of nature. Improvements in forecasting techniques over the last several decades, changes in watershed characteristics, the relatively short period of record, and the lack of consistent data make empirical establishment of meaningful frequency distributions exceedingly difficult. Though it is beyond the scope of this work to determine the historical frequency distributions or accuracy levels for any particular river, the figure below for the

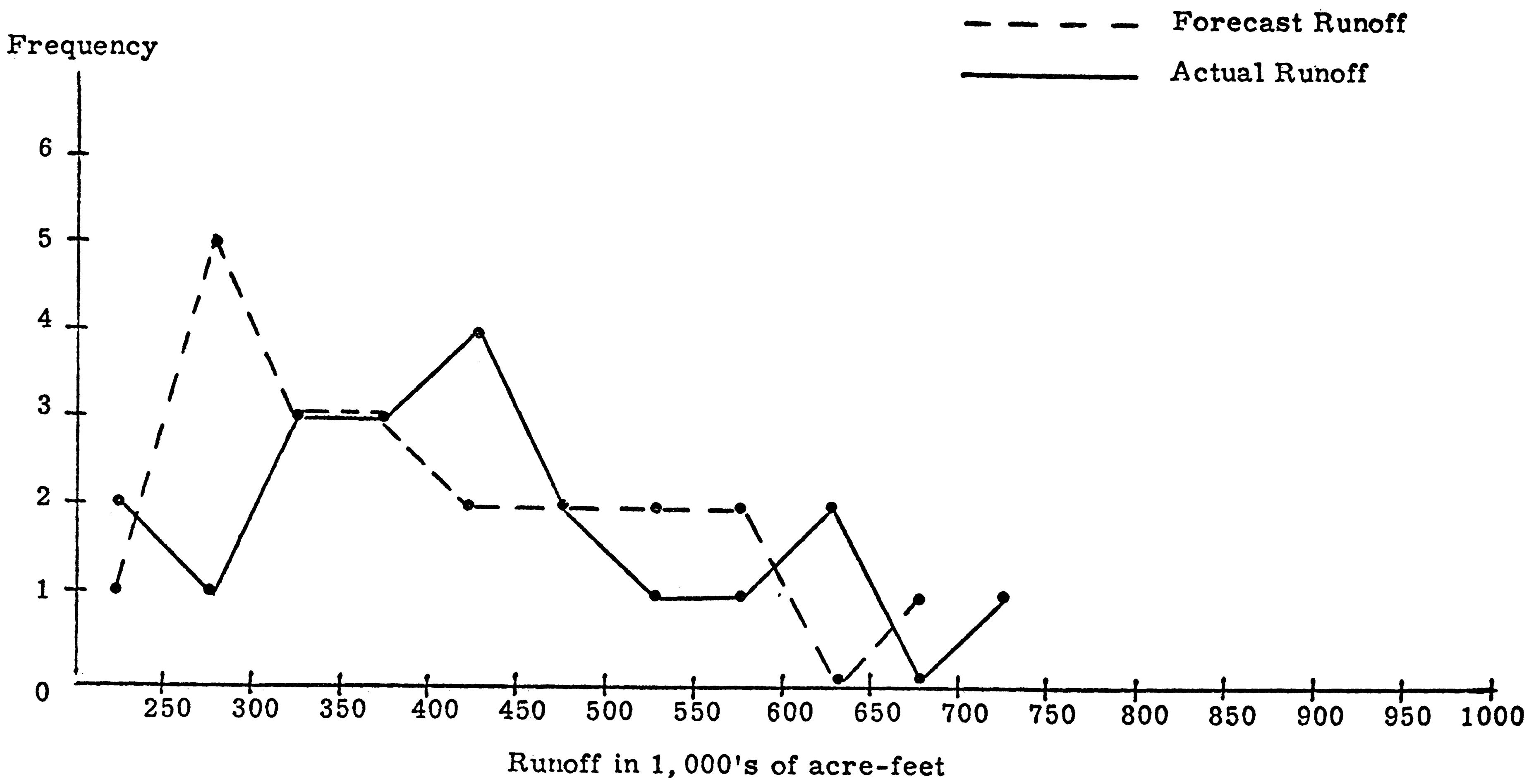

Fig. 12. Frequency distribution of actual and forecast runoff at the gaging station near Pueblo, Colorado, 1951-1960 (Oct.-Sept. forecast made May 1). (Source: Water Supply Outlook, U.S. Weather Bureau)

water year forecasts (September-October) for the gaging station on the Arkansas River near Pueblo, Colorado, shows the basic relationship. Runoff is separated into increments of 50,000 acre feet, starting with 250,000. For the interval studied (1951 to 1968), the frequency distribution for the forecast falls noticeably to the left of the frequency distribution for historical runoff and does not represent very well the extreme flows that have occurred.

Distributions with similar inaccuracies were calculated for this study and are shown in Table 44. These figures are calculated by using the Bayesian formulation presented in Chapter II. An initial historical frequency distribution and four historical forecast accuracy levels are assumed. Based on this information, it is then possible to derive the conditional probabilities for each forecast at each accuracy level. The following symbols are used throughout the table.

UH = Very High
H = High
AA = Above Average
A = Average
BA = Below Average
L = Low
VL = Very Low

various surface water supply conditions

L = Low
A = Average
H = High

various reservoir supply conditions

TABLE 44

DERIVATION OF CONDITIONAL PROBABILITY DISTRIBUTIONS FOR FOUR LEVELS OF FORECAST ACCURACY

Historical Frequency Distribution

	L	A	H
VH	.01	.023	.04
H	.025	.035	.044
AB	.05	.071	.06
A	.07	.108	.07
BA	.055	.06	.04
L	.06	.04	.03
VL	.054	.03	.02

Σ = 1.00

Very Low Forecast

L	A	H
.03	.02	.01
.03	.02	.02
.03	.03	.02
.04	.03	.03
.07	.05	.05
.08	.08	.07
.11	.010	.08

Σ = 1.00

Low Forecast

L	A	H
.02	.02	.02
.03	.02	.02
.04	.03	.02
.04	.03	.03
.08	.06	.05
.09	.09	.07
.09	.08	.07

Σ = 1.00

Below Average Forecast

	L	A	H
VH	.02	.02	.02
H	.03	.02	.02
AB	.04	.03	.03
A	.06	.05	.04
BA	.09	.09	.08
L	.07	.08	.07
VL	.05	.05	.04

Σ = 1.00

Average Forecast

L	A	H
.02	.02	.02
.03	.04	.03
.05	.06	.04
.08	.09	.08
.06	.07	.06
.04	.06	.05
.03	.04	.03

Σ = 1.00

Above Average Forecast

L	A	H
.03	.04	.03
.05	.05	.06
.07	.08	.10
.05	.06	.07
.04	.05	.06
.03	.03	.03
.02	.02	.03

Σ = 1.00

High Forecast

	L	A	H
VH	.06	.06	.07
H	.09	.10	.10
AB	.05	.06	.07
A	.03	.03	.04
BA	.02	.03	.04
L	.02	.03	.03
VL	.02	.02	.03

Σ = 1.00

Very High Forecast

L	A	H
.10	.11	.12
.07	.08	.08
.04	.04	.05
.03	.03	.04
.02	.03	.03
.02	.02	.03
.02	.02	.02

Σ = 1.00

Forecast Frequency

	L	A	H
12.2%	.041	.041	.040
14.1%	.047	.047	.047
14.1%	.047	.047	.047
14.0%	.047	.046	.047
16.1%	.054	.054	.053
15.6%	.050	.056	.050
13.9%	.049	.047	.043

Σ = 7.02

Sum Historical

.29	.29	.28
.33	.33	.33
.32	.33	.33
.33	.32	.33
.38	.38	.37
.35	.39	.35
.34	.33	.30

Sum = 7.00

CONDITIONAL PROBABILITIES

Accuracy Level One

Numerator
Very Low Forecast

	L	A	H
VH	.0003	.0006	.0004
H	.0008	.0007	.0009
AV	.0015	.0021	.0012
A	.0028	.0032	.0021
BA	.0039	.0030	.0020
VL	.0048	.0032	.0021
L	.0059	.0030	.0016

denom. = .0461

Numerator
Low Forecast

	L	A	H
VH	.0003	.0006	.0004
H	.0008	.0007	.0009
AV	.0020	.0021	.0012
A	.0028	.0032	.0021
BA	.0044	.0036	.0020
VL	.0054	.0036	.0021
L	.0049	.0024	.0014

denom. = .0469

Numerator
Below Average Forecast

	L	A	H
VH	.0002	.0006	.0008
H	.0008	.0007	.0009
AV	.0020	.0021	.0018
A	.0042	.0054	.0028
BA	.0050	.0054	.0032
VL	.0042	.0032	.0021
L	.0027	.0015	.0008

denom. = .0504

Conditional Probability

VH	.0065	.0130	.0087
H	.0174	.0152	.0195
AV	.0325	.0456	.0260
A	.0607	.0694	.0456
BA	.0846	.0651	.0434
VL	.1041	.0694	.0456
L	.1280	.0651	.0347

Σ = 1.0001

Conditional Probability

VH	.0064	.0128	.0085
H	.0171	.0149	.0192
AV	.0426	.0448	.0256
A	.0597	.0682	.0448
BA	.0938	.0768	.0426
VL	.1151	.0768	.0448
L	.1044	.0512	.0299

Σ = 1.000

Conditional Probability

VH	.0040	.0119	.0159
H	.0159	.0139	.0179
AV	.0397	.0417	.0357
A	.0233	.1071	.0556
BA	.0992	.1071	.0635
VL	.0833	.0635	.0417
L	.0536	.0300	.0159

Σ = 1.0004

Numerator
Average Forecast

	L	A	H
VH	.0002	.0006	.0008
H	.0008	.0014	.0013
AV	.0025	.0043	.0024
A	.0056	.0097	.0056
BA	.0033	.0042	.0024
L	.0024	.0024	.0015
VL	.0016	.0012	.0006

denom. = .0548

Numerator
Above Average Forecast

	L	A	H
VH	.0003	.0011	.0012
H	.0013	.0018	.0026
AV	.0035	.0057	.0060
A	.0035	.0065	.0049
BA	.0022	.0030	.0024
L	.0018	.0012	.0009
VL	.0011	.0006	.0006

denom. = .0522

Numerator
High Forecast

	L	A	H
VH	.0006	.0017	.0028
H	.0023	.0035	.0044
AV	.0025	.0043	.0042
A	.0021	.0032	.0028
BA	.0011	.0018	.0016
L	.0012	.0012	.0009
VL	.0011	.0006	.0006

denom. = .0445

Conditional Probability

VH	.0036	.0109	.0146
H	.0146	.0255	.0237
AV	.0456	.0785	.0438
A	.1022	.1770	.1022
BA	.0602	.0766	.0438
L	.0438	.0438	.0274
VL	.0292	.0219	.0109

Σ = .9998

Conditional Probability

VH	.0057	.0211	.0230
H	.0249	.0345	.0498
AV	.0670	.1092	.1149
A	.0670	.1245	.0939
BA	.0421	.0575	.0460
L	.0345	.0230	.0172
VL	.0211	.0115	.0115

Σ = .9999

Conditional Probability

VH	.0135	.0382	.0629
H	.0517	.0787	.0989
AV	.0562	.0966	.0944
A	.0472	.0719	.0629
BA	.0247	.0404	.0360
L	.0270	.0270	.0202
VL	.0237	.0135	.0135

Σ = 9991

Numerator
Very High Forecast

	L	A	H
VH	.0010	.0031	.0048
H	.0018	.0028	.0035
AV	.0020	.0028	.0030
A	.0021	.0032	.0028
BA	.0011	.0018	.0012
L	.0012	.0008	.0009
VL	.0011	.0006	.0004

denom. = .0420

Conditional Probability

VH	.0238	.0738	.1143
H	.0429	.0667	.0333
AV	.0476	.0667	.0714
A	.0500	.0762	.0667
BA	.0262	.0429	.0286
L	.0286	.0190	.0214
VL	.0262	.0143	.0095

Σ = 1.0001

Historical Accuracy
Level Two

Very Low Forecast

	L	A	H
VH	.01	.01	.005
H	.02	.01	.005
AB	.02	.015	.015
A	.04	.04	.03
BA	.06	.05	.04
L	.10	.09	.06
VL	.16	.12	.10

Σ = 1.00

Low Forecast

L	A	H
.01	.01	.005
.025	.01	.005
.03	.025	.02
.04	.04	.03
.08	.07	.05
.13	.13	.06
.11	.08	.04

Σ = 1.00

Below Average Forecast

L	A	H
.01	.015	.01
.025	.02	.01
.03	.03	.02
.08	.07	.06
.10	.12	.09
.09	.08	.06
.04	.02	.02

Σ = 1.00

Average Forecast

VH	.01	.01	.01
H	.02	.02	.02
AB	.07	.09	.06
A	.10	.13	.11
BA	.08	.09	.07
L	.02	.03	.02
VL	.02	.01	.01

Σ = 1.00

Above Average Forecast

.02	.02	.04
.06	.06	.07
.11	.13	.13
.05	.08	.08
.02	.03	.03
.01	.02	.02
.005	.005	.01

Σ = 1.00

High Forecast

.06	.09	.08
.08	.13	.13
.05	.07	.07
.03	.06	.04
.01	.02	.02
.01	.01	.02
.005	.005	.01

Σ = 1.00

Very High Forecast

VH	.08	.13	.15
H	.06	.07	.10
AB	.05	.06	.07
A	.02	.05	.05
BA	.01	.01	.02
L	.01	.01	.01
VL	.005	.005	.01

Σ = 1.00

Sum Historical

.20	.285	.30
.29	.32	.34
.36	.42	.405
.36	.47	.40
.36	.39	.32
.37	.37	.25
.345	.245	.20

Forecast Frequency

11.3%	.029	.041	.043
13.7%	.042	.046	.049
16.9%	.051	.060	.058
17.8%	.054	.067	.057
15.3%	.051	.056	.046
14.2%	.053	.053	.036
11.3%	.049	.035	.029

Conditional Probabilities

Accuracy Level Two

Numerator
Very Low Forecast

	L	A	H
VH	.0001	.0003	.0002
H	.0005	.0004	.0002
AA	.0010	.0011	.0009
A	.0028	.0043	.0021
BH	.0033	.0030	.0016
L	.0060	.0036	.0018
VL	.0086	.0036	.0020

denom. = .0474

Conditional Probability

VH	.0021	.0063	.0042
H	.0105	.0084	.0042
AA	.0210	.0232	.0190
A	.0591	.0907	.0443
BA	.0696	.0633	.0338
L	.1266	.0759	.0380
VL	.1814	.0759	.0422

Σ = .9997

Numerator
Low Forecast

	L	A	H
VH	.0001	.0003	.0002
H	.0006	.0004	.0002
AA	.0015	.0018	.0012
A	.0028	.0043	.0021
BH	.0044	.0042	.0020
L	.0078	.0052	.0018
VL	.0059	.0024	.0008

denom. = .0500

Conditional Probability

VH	.0020	.0060	.0040
H	.0120	.0080	.0040
AA	.0300	.0360	.0240
A	.0560	.0860	.0420
BA	.0880	.0840	.0400
L	.1560	.1040	.0360
VL	.1180	.0480	.0160

Σ = 1.000

Numerator
Below Average Forecast

	L	A	H
VH	.0001	.0004	.0004
H	.0006	.0007	.0004
AA	.0015	.0021	.0012
A	.0056	.0076	.0042
BH	.0055	.0072	.0036
L	.0054	.0032	.0018
VL	.0022	.0006	.0004

denom. .0547

Conditional Probability

VH	.0018	.0073	.0073
H	.0110	.0128	.0073
AA	.0274	.0384	.0219
A	.1024	.1389	.0768
BA	.1005	.1316	.0658
L	.0987	.0585	.0329
VL	.0402	.0110	.0073

Σ = .9998

Numerator
Average Forecast

	L	A	H
VH	.0001	.0003	.0004
H	.0005	.0007	.0009
AA	.0035	.0064	.0036
A	.0070	.0140	.0077
BA	.0044	.0054	.0023
L	.0012	.0012	.0006
VL	.0011	.0003	.0002

denom = .0623

Conditional Probability

VH	.0016	.0048	.0064
H	.0080	.0112	.0144
AA	.0562	.1027	.0578
A	.1124	.2247	.1236
BA	.0706	.0867	.0449
L	.0193	.0193	.0096
VL	.0177	.0048	.0032

Σ = .9999

Numerator
Above Average Forecast

	L	A	H
VH	.0002	.0006	.0016
H	.0015	.0021	.0031
AA	.0055	.0092	.0078
A	.0035	.0086	.0056
BA	.0011	.0018	.0012
L	.0006	.0008	.0006
VL	.0003	.0002	.0002

denom. = .0561

Conditional Probability

VH	.0036	.0107	.0285
H	.0267	.0374	.0553
AA	.0980	.1640	.1390
A	.0624	.1533	.0998
BA	.0196	.0321	.0214
L	.0107	.0143	.0107
VL	.0053	.0036	.0036

Σ = .1000

Numerator
High Forecast

	L	A	H
VH	.0006	.0025	.0032
H	.0020	.0046	.0057
AA	.0025	.0050	.0042
A	.0021	.0065	.0028
BA	.0006	.0012	.0008
L	.0006	.0004	.0006
VL	.0003	.0002	.0002

denom. = .0466

Conditional Probability

VH	.0129	.0536	.0687
H	.0429	.0987	.1223
AA	.0536	.1073	.0901
A	.0451	.1395	.0601
BA	.0129	.0258	.0172
L	.0129	.0086	.0129
VL	.0064	.0043	.0043

Σ = 1.0001

Numerator
Very High Forecast

	L	A	H
VH	.0008	.0036	.0060
H	.0015	.0025	.0044
AA	.0025	.0043	.0054
A	.0014	.0054	.0035
BA	.0006	.0006	.0008
L	.0006	.0004	.0003
VL	.0003	.0002	.0002

denom. = .0453

Conditional Probability

VH	.0177	.0795	.1325
H	.0331	.0552	.0971
AA	.0552	.0949	.1192
A	.0309	.1192	.0773
BA	.0132	.0132	.0177
L	.0132	.0088	.0066
VL	.0066	.0044	.0044

Σ = .9999

Historical Accuracy
Level Three

Very Low Forecast

VH	.005	0	0
H	.01	.005	.005
AB	.02	.015	.005
A	.05	.04	.03
BA	.07	.06	.04
L	.11	.09	.05
VL	.18	.13	.085

$\Sigma = 1.00$

Low Forecast

.005	0	0
.01	.005	.005
.03	.025	.02
.05	.04	.04
.08	.07	.05
.16	.13	.07
.10	.06	.04

$\Sigma = 1.00$

Below Average Forecast

.01	.005	.005
.015	.01	.01
.03	.05	.02
.09	.08	.07
.12	.13	.09
.09	.06	.06
.025	.02	.01

$\Sigma = 1.00$

Average Forecast

VH	.01	.01	.01
H	.02	.02	.02
AB	.06	.09	.06
A	.11	.15	.12
BA	.07	.10	.07
L	.02	.02	.02
VL	.005	.01	.005

$\Sigma = 1.00$

ove Average Forecast

.02	.02	.03
.05	.05	.06
.12	.15	.13
.06	.10	.09
.03	.03	.02
.005	.01	.01
.005	.005	.005

$\Sigma = 1.00$

High Forecast

.04	.09	.08
.07	.17	.14
.05	.08	.07
.04	.05	.05
.01	.02	.02
.005	.005	.01
0	0	0

$\Sigma = 1.00$

Very High Forecast

VH	.06	.12	.18
H	.05	.08	.11
AB	.04	.06	.10
A	.03	.05	.06
BA	.01	.015	.02
L	0	.005	.01
VL	0	0	0

$\Sigma = 1.00$

Sum Historical

.150	.245	.305
.225	.340	.350
.350	.470	.405
.430	.510	.460
.390	.425	.310
.390	.320	.230
.325	.225	.145

$\Sigma = 7.00$

Forecast Frequency

10.0	.021	.035	.044
13.1	.032	.049	.050
17.5	.050	.067	.058
20.0	.061	.073	.066
16.1	.056	.061	.044
13.5	.056	.046	.033
9.9	.046	.032	.021

$\Sigma = 1.00$

Conditional Probabilities
Accuracy Level Three

Numerator
Very Low Forecast

	L	A	H
VH	.0001	0	0
H	.0003	.0002	.0002
AA	.0010	.0011	.0003
A	.0035	.0043	.0021
BA	.0039	.0036	.0016
L	.0066	.0036	.0015
VL	.0097	.0039	.0017

denom. = .0492

Numerator
Low Forecast

L	A	H
.0001	0	0
.0003	.0002	.0002
.0015	.0018	.0012
.0035	.0043	.0028
.0044	.0042	.0020
.0096	.0052	.0021
.0059	.0018	.0008

denom. = .0519

Numerator
Below Average Forecast

L	A	H
.0001	.0001	.0002
.0004	.0004	.0004
.0015	.0035	.0012
.0063	.0086	.0049
.0066	.0078	.0036
.0054	.0024	.0018
.0014	.0006	.0002

denom. = 0581

Conditional Probability

VH	.0020	0	0
H	.0061	.0041	.0041
AA	.0203	.0224	.0061
A	.0711	.0874	.0427
BA	0793	.0732	.0325
L	.1342	.0732	.0305
VL	.1972	.0793	.0346

Σ = 1.0003

Conditional Probability

.0019	0	0
.0058	.0049	.0049
.0289	.0347	.0231
.0674	.0829	.0539
.0848	.0809	.0385
.1850	.1002	.0405
.1137	.0347	.0154

Σ = 1.0021

Conditional Probability

.0017	.0017	.0034
.0069	.0069	.0069
.0258	.0620	.0207
.1084	.1480	.1019
.1136	.1343	.0620
.0929	.0413	.0310
.0241	.0103	.0034

Σ = 1.0073

Numerator
Average Forecast

	L	A	H
VH	.0001	.0003	.0004
H	.0005	.0007	.0009
AA	.0030	.0064	.0036
A	.0077	.0168	.0084
BA	.0039	.0060	.0028
L	.0012	.0008	.0006
VL	.0003	.0003	.0001

denom. = .0648

Numerator
Above Average Forecast

L	A	H
.0002	.0006	.0012
.0013	.0018	.0026
.0060	.0107	.0078
.0042	.0108	.0063
.0017	.0018	.0008
.0003	.0004	.0003
.0003	.0002	.0001

denom. = .0594

Numerator
High Forecast

L	A	H
.0004	.0025	.0032
.0018	.0060	.0062
.0025	.0057	.0042
.0028	.0054	.0035
.0006	.0012	.0008
.0003	.0002	.0003
0	0	0

denom. = .0476

Conditional Probability

VH	.0015	.0046	.0062
H	.0077	.0108	.0139
AA	.0463	.0988	.0556
A	.1188	.2593	.1296
BA	.0602	.0926	.0432
L	.0185	.0123	.0093
VL	.0046	.0046	.0015

Σ = .9999

Conditional Probability

.0034	.0101	.0202
.0219	.0303	.0438
.1010	.1801	.1313
.0707	.1818	.1061
.0286	.0303	.0135
.0051	.0067	.0051
.0051	.0034	.0017

Σ = 1.0002

Conditional Probability

.0084	.0525	.0672
.0378	.1261	.1303
.0525	.1197	.0882
.0588	.1134	.0735
.0126	.0252	.0168
.0063	.0042	.0063
0	0	0

Σ = .9998

Numerator
Very High Forecast

	L	A	H
VH	.0006	.0034	.0072
H	.0013	.0028	.0048
AA	.0020	.0043	.0060
A	.0021	.0054	.0042
BA	.0006	.0009	.0008
L	0	.0002	.0003
VL	0	0	0

denom. = .0469

Conditional Probability

VH	.0128	.0725	.1535
H	.0277	.0597	.1023
AA	.0426	.0917	.1279
A	.0448	.1151	.0896
BA	.0128	.0192	.0171
L	0	.0043	.0064
VL	0	0	0

Σ = 1.000

Conditional Probabilities

Accuracy Level Four

Numerator
Very Low Forecast

	L	A	H
VH	0	0	0
H	0	0	0
AA	.0005	0	0
A	.0035	.0032	.0007
BA	.0039	.0036	.0004
L	.0090	.0024	.0003
VL	.0178	.0048	.0002

denom. = .0503

Numerator
Low Forecast

	L	A	H
VH	0	0	0
H	0	0	0
AA	.0010	0	0
A	.0035	.0022	.0007
BA	.0083	.0048	.0004
L	.0180	.0060	.0003
VL	.0070	.0021	0

denom. = .0543

Numerator
Below Average Forecast

	L	A	H
VH	0	0	0
H	0	0	0
AA	.0010	.0021	.0012
A	.0042	.0140	.0035
BA	.0050	.0180	.0028
L	.0030	.0052	.0009
VL	.0005	.0003	0

denom. = .0617

Conditional Probability

VH	0	0	0
H	0	0	0
AA	.0099	0	0
A	.0696	.0636	.0139
BA	.0775	.0716	.0080
L	.1789	.0477	.0060
VL	.3539	.0954	.0040

Σ=1.00

Conditional Probability

VH	0	0	0
H	0	0	0
AA	.0184	0	0
A	.0645	.0405	.0129
BA	.1529	.0884	.0074
L	.3315	.1105	.0055
VL	.1289	.0387	0

Σ = 1.0001

Conditional Probability

VH	0	0	0
H	0	0	0
AA	.0162	.0340	.0194
A	.0681	.2269	.0567
BA	.0810	.2917	.0454
L	.0486	.0843	.0146
VL	.0081	.0049	0

Σ = .9999

Numerator
Average Forecast

	L	A	H
VH	0	0	0
H	0	0	0
AA	.0015	.0078	.0024
A	.0105	.0367	.0112
BA	.0017	.0066	.0012
L	0	0	0
VL	0	0	0

denom. = .0796

Numerator
Above Average Forecast

	L	A	H
VH	0	.0006	.0004
H	.0008	.0028	.0018
AA	.0065	.0227	.0084
A	.0035	.0108	.0042
BA	0	0	.0008
L	0	0	0
VL	0	0	0

denom. = .0633

Numerator
High Forecast

	L	A	H
VH	0	.0022	.0020
H	.0008	.0105	.0066
AA	.0015	.0064	.0072
A	.0021	.0054	.0035
BA	0	0	.0008
L	0	0	0
VL	0	0	0

denom. = .0490

Conditional Probability

VH	0	0	0
H	0	0	0
AA	.0188	.0980	.0302
A	.1319	.4611	.1407
BA	.0214	.0829	.0151
L	0	0	0
VL	0	0	0

Σ =1.0001

Conditional Probability

VH	0	.0095	.0063
H	.0126	.0442	.0284
AA	.1027	.3586	.1327
A	.0553	.1706	.0664
BA	0	0	.0126
L	0	0	0
VL	0	0	0

Σ =.9999

Conditional Probability

VH	0	.0449	.0408
H	.0163	.2143	.1347
AA	.0306	.1306	.1469
A	.0429	.1102	.0714
BA	0	0	.0163
L	0	0	0
VL	0	0	0

Σ = .9999

Numerator
Very High Forecast

	L	A	H
VH	.0003	.0039	.0128
H	.0005	.0032	.0053
AV	.0005	.0036	.0042
A	.0007	.0054	.0049
BA	0	0	.0008
L	0	0	0
VL	0	0	0

denom. = .0461

Conditional Probability

VH	.0065	.0846	.2777
H	.0108	.0694	.1150
AV	.0108	.0781	.0911
A	.0152	.1171	.1063
BA	0	0	.0174
L	0	0	0
VL	0	0	0

Σ = 1.000

The individual matrices show the twenty-one possible combinations of reservoir and surface supply for each forecast.

FOOTNOTES

[1] State College of Washington, Department of Agricultural Economics, Washington Agricultural Experiment Stations, Institute of Agricultural Sciences, and U. S. Bureau of Reclamation, Land and Settlements Division, Columbia Basin Project Co-operating, Estimated Cash Costs and Man Labor Requirements for the Production of Principal Crops, Columbia Basin Project, Washington, by P. M. McKains, E. R. Franklin, and J. E. Jensen, Stations Circular 272 (Pullman and Ephrata, Wash., June, 1955).

[2] Colorado State University Experiment Station, U. S., Department of Agriculture, Agricultural Research Service, Farm Economics Research Division Co-operating, Marginal Values of Irrigation Water: A Linear Programming Analysis of Farm Adjustments to Changes in Water Supply, by Loyal M. Hartman and Norman Whittelsey, Technical Bulletin No. 70 (Fort Collins, Colo., 1970).

[3] Letter from Ronald E. Moreland, Assistant Snow Survey Supervisor, Soil Conservation Service, Fort Collins, Colo., April 16, 1970.

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[5] Day, Economic Analysis: Recursive Programming and Production Response.

[6] Colorado State University Experiment Station, Marginal Values of Irrigation Water.

[7] Ibid., p. 10.

[8] Ibid., p. 16.

[9] Ibid., p. 21.

[10] Raymond L. Anderson, "A Simulation Program to Establish Optimum Crop Patterns on Irrigated Farms Based on Preseason Estimates of Water Supply," *American Journal of Agricultural Economics*, L (December, 1968), 1586-1590.

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[13] Israelsen and Hansen, *Irrigation, Principles and Practices* pp. 235-55.

[14] University of Idaho Agricultural Experiment Station, *Consumptive Irrigation Requirements for Crops in Idaho*, p. 1.

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[17] University of Idaho Agricultural Experiment Station, *Consumptive Irrigation Requirements*, p. 3.

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[20] Colorado State University Experiment Station, *Marginal Values of Irrigation Water*.

[21] Israelsen and Hansen, *Irrigation Principles and Practices*, p. 289.

[22] W. W. Wheeler and Associates and Woodward-Clyde & Associates, Consulting Engineers, "Water Legislation Investigations for the Arkansas River Basin in Colorado, Volume II, Comprehensive Report (Denver, Colo., 1968), p. 20.

[23] University of Idaho Agricultural Experiment Station, *Consumptive Irrigation Requirements*, p. 9.

[24] Letter from Earl F. Phipps, Assistant Manager, Northern Colorado Water Conservancy District, Loveland, Colo., March 8, 1971.

[25] Morlan W. Nelson, "Effects of Water Supply Forecasts on Conservation and Economic Use of Water," p. 76.

[26] Jack Hirschleifer, James C. DeHaven, and Jerome W. Milliman, *Water Supply* (Chicago and London: The University of Chicago Press, 1960), p. 186.

[27] California, Department of Water Resources, *Coordinated State Wide Planning Water Demand Study*, *Economic Demand for Imported Water*, Study Area 2, 1967, p. 7.

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[30] George O. G. Luf and Clayton H. Hardison, "Storage Requirements for Water in the United States," *Water Resources Research*, II, No. 3 (1966), 323-354.

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[34] *Ibid.*, p. 8.

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APPENDIX IV

SELECTED COMPUTER OUTPUT

The copy of computer output on the following pages shows the model results for the forecast of an average water supply at accuracy level two. The example shows the level of water utilization in the more adverse states of nature as well as the expected value, crop acreages planted, and the allocation of water to crops in the first two states of nature. Meaning of the variables is discussed below:

1) RA8, RB8, RC8, RD8, and RE8 represent surface water supplies in states of nature A through E.

2) RA9, RB9, RC9, RD9, and RE9 represent reservoir supplies in the respective states of nature.

3) RA10, RB10, RC10, RD10, and RE10 represent well water supplies in the respective states of nature.

4) OBJ in row one is the value of the objective function for the given forecast.

The other rows are internal structures for the linear programming model necessary to assure that the acreage planted in the optimization process is binding in each of the twenty-one (A to U) states of nature. The "Activity" level shows the proportion of the available supply that is utilized in each state of nature. In the example below, all of each source is utilized, since states of nature A through E represent severe shortage. It was not possible to include very much of the model output for the given forecast, but for more abundant states of nature, well water is left partially, and in some cases completely, unutilized. Reservoir water also goes partially unused for the more abundant states of nature.

X_1 = Acreage of Alfalfa

X_2 = " " Beans

X_3 = " " Corn

X_4 = " " Onions

X_5 = " " Potatoes

X_6 = Acreage of Sugar Beets
X_7 = " " Barley

XA11 to XC14 represent the distribution of the available water supply in states of nature A, B, and C to the seven crops at various levels of per acre water application. The letter represents the state of nature; the first digit represents the crop as listed above; and the second digit indicates the source of water and level of application as follows below:

1) 1 to 3 are successively smaller per acre surface water applications.

2) 4 is inadequate surface water application resulting in crop failure.

3) 5 to 7 are successively smaller per acre reservoir water applications, where the quantities correspond to those from surface sources. Both surface and reservoir applications are calculated on the assumption of 50 per cent irrigation efficiency.

4) 8 to 10 are successively smaller per acre well water applications, where the quantities are calculated on the assumption of 70 per cent efficiency in application.

As can be seen from the output for an average forecast at accuracy level two, in state of nature A, all lower value crops planted are abandoned (alfalfa, beans, corn, barley); onions are watered from reservoir and well water sources at the highest yield level; potatoes are watered from well water at the intermediate yield level; sugar beets are watered partially from surface and reservoir sources at the highest yield level and partially abandoned. In state of nature B, alfalfa, beans, and barley are abandoned; corn is mostly abandoned, except for a small acreage watered from well water at the intermediate yield level; onions are watered with surface and reservoir water at the highest yield levels; potatoes are watered entirely from well water at the intermediate yield level; and sugar beets are watered from surface and reservoir sources at the highest yield levels.

The various combinations of yield level, water source, and abandonment observed in the twenty-one states of nature for the sixty runs of the model undertaken are too varied to describe here. The model does provide a rich and interesting picture of the production flexibility inherent in situations where there is substitution between inputs and the output varies over a specified range in relation to the level of the input.

```
SECTION 1 - ROWS

NUMBER  ...ROW..  AT  ...ACTIVITY...  SLACK ACTIVITY  ..LOWER LIMIT.  ..UPPER LIMIT.  .DUAL ACTIVITY

    1   OBJ       BS  1126824.82917   1126824.82917-       NONE            NONE          1.00000
    2   RA1       EQ        .               .                .               .            .40368
    3   RA2       EQ        .               .                .               .            .47554
    4   RA3       EQ        .               .                .               .            .52847
    5   RA4       EQ        .               .                .               .           1.42384-
    6   RA5       EQ        .               .                .               .            .31537-
    7   RA6       EQ        .               .                .               .            .68724
    8   RA7       EQ        .               .                .               .            .40368
    9   RA8       UL    14000.00000         .              NONE        14000.00000        .60743-
   10   RA9       UL     8000.00000         .              NONE         8000.00000        .57113-
   11   RA10      UL    10000.00000         .              NONE        10000.00000        .74101-
   12   RB1       EQ        .               .                .               .            .08740
   13   RB2       EQ        .               .                .               .            .10689
   14   RB3       EQ        .               .                .               .            .12124
   15   RB4       EQ        .               .                .               .            .56607-
   16   RB5       EQ        .               .                .               .            .20391-
   17   RB6       EQ        .               .                .               .            .00643
   18   RB7       EQ        .               .                .               .            .08740
   19   RB8       UL    14000.00000         .              NONE        14000.00000        .13078-
   20   RB9       UL    14000.00000         .              NONE        14000.00000        .12093-
   21   RB10      UL    10000.00000         .              NONE        10000.00000        .15360-
   22   RC1       EQ        .               .                .               .            .05799
   23   RC2       EQ        .               .                .               .            .07099
   24   RC3       EQ        .               .                .               .            .08055
   25   RC4       EQ        .               .                .               .            .37962-
   26   RC5       EQ        .               .                .               .            .13628-
   27   RC6       EQ        .               .                .               .            .00204
   28   RC7       EQ        .               .                .               .            .05799
   29   RC8       UL    14000.00000         .              NONE        14000.00000        .08676-
   30   RC9       UL    20000.00000         .              NONE        20000.00000        .08020-
   31   RC10      UL    10000.00000         .              NONE        10000.00000        .10226-
   32   RD1       EQ        .               .                .               .            .34978
   33   RD2       EQ        .               .                .               .            .42814
   34   RD3       EQ        .               .                .               .            .48585
   35   RD4       EQ        .               .                .               .           2.28959-
   36   RD5       EQ        .               .                .               .            .82195-
   37   RD6       EQ        .               .                .               .            .01231
   38   RD7       EQ        .               .                .               .            .34978
   39   RD8       UL    24500.00000         .              NONE        24500.00000        .52328-
   40   RD9       UL     8000.00000         .              NONE         8000.00000        .48369-
   41   RD10      UL    10000.00000         .              NONE        10000.00000        .61676-
   42   RE1       EQ        .               .                .               .            .32321
   43   RE2       EQ        .               .                .               .            .40156
   44   RE3       EQ        .               .                .               .            .37137
   45   RE4       EQ        .               .                .               .           2.50629-
   46   RE5       EQ        .               .                .               .            .96505-
   47   RE6       EQ        .               .                .               .            .20438-
   48   RE7       EQ        .               .                .               .            .32321
   49   RE8       UL    24500.00000         .              NONE        24500.00000        .48239-
```

```
SECTION 2 - COLUMNS

NUMBER  .COLUMN. AT   ...ACTIVITY...  ..INPUT COST..  ..LOWER LIMIT.  ..UPPER LIMIT.  .REDUCED COST.

   213  X1       BS     3689.87750        8.54000-     2940.00000      7770.00000          .
   214  X2       LL     1050.00000       25.68000-     1050.00000      4200.00000         1.06729-
   215  X3       UL     5250.00000       20.90000-     2100.00000      5250.00000         5.92228
   216  X4       UL     1680.00000       38.58000-         .           1680.00000       165.56946
   217  X5       UL     2100.00000       84.92000-         .           2100.00000        23.30538
   218  X6       UL     3150.00000       35.40000-         .           3150.00000        49.49147
   219  X7       LL     1680.00000       22.88000-     1680.00000      3150.00000         7.88853-
   220  XA11     LL         .              .89951          .                 NONE         1.55174-
   221  XA12     LL         .              .68340          .                 NONE          .91745-
   222  XA13     LL         .              .41188          .                 NONE          .58154-
   223  XA14     BS     3689.87750         .00885-         .                 NONE          .
   224  XA15     LL         .              .72889          .                 NONE         1.55175-
   225  XA16     LL         .              .56357          .                 NONE          .91748-
   226  XA17     LL         .              .32833          .                 NONE          .58159-
   227  XA18     LL         .              .54905          .                 NONE         1.49260-
   228  XA19     LL         .              .42852          .                 NONE          .94622-
   229  XA110    LL         .              .23134          .                 NONE          .62470-
   230  XA21     LL         .             1.21263          .                 NONE          .86305-
   231  XA22     LL         .              .99828          .                 NONE          .77368-
   232  XA23     LL         .              .72464          .                 NONE          .62212-
   233  XA24     BS     1050.00000         .08071-         .                 NONE          .
   234  XA25     LL         .             1.06023          .                 NONE          .86298-
   235  XA26     LL         .              .86394          .                 NONE          .77371-
   236  XA27     LL         .              .61684          .                 NONE          .62101-
   237  XA28     LL         .              .89403          .                 NONE          .85346-
   238  XA29     LL         .              .72216          .                 NONE          .72892-
   239  XA210    LL         .              .50162          .                 NONE          .57896-
   240  XA31     LL         .             1.10820          .                 NONE          .36787-
   241  XA32     LL         .              .89810          .                 NONE          .27425-
   242  XA33     LL         .              .53967          .                 NONE          .32896-
   243  XA34     BS     5250.00000         .13363-         .                 NONE          .
   244  XA35     LL         .              .98837          .                 NONE          .36790-
   245  XA36     LL         .              .79650          .                 NONE          .27420-
   246  XA37     LL         .              .45613          .                 NONE          .32901-
   247  XA38     LL         .              .85332          .                 NONE          .39664-
   248  XA39     LL         .              .68570          .                 NONE          .26785-
   249  XA310    LL         .              .35913          .                 NONE          .37212-
   250  XA41     LL         .             4.64324          .                 NONE          .00000-
   251  XA42     LL         .             3.85453          .                 NONE          .48500-
   252  XA43     LL         .             3.09254          .                 NONE          .94326-
   253  XA44     LL         .             1.69424-         .                 NONE         3.51292-
   254  XA45     BS      430.00000        4.45084          .                 NONE          .
   255  XA46     LL         .             3.63036          .                 NONE          .48492-
   256  XA47     LL         .             2.93643          .                 NONE          .94328-
   257  XA48     BS     1250.00000        4.23968          .                 NONE          .
   258  XA49     LL         .             3.48283          .                 NONE          .53455-
   259  XA410    LL         .             2.76332          .                 NONE          .95765-
   260  XA51     LL         .             2.74491          .                 NONE          .18242-
   261  XA52     LL         .             2.43339          .                 NONE          .00799-
```

```
NUMBER  .COLUMN.  AT  ...ACTIVITY...  ..INPUT COST..  ..LOWER LIMIT.  ..UPPER LIMIT.  .REDUCED COST.

   262  XA53      LL        .              1.87885          .              NONE           .31956-
   263  XA54      LL        .               .25966-         .              NONE           .96986-
   264  XA55      LL        .              2.58880          .              NONE           .18244-
   265  XA56      LL        .              2.30631          .              NONE           .00802-
   266  XA57      LL        .              1.76628          .              NONE           .31960-
   267  XA58      LL        .              2.41569          .              NONE           .19681-
   268  XA59      BS    2100.0C000         2.16789          .              NONE           .
   269  XA510     LL        .              1.64521          .              NONE           .30038-
   270  XA61      BS    1090.04553         2.53216          .              NONE           .
   271  XA62      LL        .              2.16329          .              NONE           .06515-
   272  XA63      LL        .              1.59530          .              NONE           .32943-
   273  XA64      BS     980.52051          .29240-         .              NONE           .
   274  XA65      BS    1079.43356         2.33976          .              NONE           .
   275  XA66      LL        .              1.98912          .              NONE           .06507-
   276  XA67      LL        .              1.43919          .              NONE           .32944-
   277  XA68      LL        .              2.12860          .              NONE           .
   278  XA69      LL        .              1.79159          .              NONE           .11471-
   279  XA610     LL        .              1.26608          .              NONE           .34381-
   280  XA71      LL        .               .75154          .              NONE           .48485-
   281  XA72      LL        .               .63260          .              NONE           .30007-
   282  XA73      LL        .               .46268          .              NONE           .22702-
   283  XA74      BS    1680.00000          .00885-         .              NONE           .
   284  XA75      LL        .               .65348          .              NONE           .48489-
   285  XA76      LL        .               .55277          .              NONE           .30004-
   286  XA77      LL        .               .39736          .              NONE           .22699-
   287  XA78      LL        .               .54976          .              NONE           .45447-
   288  XA79      LL        .               .47330          .              NONE           .23453-
   289  XA710     LL        .               .32462          .              NONE           .23501-
   290  XB11      LL        .               .24394          .              NONE           .28331-
   291  XB12      LL        .               .18533          .              NONE           .15883-
   292  XB13      LL        .               .11170          .              NONE           .10168-
   293  XB14      BS    3689.87750          .00240-         .              NONE           .
   294  XB15      LL        .               .19766          .              NONE           .28331-
   295  XB16      LL        .               .15283          .              NONE           .15884-
   296  XB17      LL        .               .08904          .              NONE           .10170-
   297  XB18      LL        .               .14890          .              NONE           .27057-
   298  XB19      LL        .               .11621          .              NONE           .16502-
   299  XB110     LL        .               .06274          .              NONE           .11098-
   300  XB21      LL        .               .32885          .              NONE           .11352-
   301  XB22      LL        .               .27072          .              NONE           .10626-
   302  XB23      LL        .               .19651          .              NONE           .08892-
   303  XB24      BS    1050.00000          .02189-         .              NONE           .
   304  XB25      LL        .               .28752          .              NONE           .11350-
   305  XB26      LL        .               .23429          .              NONE           .10627-
   306  XB27      LL        .               .16728          .              NONE           .08862-
   307  XB28      LL        .               .24245          .              NONE           .11145-
   308  XB29      LL        .               .19584          .              NONE           .09662-
   309  XB210     LL        .               .13603          .              NONE           .07963-
   310  XB31      LL        .               .30053          .              NONE           .00979-
   311  XB32      LL        .               .24355          .              NONE           .00138-
   312  XB33      LL        .               .14635          .              NONE           .03319-
```

```
NUMBER  .COLUMN.  AT  ...ACTIVITY...  ..INPUT COST..  ..LOWER LIMIT.  ..UPPER LIMIT.  .REDUCED COST.

   313  XB34      BS    4576.66635       .03624-            .              NONE             .
   314  XB35      LL        .            .26803             .              NONE          .00980-
   315  XB36      LL        .            .21600             .              NONE          .00136-
   316  XB37      LL        .            .12370             .              NONE          .03320-
   317  XB38      LL        .            .23141             .              NONE          .01598-
   318  XB39      BS     673.33365       .18595             .              NONE             .
   319  XB310     LL        .            .09739             .              NONE          .04248-
   320  XB41      BS     784.38613      1.25918             .              NONE             .
   321  XB42      LL        .           1.04530             .              NONE          .14850-
   322  XB43      LL        .            .83866             .              NONE          .28975-
   323  XB44      LL        .            .45946-            .              NONE         1.11053-
A  324  XB45      LL        .           1.20701             .              NONE             .
   325  XB46      LL        .            .99806             .              NONE          .14848-
   326  XB47      LL        .            .79632             .              NONE          .28976-
   327  XB48      BS     895.61387      1.14974             .              NONE             .
   328  XB49      LL        .            .94450             .              NONE          .15917-
   329  XB410     LL        .            .74938             .              NONE          .29285-
   330  XB51      LL        .            .74438             .              NONE          .02186-
   331  XB52      LL        .            .65990             .              NONE          .00172-
   332  XB53      LL        .            .50952             .              NONE          .09979-
   333  XB54      LL        .            .07042-            .              NONE          .35933-
   334  XB55      LL        .            .70205             .              NONE          .02187-
   335  XB56      LL        .            .62544             .              NONE          .00173-
   336  XB57      LL        .            .47899             .              NONE          .09980-
   337  XB58      LL        .            .65510             .              NONE          .02496-
   338  XB59      BS    2100.00000       .58790             .              NONE             .
   339  XB510     LL        .            .44616             .              NONE          .09566-
   340  XB61      BS     508.49057       .68669             .              NONE             .
   341  XB62      LL        .            .58666             .              NONE          .03464-
   342  XB63      LL        .            .43262             .              NONE          .12329-
   343  XB64      LL        .            .07930-            .              NONE          .15788-
   344  XB65      BS    2641.50943       .63451             .              NONE             .
   345  XB66      LL        .            .53942             .              NONE          .03462-
   346  XB67      LL        .            .39029             .              NONE          .12329-
A  347  XB68      LL        .            .57725             .              NONE             .
   348  XB69      LL        .            .48586             .              NONE          .04531-
   349  XB610     LL        .            .34334             .              NONE          .12639-
   350  XB71      LL        .            .20381             .              NONE          .06188-
   351  XB72      LL        .            .17155             .              NONE          .02875-
   352  XB73      LL        .            .12547             .              NONE          .02252-
   353  XB74      BS    1680.00000       .00240-            .              NONE             .
   354  XB75      LL        .            .17722             .              NONE          .06189-
   355  XB76      LL        .            .14990             .              NONE          .02874-
   356  XB77      LL        .            .10776             .              NONE          .02251-
   357  XB78      LL        .            .14909             .              NONE          .05534-
   358  XB79      LL        .            .12835             .              NONE          .01464-
   359  XB710     LL        .            .08803             .              NONE          .02424-
   360  XC11      LL        .            .16262             .              NONE          .18716-
   361  XC12      LL        .            .12355             .              NONE          .10477-
   362  XC13      LL        .            .07446             .              NONE          .06709-
   363  XC14      BS    3689.87750       .00160-            .              NONE             .
```

SECTION III

EFFECTS ON MULTI-PURPOSE RESERVOIR OPERATIONS

CHAPTER XII

INTRODUCTION

Multiple purpose water reservoirs are operated on the basis of forecasts of future hydrologic events. In the case of reservoirs in basins where the major portion of the water supply comes from melting snow pack, the hydrologic events are the accumulation of the snow and the rate of melt from the accumulated snow pack. The forecasts of these events are based on historic samples from various locations in the river basin. Deviation from the historic pattern and occurrences at non-sample points could cause errors in the forecasts which in turn could result in improper operating decisions by the reservoir operation staff causing economic losses and inefficiencies.

Various agencies throughout the western United States and Canada are working to improve the streamflow and water supply forecasts. In the U.S. these include the Corps of Engineers, the Soil Conservation Survey, the United States Weather Bureau, the Forest Service and the California Department of Water Resources. The main thrusts of this research are in the area of long range weather forecasting, increasing the areas surveyed through remote sensing apparatus and increasing the frequency of reporting through automatic telemetry which reports on a daily basis. The first two areas mentioned above are primarily designed to aid in forecasting the seasonal water supply while the last is designed to improve the day-to-day streamflow forecasts.

The study reported in this section investigates the causal relationship between errors in streamflow and water supply forecasts and any resulting inefficient reservoir operation. To estimate the economic benefit of avoiding these inefficiencies through improvements in streamflow forecasting, a computer simulation model is developed. This model generates erroneous forecasts about forthcoming hydrologic events and then operates the reservoir in question on the basis of these forecasts. Following Congressionally imposed guidelines, the reservoir operation model developed here accepts the requirements that minimization of flood losses represents the overriding objective of the reservoir operation.

Within this constraint, losses to conservation users are minimized. The Palisades-Jackson Reservoir complex on the Snake River in Wyoming and Idaho is used to test the estimation methodology.

Chapter XIII below presents an analysis of the economic costs involved in the operation of a multiple purpose reservoir. The analogy is drawn between a reservoir and a warehouse and the potential opportunity costs of satisfying one demand as opposed to another are discussed. Chapter XIV traces the path between an error in forecasting and inefficient reservoir operation. The conditional probabilities of inefficient operation are discussed and the critical state of the system for inefficient operation is defined. This chapter sets the groundwork for the simulation model by defining the conditions under which a loss constitutes inefficient operation due to forecast errors and the conditions under which the loss is simply not within the reservoir's range of protection.

Chapter XV begins the case study of the Upper Snake River Basin. A summary of the hydrologic, geographic and economic conditions of the basin as reported by other workers is presented. This chapter also presents a quite lengthy analysis of the water right institutions in the basin. This discussion is drawn from the records of the Idaho Water District No. 36 and interviews with various people in the District. The effects of these water right institutions on the possibility of benefits from improved forecasts is also discussed.

Chapter XVI introduces the simulation model used for benefit estimation and discusses the results of the simulations. The results of Paired-Comparison T-tests on the samples of output generated by the simulator are then presented. Based on these results, economic benefits are estimated in cases for which significant differences were noted. Chapter XVII presents conclusions on the validity of the results shown in Chapter XVI and makes recommendations concerning the need for future analysis.

Appendix I explains the basic tool of reservoir operation - the Flood Control Reservation Diagram. It is this diagram that allows the operator to determine whether or not he should make releases from the reservoir to create additional vacant flood control storage space. The second appendix, Appendix II is designed for the computer programmer or other specialist who is interested in the detail of the reservoir operations simulation model developed below. This appendix includes a verbal description of the model, flow charts illustrating the model and a Fortran Statement listing.

CHAPTER XIII

THE RESERVOIR AS A WAREHOUSE

The reservoirs of the Western United States act as warehouses to store non-certain supplies of water to fulfill known demands for the water. Such storage is necessary because supply and demand are generally out of phase both with respect to timing and quantity. The major source of water supply is the winter snow pack which accumulates in the Cordillera. This serves all of the areas East of the Coast Range both in the North and the South and also the Coastal Plain in the South.

Operating decisions in warehouse models are basically inventory decisions of how much of a commodity ought to be stocked to avoid a loss. The usual simple inventory model presupposes a fairly certain flow or supply of the commodity stored and a pattern of uncertain demands. By contrast, in a reservoir model, the demands for the output of the warehouse are generally well known both as to quantity demanded and the timing of the demand, but the supply is known only in terms of conditional forecasts. When we make operating decisions on the basis of these forecasts and criteria discussed below, we are operating under risk (we have some knowledge of the probability distribution of the occurrence of the events) as opposed to uncertainty where we would have no knowledge, or under certainty where the probability of the forecasted event's occurrence is one. (Unfortunately the term "uncertainty" is often used in the literature in situations where "risk" would be more appropriate. We will do so below but the connotation is decisions under risk.)

Multiple purpose reservoirs may be considered warehouses storing a homogeneous product measured in terms of acre-feet of water. Water quality differentiations will be ignored since they are not central to the purpose of this study. Demands for water by the various users in the water service area result in flows out of the warehouse. Assume that demands come from a pulp mill (for process and cooling water), a powerhouse (energy generation), and an irrigation project. Each of these users demands a specific flow in units of acre-feet per time period while the power generation demand also involves a certain head of water behind the dam.[1] The other users of the reservoir "storehouse" are recreation and flood control. Recreation users are interested in a narrow range of the stock of water held in the project since this will determine the quantity and quality of recreation supplied. Flood control agencies are interested in the negative stock, i.e., the quantity of vacant flood control space available to control a potential flood. This is the opposite of the flow demands mentioned above. The users previously discussed are interested in a large stock of water to provide a flow to meet their demands, whereas flood control is interested in a negative stock to absorb an expected inflow.

These various uses are complementary or competitive depending on their relative use patterns over time. For instance, if the required draw-down of the head to provide additional flood control capacity coincided with a peak period in the demand for hydro-electric production, then the two uses could be partially or wholly complementary. If, however, the draw-down for flood control corresponded with a low load period in power production to be followed by a peak load period during which time the power head would be lower than desirable, then the uses would be competitive. If flood control potential and hydro-electric production are competitive, the rules for economic efficiency would require that the trade-off between flood control and hydro-electric production be carried to the margin. In this case the criterion for efficiency would be the equation of the expected opportunity cost of not having an extra foot of flood control (i.e., the benefit of flood protection is the diminution of the potential flood losses) and the expected opportunity cost of the power or energy lost through drawing down the head an extra foot.

If the flood control and power production are complementary, then there are three alternatives to consider. First assume, that by coincidence, the amount of draw-down required for flood protection is precisely equal to the amount required to meet the peak load requirements of the power plant and that their timing is coincident. In evaluating the benefit of flood draw-down, we again use the value of the potential flood damage prevented by drawing down the extra portion. Since an equivalent draw-down of the head was necessary for power production, however, there will be no marginal (opportunity) cost for the extra flood protection in terms of power foregone.

Secondly, consider the case where the flood draw-down is smaller both in terms of total quantity and rate of discharge than the power draw-down. In this case the benefits would be the sum of the two types of benefits over the coincident range, plus the benefits from the remaining portion of the flood control draw-down. However, a portion of the flood benefit could only be provided by removing a portion of the future energy production which may not be replaced if the flood does not occur. There is thus an expected opportunity cost (marginal cost) of the flood control which can be measured by the net cost of supplying energy from the next best alternative source. From the standpoint of economic efficiency flood draw-down should not be carried further than the point where its expected marginal benefits are equal to these alternative power production costs.

Flow users will be competitively interested in the stock of water if the combined sum of the flow demands is greater than the inflow volume at any given time during the year. Any user whose demand schedule and use pattern is not coincidental with any other particular use pattern will be considered a competitive user. This would apply whether the demands and flows of water over the year were constant or whether they both followed cyclical annual variations. In the event that the supply and demand cycles were 180 degrees out of phase, then any draw-down of the reservoir while the supply cycle is at peak and which could not be replaced before the demand for outflow exceeds the inflow would be competitive with respect to demands which will occur while the supply cycle is at the trough and the demand cycle is at the peak. Thus benefits derived from the draw-down during the flood would have to be weighed against opportunity costs of foregone uses during the low flow period.

Traditional economic theory would say that the optimal operation of these reservoirs would maximize the sum of the net expected benefits of the users. In fact numerous dynamic programming models for this purpose are discussed in the literature.[2] These models however are generally incapable of incorporating the insitutional, social and political constraints that in fact exist and constrain the operation of the reservoir.

The existence of these constraints means that in general the reservoirs are not operated in a manner which equates the expected benefits and costs at the margin. In the western snowmelt area, flood control is generally considered paramount in multiple purpose operation. The releases to be made in the face of various inflow forecasts are to a large extent fixed by Congressional action at the time the money is appropriated for the reservoir.[3] A Corps of Engineers publication states:

> The regulation schedule for the conservation phase usually consists of a rule or guide curve indicating elevations which may not be exceeded at any particular time except for the purpose of storing flood waters.... Flood control regulations are normally the same in multiple purpose reservoirs as for separate flood control projects.[4]

The operation of the reservoirs within these constraints does consider the needs of the various users in the service area however. The various groups are usually keen observers of the forecasts, the storage and the releases and are vocal in demanding that their interests are served. Residents of the areas flooded by releases in excess of channel capacity demand that precautionary releases greater than necessary for conservation uses are made whenever the forecasts and the storage approach a critical state. The irrigators and other water supply demanders on the other hand are equally vocal in demanding that flood control space evacuation releases be delayed until the last possible moment. This would permit the discovery of a larger proportion of forecasting errors which might cause water to be "wasted" down the channel, but would increase the risk of flooding if the forecast had underestimated the size of the flood. Our observations of the operations procedures in Idaho and California indicate that Reservoir Regulation Sections of both the Corps of Engineers and the Bureau of Reclamation take the desires of these vocal constituencies very seriously. Because of this lobbying, the discretionary operations are designed to minimize the weighted sum of the complaints from the various groups. As a consequence, the operation of the reservoirs will only be coincidentally "efficient" as defined in the theoretical discussion above. However, it might be argued that in terms of overall social utility such a complaint-oriented mode of operation may best reflect the needs and desires of the people in the water service area.

Throughout this paper, the operation of a reservoir will be said to have been inefficient if the sum of the losses incurred by all users is greater than those incurred under the assumption of perfect stream flow forecasts. The terms efficient or optimal operation will indicate operation in which the sum of the losses is minimized. It will be assumed that the reservoirs are operated "rationally," i.e., to minimize losses according to the information available at the time of the decision.

FOOTNOTES

[1] Because of the well established relationship between the "head" of water behind a dam and the volume of water in a reservoir, releases will be discussed in terms of feet of head or acre-feet of water interchangeably.

[2] Reuven Amir, Optimal Operation of a Multi-Reservoir Water Supply System, Report EEP-24, Stanford University Program in Engineering-Economic Planning, (Stanford, California: 1967); Gary N. Dietrich and Daniel P. Loucks, "A Stochastic Model for Operating a Multipurpose Reservoir," Proceedings of the Third Annual American Water Resources Conference, The American Water Resources Association, (Urbana, Illinois: 1967), p. 92; Harold A. Thomas Jr. and Peter Watermeyer, "Mathematical Models: Stochastic Sequential Approach" in Design of Water Resource Systems edited by Arthur Maass et al., (Cambridge, Mass: Harvard University Press, 1962), Ch. 14.

[3] The flood control regulations specify the maximum rate at which flood control space may be vacated. As specified in the Flood Control Act of 1944 preliminary operation regulations are included in planning documents presented to Congress for approval. (Flood Control Act Statutes at Large vol. LVIII (1946)).

[4] U.S., Dept. of the Army, Corps of Engineers, Reservoir Regulation, E.M. 1110-2-3600, (Washington, D.C.: Government Printing Office, 1959), p. 11.

CHAPTER XIV

FORECAST ERRORS AND INEFFICIENT RESERVOIR OPERATION

The Mechanism By Which Forecast Errors Cause Losses

As discussed above, multipurpose reservoirs are operated on the basis of streamflow forecasts. An error in streamflow forecasts, however, will not necessarily cause inefficient reservoir operation as the discussion below indicates.

It has been shown in the preceeding chapter that flood control users demand the availability of sufficient vacant storage space to reduce excessive inflows. The inflow is transformed into increments in storage and a release rate from the reservoir which either does not exceed the channel capacity at the critical location downstream or is at least less then the inflow rate. The sum of the reservoir filling rate and the release rate must of course equal the inflow rate.

The variables for the flood control stock decision are the flood control rule curve and the streamflow forecast. (See Appendix I for a discussion of the rule curves and the Flood Control Reservation Diagram.) If the relationship between the rule curve and the forecasted inflow indicates that insufficient flood control space is available to fill the demand presented by a projected inflow (in reservoir operations jargon, the flood control reservation is "encroached"), the storage will be reduced by making releases in excess of the inflow. If the relationship between the storage, the rule curve and the forecasted inflow are such that control could be maintained or flood control encroachment overcome only by a release exceeding channel capacity, then under certain conditions to be discussed below in the Snake River case study a controlled innundation at the point of channel capacity would be permitted. If the forecasts were in error and the purposeful exceedence of channel capacity were subsequently found to be unnecessary, then a loss would have occurred which could have been avoided with a better streamflow forecast.

The key factor to notice is that storage, the rule curve and the error in the streamflow forecast must be in a critical relation to each other to cause an economic loss. In the case discussed above, it is necessary that the three variables indicate a flood control space encroachment of such a magnitude that first, a release exceeding channel capacity is warranted and second, that the magnitude of the forecast error be such that the encroachment could have been corrected without exceeding channel capacity. (After the error becomes apparent, the release can be shown to be inefficient because the expected flood protection benefit from the water released in excess of the requirements is zero while there are positive costs of the excessive release rate.) This situation is illustrated on the left hand side of Figure 13.

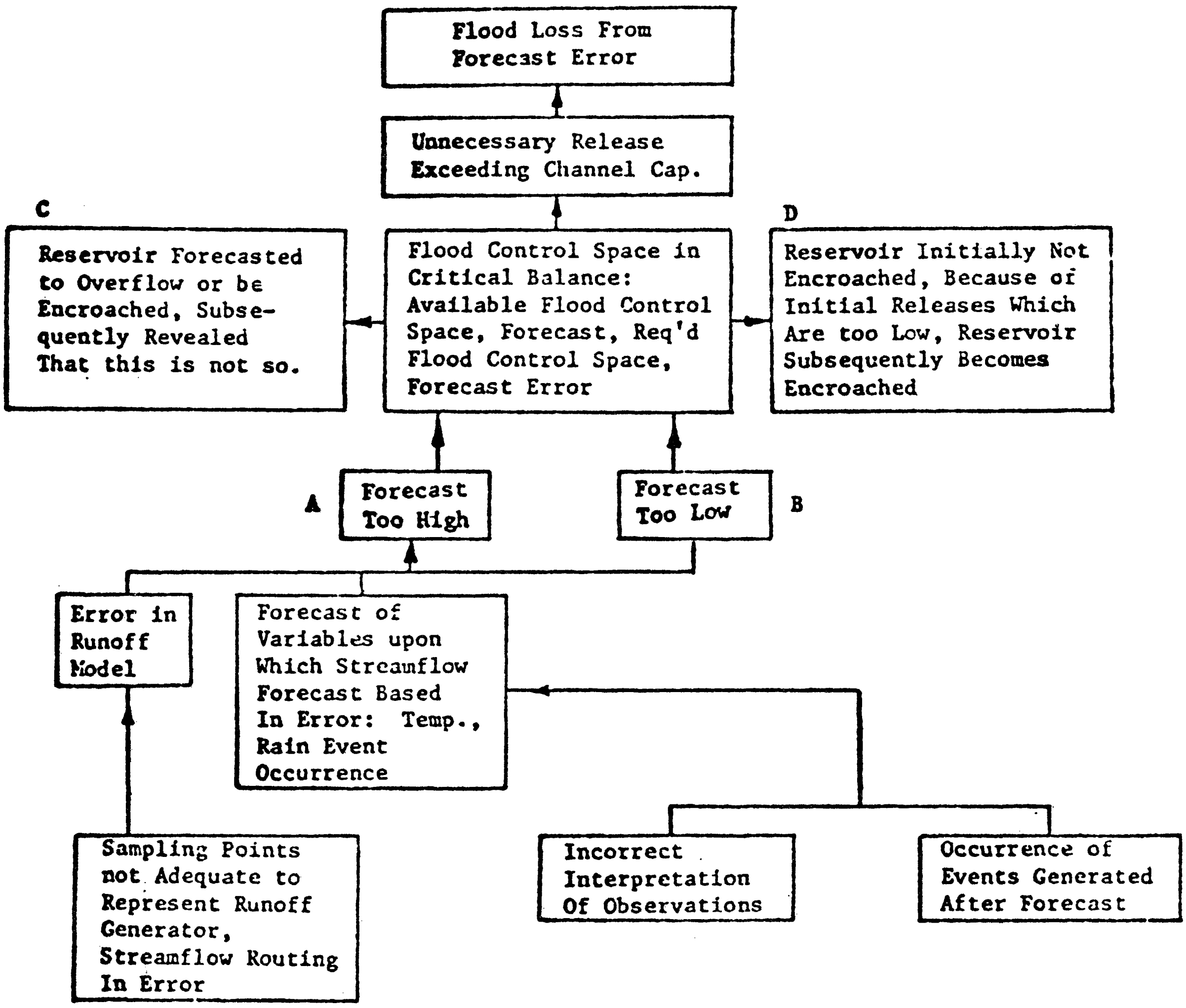
Had the forecast erred on the low side and the three variables were again in the critical relationship an avoidable loss could also occur. Such a loss would arise if the forecast and rule curve indicated that there was no need to draw the reservoir down to create additional flood control space. If a subsequent "preventable" loss occurred, the error in streamflow forecasting has caused inefficient reservoir operation. (Preventable loss in the sense that it would not have occurred with an accurate forecast.) This type of loss is also illustrated in Figure 13.

If the timing of the demand for flood control storage is such that it is competing with irrigation storage, the error can cause a loss of irrigation benefits in two ways. First, the flood control releases may escape from the water service area without being used and the water service area could be short of water during the irrigation season as a result. Second, to avoid losing the water from the service area, the irrigators apply excess water to their field (a practice known as pre-irrigation) at a time when the value of the marginal product of the water is much lower than later in the year. This practice has an even lower net marginal product than would be expected because it carries some positive cost through soil erosion and leaching of the soil. Here again the critical relation must exist between the relevant variables for an economic loss to occur. This is illustrated in Figure 14.

In most years, the flood control use and the conservation use will conflict only during a short period of time in the sense that flood releases could cause the water service area to be short of water during

Figure 13

Schematic Illustrating Cause of a Flood Control Loss From a Forecast Error



A: Error in Forecast, Forecast too High

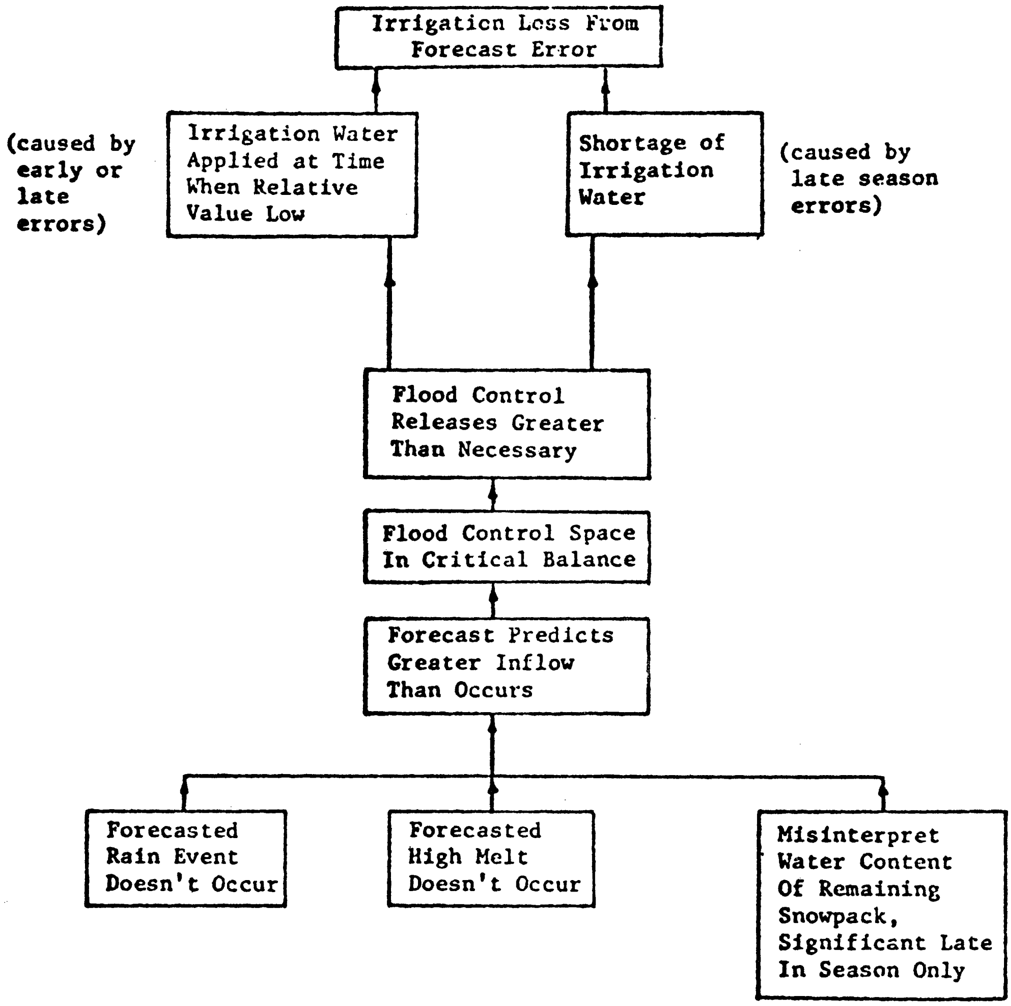
B: Error in Forecast, Forecast too Low

C: Insight into "Critical Balance Black Box" When Forecast too High

D: Insight into "Critical Balance Black Box" When Forecast too Low

Figure 14

Schematic Illustrating Loss From Irrigation Shortages Both Early and Late in Season



the irrigation season. During seasons of large supply, a good estimate of the lower bound of the available water supply is known beginning in April or May depending on the altitude and latitude of the basin. This early season knowledge of the lower bound of the water supply permits early season flood releases with a small risk that additional flows sufficient to fill the vacated flood control space will not occur later in the season. Hence the risk of a net reduction of the late season conservation storage through an early season forecast error is small.

Later in the season during a year with a large supply of water however, when 85-95% of the snow-melt runoff has already occurred the situation is more critical. At this time the reservoir should be nearing capacity and the objective is to store every drop of water available as soon as the flood control operation may be ended. The problem lies in forecasting this date accurately. If the operation is continued past the end of the snowmelt season, valuable water could be lost downstream. If it is ended too early, there is a high probability of the reservoir being in the critical state which could lead to flood losses. The risk to the conservation operation is very high because the streamflow at this time of year has a tendency to drop quickly to the level where none of the inflow can be stored because of prior downstream natural flow water rights.

During seasons with a small runoff there is little risk of loss from forecast errors and little competition between the conservation operation and the flood control operation. In these years a good estimate of both the lower and upper bound of the water supply may be forecasted with reasonable certainty early in the season. By early April or May it is possible to estimate the maximum probable seasonal water supply. It is likely in these cases that no draw-down will be required for control of the most probable runoff and only a small draw-down for the maximum probable runoff. In this case storage space allocated to flood control in larger years may be allotted to the conservation uses and all inflows in excess of downstream natural flow rights can be stored.

It is during years when a medium-sized snow pack has accumulated that the conservation operation and the flood control operation are competitive for storage space for the longest period of time. In this case the snow pack is not so large that massive releases must be made to evacuate flood control space before the season starts, but the pack is large enough that in the event of a rapid early thaw, the reservoir could become seriously encroached making releases in excess of the downstream channel capacity necessary. On the other hand, if flood control space is evacuated in advance and the pack melts at a slow regular rate, which does not cause inflows to greatly exceed the natural flow rights downstream, then the vacated storage space may not be filled. Thus early or late season forecast errors could cause losses to the competing use of the storage space.

The Probability of Occurrence

Estimation of the benefits to be obtained from an improvement in streamflow forecasting requires an estimate of the change in expected losses caused by errors in streamflow forecasting. This in turn requires an estimate of the probability of a streamflow forecast error causing a measurable economic loss. As was pointed out in the preceding section, a loss requires that the streamflow forecast, the storage in the reservoir, the time of the year and the downstream channel capacity be in a critical relationship to each other. More formally, the probability function of a loss through an error in streamflow forecasting is a jointly distributed function of the probability of a loss through unnecessary deliberate flooding (Type 1 flood loss) a flood loss through not implementing a possible draw-down (Type 2 flood loss), an irrigation loss through shortage in irrigation supply due to earlier excess flood releases (Type 1 irrigation loss) and the loss from a reduction in the net value of the water applied through the combination of mistimed application of the water to the fields and the leaching effects of excess pre-irrigation (Type 2 irrigation loss).

The probability functions of each of these losses may not be independent of the other and will be conditional on the time of the year, the storage in the reservoir and the size of the error. In the case of flood losses where an additional days flooding may not be significant if the land was innundated the day before, we must also consider the probability of an error in forecasting causing an additional day's flooding given that the river was in flood on the 1st, 2nd,...nth previous day or not in flood on those days.

The above discussion may be summarized in formulae. Let:

A = loss caused by forecast error
B = Type 1 flood loss
C = Type 2 flood loss
D = Type 1 irrigation loss
E = Type 2 irrigation loss
F = Storage in the reservoir
G = Time of year
H = given size of error
P = probability of event

Then as is known from elementary statistics, assuming C independent, but B, D and E not independent, the probability of event A occurring is:

$$P(A) = P(B + C + D + E) = P(B) + P(C) + P(D) + P(E) - P(BD) - P(BE) - P(DE) + 2P(DBE)$$

for illustrative purposes consider only the probability of a Type 1 irrigation loss:

$$P(D) = P(D/F) \cdot P(F) + P(D/G) + P(D/B) \cdot P(B/H) \cdot P(H/G)$$

where the expression $P(D/F)$ indicates the conditional probability of event D given the occurrence of event F. The probability of the other types of loss are defined in a similar fashion.

The characteristics which increase the probability of events B and C (Type 1 and 2 flood losses) i.e., those characteristics that make the reservoir more sensitive to forecast errors, can be enumerated. The basic hydrologic characteristics are the size of the runoff, the restriction on downstream flow, and the size, number and degree of control of various tributary inflows between the dam site and the constraining point in the downstream channel. The way in which these factors combine determines the sensitivity of the various operations to the forecast errors. The reservoir will be more sensitive to economic loss from errors:

i) the smaller the channel capacity downstream of the dam relative to the size of the flood

ii) the smaller the amount of storage available relative to the size of the flood

iii) The fewer the number of unforecasted and/or uncontrolled inflows between the dam and the point of occurrence of flood damages[1]

iv) the greater the proportion of the snow pack which is at low elevations (increasing the chance of large early runoff before irrigation diversions have increased significantly and reduced the amount of storage in the reservoir)

v) the smaller the maximum irrigation diversions that can be implemented during flood releases.

The hydrologic factors increasing the probability of events D and E (Type 1 and Type 2 irrigation losses) are:

i) the amount of conservation storage relative to the annual irrigation demand - the smaller the storage the greater the sensitivity

ii) the smaller the carryover storage from one year to the next the greater the sensitivity

iii) the greater the proportion of the conservation space considered to be joint use space for flood control and conservation the greater the sensitivity

iv) the lower the availability of alternative irrigation water supplies the greater the sensitivity

v) the greater the time lag between the normal spring runoff and the peak demand for irrigation water.

The considerations discussed in the preceeding two chapters will be utilized in the reservoir operation model discussed below. The next chapter, however, will describe the Snake River Basin and set the stage for the simulations needed to estimate the benefits from improved streamflow forecasts.

FOOTNOTES

[1] This statement is somewhat counterintuitive, but this factor was suggested by Mr. Eldo McClendon, Chief of the Missouri River Reservoir Control Center in personal correspondence. This situation arises on the main stem of the Missouri where a large portion of the runoff occurs from melting snow on the plains. This runoff is more difficult to forecast than the mountain snowpack in the long-range and occurs in more erratic patterns. The effect of large unforecasted inflows entering the main stream downstream of a reservoir can make the most careful releases inappropriate.

CHAPTER XV

THE UPPER SNAKE RIVER BASIN

General Basin Description

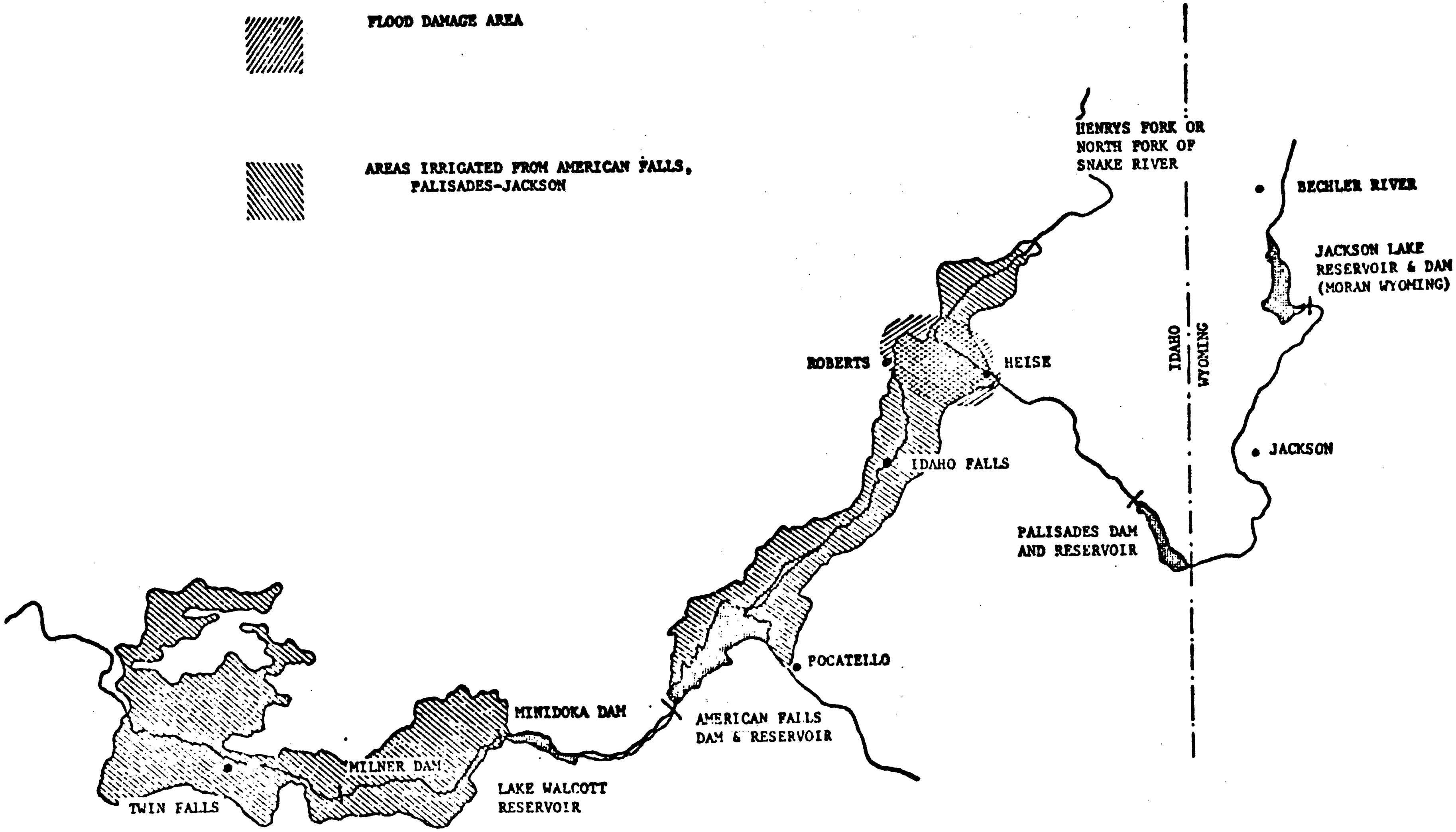
The Upper Snake Basin[1] is the portion of the Snake River drainage area from the source down to Weiser, Idaho on the Idaho-Oregon boundary. This area is 73,000 square miles in size and encompasses most of Southern Idaho, Western Wyoming, Northern Utah, and Eastern Oregon. The river rises near the Southwestern corner of Yellowstone National Park on the west side of the Continental Divide, and winds its way through various mountain groups including the Tetons before emerging on the Snake River Plain near Heise, Idaho. The river runs along the southern edge of the plain for about 170 miles before entering a deep canyon near Milner, Idaho. Technically, the "Upper Snake Basin" continues for several hundred more miles but the character of the basin changes below Milner, and we can restrict ourselves to considering only the portion upstream of Milner.

The climate in the basin varies with altitude and location. The mean temperatures are moderate to cool with summers being warm to dry and hot, while the winters are cool to cold and damp. The precipitation also varies with altitude and location. Some portions of the headwater area are in rain shadow from the surrounding mountains, while others receive Pacific air masses through various valleys and consequently receive more precipitation. Representative amounts are Moran 21.21 inches and Pocatello 16.21 inches.[2] The precipitation falling as snow is of obvious interest to this report. Once again differences exist between the alpine and the valley stations. The Bechler River, Wyoming precipitation station receives an average snowfall of some 300 inches. Jackson, Wyoming located in Jackson Hole receives only 80 inches on average whereas Moran, located just downstream from Jackson Lake, receives over 130 inches on average. For comparison, Idaho Falls (on the plain not far from Pocatello) receives only about 40 inches of snow on average.[3]

The Upper Snake Basin has a population of 320,000 people (see Figure 15 for a map of the region) according to the 1970 census,[4] and an

Figure 15

Upper Snake River Water Service Area



economy based on agriculture and agricultural products processing with a secondary base in mineral exploitation and some timber exploitation. The basin had 2,257,248 acres of land under irrigation in 1970 and a further 4 million acres classed as potentially irrigable.[5] The main crops grown in the area are wheat, barley, sugar beet, and potatoes. Livestock is also raised.

The agricultural products processing industry is concentrated in the Burley, Idaho Falls, Twin Falls area. It consists primarily of suger beet processing, processing of the potato crops, and canning of vegetables such as sweet corn. About 50% of the employment in the food or agricultural processing industry for the state of Idaho is located in the plains portion of the Upper Snake River Basin.[6]

A significant portion of the mining and minerals production in Idaho occurs in the Upper Snake area. In 1966, 34.1% of the total state employment in this category occurred here. The forest products industry plays a less significant role. Only 2.8% of the total state employment in the forest and wood products industry occurs in the Upper Snake area.[7]

There are 14 major streamflow control devices (over 5,000 acre-feet of storage) in the basin located on the main stem of the Snake River as well as on the various tributaries. These include dams on the Henry's Fork or North Fork of the Snake River, the Blackfoot River, Portneuf River, and Salmon Falls Creek. Here we are primarily concerned with the Main Stem reservoirs, in particular: Jackson Lake Reservoir, Palisades Reservoir and American Falls Reservoir. The other two reservoirs currently on the main stem are the Lake Walcott Reservoir behind the Minidoka Dam about twenty-five miles upstream from Burley, Idaho and a small lake behind Milner Dam which is primarily a diversion structure located about ten miles below Burley, Idaho.

Jackson Lake Reservoir was formed by constructing a control dam on the outlet of Jackson Lake. The reservoir is located in Jackson Hole just upstream from Moran, Idaho. The dam was built in 1907 and raised between then and 1919 to its current height. Present capacity of the reservoir is 847,000 acre-feet. The dam has 20 sliding gates to control the outflow and a release capacity of 20,000 cfs. The dam and reservoir are operated for flood control, irrigation and recreation.

Palisades Dam and Reservoir[8] are located just west of the Idaho-Wyoming border where the river emerges from the Grand Canyon of the Snake and begins its trip across the Snake River Plain. The dam is an earth-filled structure 260 feet high. The reservoir has a total capacity of 1,400,600 acre-feet and an active storage of 1,200,000 acre-feet. The dam has a controlled outlet discharge, an uncontrolled spillway and a by-pass discharge with a combined release capacity of 90,000 cfs. A power plant is connected to the reservoir by a power discharge tunnel with a capacity of 10,000 cfs at the minimum power head. The installed capacity of the plant is 114,000 KW. The transmission network consists of 6-115 KV lines totalling 230 miles and forming a network with American Falls and Minidoka Projects. The dam and reservoir are operated for flood control, irrigation and power.

American Falls Dam and Reservoir are located in the vicinity of Pocatello about 150 miles downstream from Palisades. The reservoir has a usable capacity of 1,700,000 acre-feet. A power plant in connection with the reservoir has a rated capacity of 27,500 kilowatts. American Falls differs from the other two reservoirs in that it has a considerable area of irrigated agriculture above it which contributes a large ground water return flow to the storage in the reservoir. The dam is operated for irrigation and power production purposes.[9]

This section will concern itself basically with the joint operation of Palisades-Jackson. Although the other reservoirs have an influence on the overall water availability in the Upper Basin, the Palisades-Jackson system represents the key one for operations. The operations of these two will also be influenced by events downstream, particularly those involving American Falls. This issue will be discussed later.

Demands On The "Warehouse" - Palisades-Jackson Reservoirs

Palisades-Jackson is operated by the Bureau of Reclamation in cooperation with the Corps of Engineers (who regulate the overall Columbia system), the Watermaster of Idaho Water District #36 and the managers of the local Canal Companies. The flood control operation is carried out on the basis of a flood control reservation diagram (described in the Reservoir Regulation Appendix) and forecasts of remaining season runoff and streamflow provided by the Soil Conservation Service, the Corps of Engineers and the Bureau of Reclamation's own research (see the Appendix on snow surveying and streamflow forecasting). As in all reservoir operation procedures in which releases are made according to forecasts of streamflow, proper operation is dependent upon the accuracy of the forecast. The Bureau of Reclamation Reservoir Regulation Staff indicates that the basic operating plan is established on the basis of the seasonal runoff forecast and that the short term forecasts permit the operating plan to be carried out in the best manner. For example, if the flood control diagram indicates that an evacuation is necessary, the rate of draw-down is either determined by auxilliary flood regulations or at the operator's discretion under the constraint that releases cannot exceed inflows.

Flood Control Demands

The major local flood control benefits arise in the reach between Heise and Roberts.[10] Damages in this area occur with releases as low as 10,000 cfs which is below the mid-summer average irrigation demand. A levee extension is currently being designed to raise the capacity of the reach and avoid these low flow damages. The major damages occur with flows above 20,000 cfs. (This will be the initial damaging flow after completion of the levee system also.) The flood plain in this reach is used predominately for agriculture and the losses are of two types. The first is simple over-bank flooding with subsequent damage or total loss to crops, equipment and buildings. The second type of flood damage arises from avulsions or the cutting of new channels through this deltic area. The Palisades-Jackson reservoir system also contributes to the prevention of flood losses on the main Columbia below its confluence with the Snake by moderating and delaying the peak on the Snake.

The channel constriction in the Heise-Roberts area constitutes the main constraint to the flood control operation. Release from Palisades may be raised above 20,000 cfs only when certain criteria are satisfied. A constraint on the amount of flood control water to be released is imposed by the objective of having Palisades full of irrigation water at the end of the flood season. Non-filling is not as critical here as it is elsewhere in the West, because distribution of the water storage rights (also discussed below) results in a number of irrigators owning carry-over storage in the reservoir. The full effects of the reservoir not filling in any one year would only be felt several years later if there were a series of dry years in a row. Flood releases in excess of the irrigation demands do carry a positive cost, however. The irrigators do not like to see water spilled passed Milner Dam where it is lost to their canal and storage system. Their reaction is to divert as much water as possible during flood releases and practice preirrigation. This practice consists of applying large quantities of water to the land, even though there is no crop growing to use the water, in the hope that it will increase the soil moisture and raise the ground water table. The net benefits of this practice may be reduced however since it leaches soil nutrients out of the growing zone, creates drainage problems and promotes erosion.

As discussed above, the sensitivity of the flood control operation to forecast errors is a function of:

i) the amount of available storage relative to the size of the flood
ii) the size of the downstream channel capacity relative to the size of the flood and the amount of storage available
iii) the number of uncontrolled tributary inflows between the dam and the point of occurrence of flood losses
iv) the proportion of the snow pack which is at low elevations
v) the size of the maximum irrigation diversions between the dam and the point of critical flow.

The Upper Snake is relatively insensitive to errors in forecasts. During the 1960's the average April 1 flood control space available was about 25% of the April 1 forecast for total season runoff. Also during the 1960's the average yearly peak inflow was about 27,000 cfs. When this is compared to the channel capacity of 20,000 cfs at Heise, it can be seen that even an error of 20% of the average peak constitutes only 27% of the channel capacity.

There are few uncontrolled tributaries between the dam and the critical point at Heise. Those that do enter receive runoff primarily from low elevations which indicates that their peak would be contributed before the main peak. One tributary, the Henry's Fork, does enter in the flood prone area between Heise and Roberts but it is controlled by several dams and has a considerable irrigated area making diversions possible.

The snow pack in the Upper Snake area is concentrated at high altitudes. During the 1960's the peak occurred before May 21st only twice. Out of the ten years it occurred six times in June. This is significant because the final snow surveys are carried out at the first of May and thus provide final figures on how much water there is in the pack. The lateness of the peak provides substantial time for the previous errors to become known and corrective action to be taken.

Very little irrigated agriculture is carried on between Palisades and Heise. Hence high releases at the dam cannot be diminished by large irrigation diversions before they reach Heise. This factor tends to make the operation more sensitive to forecast errors.

Wildlife and Fisheries Management Demands

Wildlife and fisheries management also impose constraints on the flood control operation. The reaches of the river flooded by the Palisades reservoir are prime nesting ground for Canada Geese and wild ducks. Since the filling of the reservoir, the waterfowls have begun to nest immediately downstream from the dam. This reach is 65 miles in length with nesting sites on both banks of the river and on about 1000 acres of islands in the stream. The annual production is 6500 ducks and 1000 geese. Using methods outlined in Senate Document 97, Supplement 1 (September, 1964) the value of this production is $3,000 for the ducks and $10,500 for the geese. The loss of geese from high flows varies from 50 to 75% of the annual crop with the average over the last 10 years being 58%.[11]

The ideal release pattern for waterfowl management requires sufficiently large releases during January, February, and March to push the nesting sites to a height which will not be exceeded before the end of May. The nesting sites are chosen early but renesting is possible. The crucial period is during the last ten days of March, when the final nests are built and the eggs are laid. Once the eggs are laid, the previous high release should not be exceeded until the end of May so that the nest containing the eggs are not inundated.

This ideal release pattern for waterfowl management conflicts both with flood control and irrigation. The initial large releases are required before accurate water supply forecasts are available--the major problem being that only a fraction of the total snow pack is on the ground at that time. Thus these large releases would be made at a time of great uncertainty concerning the availability of water for the irrigation supply. The maximum release that would not be exceeded during the flood season is also unknown at this time. If the prediction of a maximum flood release were too low, either it would be exceeded and the nests destroyed or the flood control operation would be hindered. (It should be noted that with the critical period for the waterfowl ending at the end of May, a late start of the runoff season may mean that flows are naturally in line with the nesting requirements and the release scheduling problem from the reservoir may not arise.)

The operation for the wild fowl management is very sensitive to errors in forecasts for two reasons. First, the decisions must be made early in the snow accumulation season (as discussed above). Second, the margin of error in a flood release is much smaller than it is when only agricultural or private property damages are concerned. The nests are very close to the water's edge and relatively small increase in the flow are sufficient to dislodge them.

Irrigation Demands

The conservation operations at Palisades-Jackson for both water supply and power generation are subordinate to flood control operations during the spring runoff period. The operation for irrigation purposes is based on the pattern of natural flow rights and storage rights in the system. The operation is administered by the Watermaster of District 36 in conjunction with the managers on the Bureau projects. To understand the irrigation water supply operation of the reservoirs and hence see where the benefits from streamflow forecasting improvements could arise, it is necessary to consider in some depth the organization of the irrigated agriculture industry and the distribution of water rights.

Idaho Water District #36 is the geographic area composed of all of the Idaho counties bordering both the mainstem of the Snake and the Henry's Fork branch from the Wyoming state line to Twin Falls and Jerome counties. All the water users in this area who have flow rights or storage rights are members of the District. The membership annually elect The Committee of Nine which is the executive body of the district. The Watermaster acts as the manager of the district. Because so much of the District's business is dependent upon stream-flow records, an agreement has been reached between the U.S. Geological Survey, the State of Idaho and the Water District whereby the District Engineer of the Geological Survey will also serve as Watermaster.[12]

The allocation of irrigation water among users on the Upper Snake involves use of streamflow or natural flow water rights and rights to stored water. Both of these are allocated on a prior appropriation basis. The earliest natural flow right on the Heise to Milner portion is dated June 11, 1880. There are four rights with this date providing a total of 40 second-feet of water (40 second-feet = 40 cfs for a twenty-four hour period). The latest right on the river is dated June 1, 1936 and entitles the State of Idaho to 100 second-feet of water. The total accumulation of prior rights is 33,815.97 second-feet of water which means that for the State of Idaho to divert any water by this right the natural river flow has to average 33,815.97 cfs of flow for the previous twenty-four hours.

Calculation of the natural flow at any point is a complex matter. The problem is made more difficult by the entry of various tributaries, the changes in storage in the various reservoirs, the fact that some ground water pumping operations are tributary to the Snake during the entire season while others are tributary to the main river only when its flow exceeds a certain level. The calculations are carried out in the watermaster's office with the aid of records from some thirty-six gauging stations, and special studies to determine the theoretical natural flow. Consider the following example of the process.

There is (normally) enough inflow below Blackfoot so that

> part of the October 11, 1900, right remains in effect throughout the irrigation season. Prior to the construction of the American Falls Reservoir this inflow was impounded. Studies by T.R. Newell related the inflow above the reservoir flow line to that below. All significant tributaries were measured where they entered the reservoir. These same points are now measured periodically during the irrigation season and their total is the measured inflow. The Newell formula (unmeasured inflow = 840 plus 1/3 measured inflow) is used to compute the flow available to the 1900 right. Since 1964 pumping diversions from the Portneuf River by the Bureau of Indian Affairs have reduced the measured inflow. Theoretical inflow is now computed.... (annually). This theoretical inflow is credited to the lower valley canals.[13]

Most of the users in the Heise/Milner reach also have storage rights in the various reservoirs. Many of the downstream users will have storage in all of the reservoirs upon which they can call when their natural flow right is cut or when their decree does not provide sufficient water for their uses. The allocation of these storage rights is no less complex than the allocation of the natural flow rights discussed above. The first question to consider is the right of the reservoirs to store water. In the case of American Falls Reservoir, if it is not filled it obtains part of a March 30, 1921 decree to the U.S.B.R. This water right decree gives American Falls one-half of the first 1700 second-feet of flow and all of the remaining 6300 feet. The accumulated decrees prior to this right total 33,398.97 second-feet. If the natural flow is greater than this amount and American Falls is not filled, water is stored in American Falls or in upstream reservoirs to American Falls account. (This technique of storing water in an upstream reservoir for a downstream account introduces greater flexibility into the system. It is not unusual for American Falls to have physically empty space even though all storage rights are filled by water kept upstream on American Falls account.) Palisades being a newer dam does not have a decreed right. It can store water only after all other decreed right demands have been filled (with certain exceptions written in to the Palisades contract).

The next point to be considered is the delivery of stored water. Requests are made by the users to the canal companies or the irrigation district for water in specific quantities. These are aggregated by company and transmitted to the Watermaster. The Watermaster's office checks on the availability of water and requests the release from the Bureau. If the reservoir was full at the end of the flood season (or in the case of American Falls if it has refilled since--through ground water return--) then the company can claim the entire storage it has contracted for. It may rent additional water from other storage holders who have better natural flow rights and do not expect to use their storage this year. If the reservoirs did not fill, the proration of available storage among those holding storage rights is more complex. The allocation is based on the amount and location of stored water that the contractor had at the end of the previous water year. In this sense there are no priority storage rights in the reservoirs, but the availability of storage to an individual contractor in a non-filling year will be a function of his natural flow priority and the amount of his diversion in the preceding year.

An example of the problems of allocation when the reservoirs do not fill and of the interchange of physical storages that may take place is given in Eagle.

> Additional reservoirs have increased the degree of control on the river. At the same time they have made more complicated the river computations. Water is credited to the various reservoirs in accordance with their several priorities. Reservoirs are operated to retain as much as possible in upstream reservoirs. This sometimes results in differences of opinion over reservoir allotments. In 1961 American Falls Reservoir failed to fill. This was the first year since 1935 that this had occurred. In the intervening years, Island Park and Grassy Lake reservoirs (on Henry's Fork) had been completed. These two reservoirs in 1961 stored 81,500 acre-feet of water creditable to the American Falls priority. Also 55,000 acre-feet of water had been stored in American Falls that was creditable to Palisades...from winter water savings, there was no water available for storage to Palisades storage rights.
>
> There was about 190,000 acre-feet of storage in the three Henry's Fork reservoirs at the beginning of the 1961 irrigation season. However, much of this belonged to the downstream reservoirs because of the storage adverse to American Falls and overuse of natural flow without replacement from Henry's Fork during the 1960 season. Only 81,000 acre-feet was creditable to these reservoirs. This

> was supplemented by rental of 31,253 acre-feet of American Falls storage from Idaho Power Company and 13,000 acre-feet from other sources. It was not necessary to run any of Henry's Fork storage down to lower valley users.[14]

As can be seen in this exerpt, the upstream reservoir, Palisades, was credited with storage in the downstream reservoir, American Falls. In addition while the Henry's Fork Reservoirs owed water to the lower river users they were able to rent water from other storage contractors in American Falls which was subsequently released to the lower river users. This meant that Henry's Fork users did not have to let their water go downstream to fulfill a debt.

Water right decrees are granted on the basis of beneficial use. However, there is some feeling that in Southeastern Idaho many of the irrigators are applying so much water that the marginal net product is either negative or at least not greater than zero. There is presently no inducement for a right holder to attempt to save water when he is using his natural flow right. If a right holder does not use his full entitlement when it is available, it automatically is available for a more junior right. The right holder cannot appropriate any benefit for himself by not using his full entitlement.

Storage rights are made available to anyone wishing to contract for storage space in new reservoirs. The Bureau of Reclamation's policy in Eastern Idaho seems to be different from that announced for the rest of Region 1. The policy for this area is to build sufficient reservoirs to remove all practical uncertainty from irrigation supply. In the remainder of Region 1, the policy ennunciated for the Columbia-North Pacific Framework Study is one of accepting planned shortages not exceeding 20% of the irrigation requirements in any one year and 50% in any 10 year period. This policy of building on demand to prevent all possible shortages is fostering the high water utilization of many of the irrigators served by the Minidoka-Palisades project.[15]

The lack of incentive to conserve water that is available under natural flow rights presently held and the policy of the Bureau of Reclamation to build storage on demand results in an over-application of water in good to average years and a proper to slightly less than required in dried years. The availability of water makes the conservation operation for irrigation purposes relatively insensitive to forecast errors. However, it would appear that this situation of effective over-supply may change within the next ten years. First, the Idaho Department of Water Administration is attempting to obtain the first proper adjudication of the Eastern Idaho water rights. Second, significant quantities of presently unirrigated but irrigable land exist. Since new rights are limited to an application of five acre-feet of water per acre, this limit may also be imposed under an adjudication of present rights. Some of the Bureau of Reclamation projects in the area are using as much as thirteen acre-feet per acre. In the ten year period 1959 through 1968, the average application for District #36 was 6.56 acre-feet per acre for the sixty-two entities diverting Snake River water.

Table 45 examines the upper tail of the distribution of diversions for each year in the period 1959-1968. As can be seen the average diversion is above the 5.0 acre-feet per acre limit in every year and in all years but one more than 20% of the canals irrigating between 5 and 10% of the irrigated acreage diverted more than twice the 5.0 acre-foot limit. Thus if we assume the successful adjudication of the water rights and the imposition of a general 5 acre-foot limitation, there could be considerable savings in water to be applied to new lands. (The data provided on the next page are somewhat misleading because they include water released from storage. The 5 acre-foot figure applies only to applications from natural flow rights. The data does show, however, that there is considerable over-application of water since the 5 acre-foot per acre level is considered adequate for most of the land in the District.) As is seen in Table 45 more than twice this amount is being applied to one-third of the land in the District.

Even with the water saving discussed above, the Upper Snake will be a water-short area if all of the presently irrigable land were to be irrigated. Table 46 shows the quantities of potentially irrigable lands in the Upper Snake Basins (including the Henry's Fork Basin.)

TABLE 45

ANALYSIS OF WATER DIVERSIONS IN IDAHO WATER DISTRICT #36

1959 - 1968

YEAR	ACREAGE DIVERSION ACRE-FEET/ACRE	NO. OF CANALS DIVERTING MORE THAN 10 ACRE-FEET/ACRE	NO. OF ACRES TO WHICH MORE THAN 10 ACRE-FEET/ACRE APPLIED	MAXIMUM DIVERSION ACRE-FEET/ACRE	NO. OF ACRES IRRIGATED BY LARGEST IRRIGAT.	TOTAL ACREAGE IRRIGATED
1959	6.8	16	70,288	13.4	7,000	1,001,800
1960	6.9	18	86,785	14.5	130	997,347
1961	5.8	7	28,300	13.5	7,000	1,002,566
1962	7.0	24	89,618	17.6	25	997,828
1963	6.3	13	61,165	12.5	7,000	998,592
1964	6.3	16	69,126	12.2	1,000	1,017,922
1965	6.5	22	90,520	15.7	70	1,017,350
1966	7.0	19	91,170	14.0	930	1,014,182
1967	6.8	21	87,223	19.0	103	1.041,975
1968	6.4	21	101,470	14.2	10,500	1,041,975

Source: Derived from: Idaho Water District #36, Annual Report years 1959-1968, Table entitled "Diversions during - irrigation season by Snake River Canals; (Boise, Idaho: 1959-1968.

TABLE 46

POTENTIALLY IRRIGABLE LANDS
UPPER SNAKE BASINS

COUNTY	CLASS 1*	CLASS 2**	CLASS 3***	TOTAL
Bannock	5,500	117,400	77,500	200,400
Bingham	135,400	46,900	103,900	286,200
Blaine	0	29,400	31,000	60,400
Bonneville	49,700	137,200	26,800	213,700
Butte	63,400	67,300	248,000	378,700
Camas	9,900	53,200	32,400	95,500
Caribou	21,700	149,100	65,900	326,700
Cassia	91,500	257,800	81,800	431,100
Clark	29,800	72,800	92,800	195,400
Custer	0	0	110,400	110,400
Elmore	400	24,300	8,400	33,100
Fremont	25,500	77,700	18,300	121,500
Gooding	6,700	17,400	10,300	34,400
Jefferson	23,100	116,700	44,800	184,600
Jerome	0	12,300	40,200	52,500
Lemhi	0	15,300	27,200	42,500
Lincoln	0	15,300	85,000	100,300
Madison	33,700	44,200	9,400	87,300
Minidoka	9,800	17,600	8,600	36,000
Oneida	5,100	5,800	0	10,900
Owyhee	500	18,400	14,500	33,400
Power	72,800	161,500	159,500	393,800
Teton	25,100	48,000	8,600	81,700
Twin Falls	95,600	217,700	88,600	401,900
TOTAL	705,200	1,723,300	1,393,900	3,822,400

Source: Idaho Water Resources Board, Potentially Irrigable Lands in Idaho, (Boise, Idaho, 1970), Table 14, p. 25.

*Class 1 land is generally composed of silt loams and is flat or gently rolling.

**Class 2 lands are of good quality and capable of producing most climatically adapted crops. Somewhat lower yields will be obtained for the same expenditure than on Class 1 lands.

***Class 3 lands have soil not suited for row crops but do have some limited potential for small grains and forage crops.

Power Generation Demands

The operation of Palisades for power generation is incidental to the irrigation and flood control operations. Any releases required for any purpose are routed through the power penstocks up to their capacity. This includes any releases required to fill the prior storage right of the American Falls Reservoir.[16] The average irrigation release in the summer is about 10,000 cfs. In the winter only about 2,000 cfs is released, basically to fill American Falls Reservoir as provided in the storage contracts (this will be discussed further below). Since the power generators utilize about 8,000 at their rated head only 80% of the midsummer releases are utilized whereas the winter release are 75% below the rated capacity. The power from the Palisades plants is utilized on the Bureau of Reclamation's projects for pumping purposes as well as by the City of Idaho Falls, three REA cooperatives, the Minidoka Power System, the Idaho Power Company, and the Utah Light and Power Company.[17] Operational studies have indicated that the average annual production of the Palisades power plant is 611,000,000 kilowatt-hours and that the dependable capacity to meet peak loads during the December critical period is 26,700 kilowatts. On these parameters the annual power benefits from Palisades are $2,440,000 using power values of 3.45 mills per kwh and $15.77 per kw of dependable capacity.[18]

Recreational Demands

The operation of the reservoirs for recreational purposes involves both the level of the reservoir and the amount of flow downstream. The Jackson Lake Reservoir is located in Jackson Hole. The lake and its surrounding mountains rank high on indices of aesthetic attraction. Many visitors a year enter the surrounding recreational user charge area to view and photograph the lake. Maintenance of the aesthetics of the lake require that the water level be kept reasonably constant to prevent exposure of mud flats. (The same is true of Palisades but to a lesser extent.) Another prominent feature of recreation in this portion of the Snake is float trips down the river between Jackson Lake and the town of Jackson. This activity requires maintenance of the flow at fairly uniform levels with sufficient flow to float the heavy rafts that tourists are carried on. (Any recreational use of a river, fishing, boating, swimming, etc., requires that the flow be kept reasonably constant or at least that alterations of flow not be made at extreme rates.)

Since the recreation season generally does not start until after the peak of the flood season there is little conflict between recreation and flood control. However, the recreational demand for maintenance of the reservoir level does conflict with the irrigation water supply operation and the irrigation release schedule may conflict with float trip requirements.

Economic Values of the Demands on the Reservoir

While the hydrologic data base in the Upper Snake Basin is well suited to the analysis of the type undertaken here, the economic data base leaves much to be desired. Any attempt to formulate benefit and damage functions borders on pure speculation.

The Corps of Engineers has formulated a flood-stage damage function for the area, but it is formulated strictly in terms of the maximum release of the flood season. The effects of duration of any innundation and the number of innundations in any season are ignored. It is not indicated whether or not the damages shown include some adjustment factor for probable duration or number of innundations etc. The flood damage schedule was formulated using 1967 data. Most of the flood areas are agricultural land, so that we may assume that the real values have not changed significantly since then. The Corps' figures must be adjusted for inflation however. A 6% per year rate has been assumed. The resulting flood damage schedule is:[19]

Streamflow (CFS)	Damages ($)
20,001	37,550.
22,500	84,489.
25,000	163,614.
27,500	301,747.
30,000	481,454.

The value of additional acre-feet of water saved by improvement of streamflow forecasts also is difficult to estimate. Several factors contribute to this difficulty:

1) the lack of consensus concerning the optimum application of water to the fields
2) the size of the water service area and the variety of crops grown result in a wide variation in yields; hence the value of water saved depends on the quality of land to which the "saved" water is applied
3) the difficulty in determining the productivity of excess pre-irrigation during the spring flood releases.

To evaluate the saved water in view of these problems, we will assume:

1) that the adjudicated rights are restricted to an application of 5 acre-feet per acre
2) that the irrigable land is put into production either using Snake River water directly or through exchanges of water rights
3) that the average value per acre foot of water in the present water use area may be applied to the new areas.

The use of the average value of water rather than the marginal is justified by the fact that the water savings are more important in terms of firming up a long-run water supply than they are in providing a few additional acre-feet of water in any given year. The behavior of the present water-rights holders indicates that the decision concerning the amount of water to apply is based on long run considerations of utilizing the total proportion of the allotment available. (See the description of the water rights system above.) Given the above assumptions, the value per acre-foot of water saved by the improvements of streamflow forecasts is taken to be $5.00-$10.00 per acre-foot.[20]

Analysis of Operations Charts

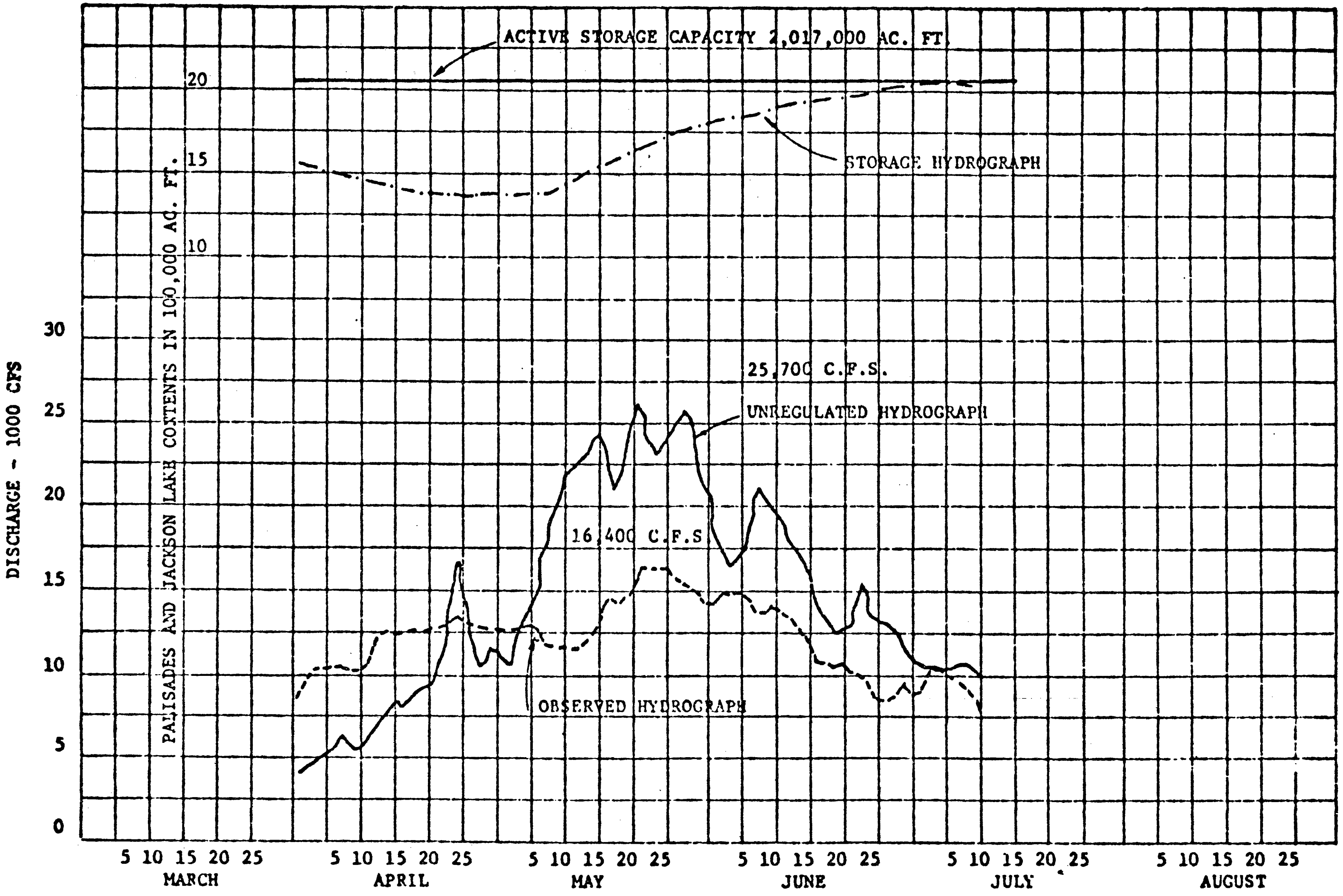
To ascertain how improved runoff forecasts could have made the operation of Jackson Lake and Palisades Reservoirs more efficient with respect to the above operational requirements, the hydrograph for the two reservoirs were analyzed for the period of record since the completion of the Palisades dam in 1956. The analysis was carried out with the assistance of Mr. Richard Lindegrin[21] of the Bureau of Reclamation who has been involved in the operational decision process since the completion of Palisades.

As discussed previously, in all but extremely small runoff years with a low carryover and extremely large runoff years with a large carryover, improvements in the short-term forecast (five to thirty days) would make reservoir operations easier and allow the decisions to be made with more confidence. This extra confidence would permit some greater degree of finesse in the operations. An example of the kind of finesse that could be achieved occurred in 1969 (Figure 16) when the operational charts indicate that the observed flow at Heise peaked at 16,400 cfs in the third week in May and declined to 8500 cfs in the third week in June. The reservoir filled on the 25 June.[22] Although no losses occurred through excessive releases and no irrigation shortages occurred, a 100% confidence forecast on the 15 May of the runoff over the next six weeks would have permitted a faster fill of the reservoir, earlier maximum storage and a smoother outflow hydrograph with a smaller peak discharge and a higher discharge over most of the subsequent period. This would have permitted the smooth table top hydrograph which is the hydrologist's objective. Other than some added benefits for a few early tourists, however, there would have been no economic benefit or increased efficiency of operation.

Preventable losses did occur in 1965, 1964 and 1963 when releases in excess of 20,000 cfs at Heise were made. In 1965 and 1964, Figure 17 and Figure 18, the inflow hydrographs fell rapidly during the end of June. At this time the reservoirs were high (1.9 million acre-feet in each case) but not full. As the recession appeared to have started, the releases were cut back drastically to fill the reservoir (in each case a maximum fill plan was used with only requested irrigation releases and downstream prior right releases being made). In both years as soon as the maximum fill decision had been made (about four days after the apparent start of recession) the inflow hydrograph began to peak again. In 1965 the outflow was raised to 20,200 cfs for 2 days and in 1964 it was raised to 20,900 cfs for a period of 5 days. In each year this was the first exceedence of the 20,000 cfs limit, indicating that any damages would be more than marginal. In both cases a confident 10-day

Figure 16

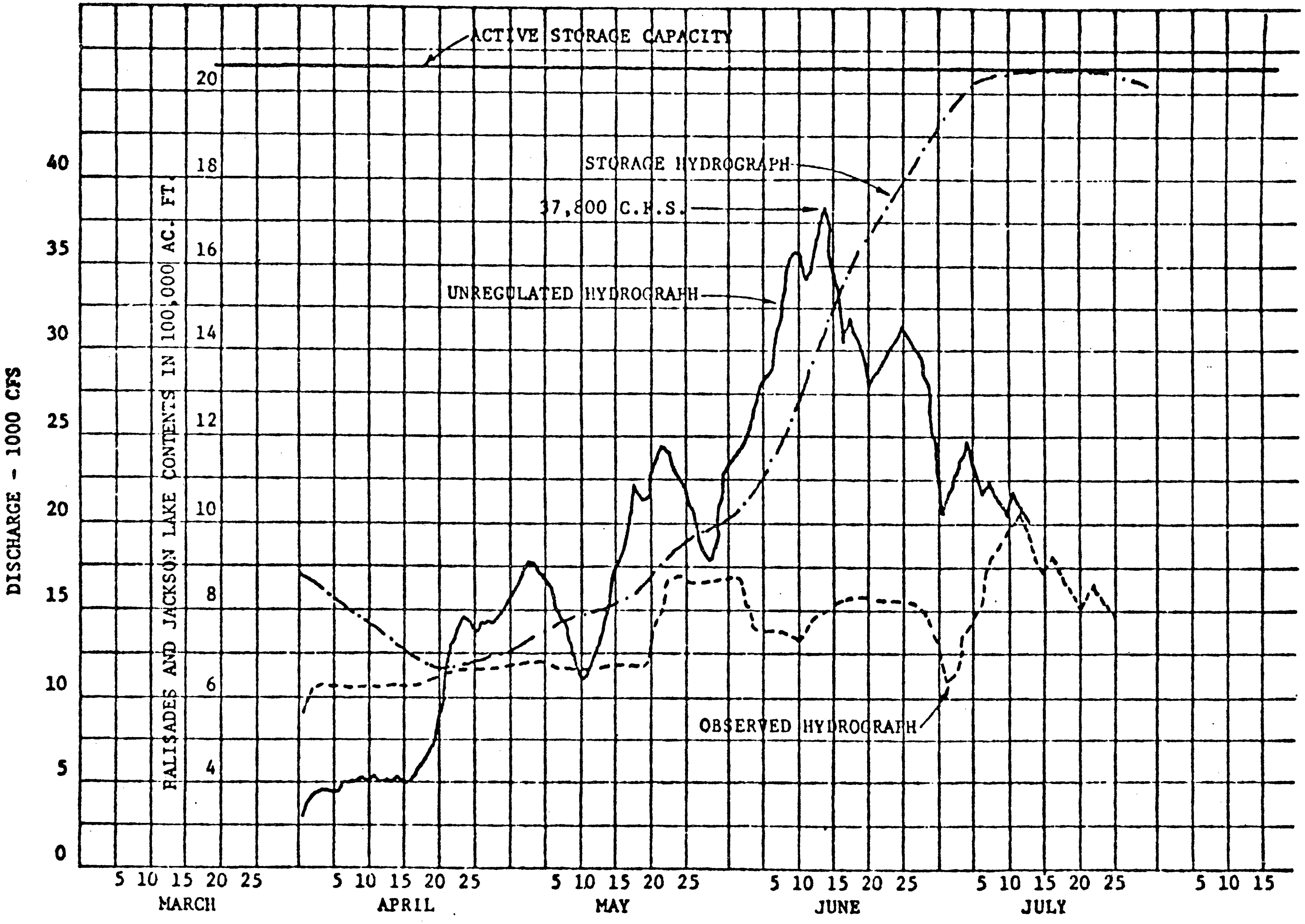
1969 Hydrograph of Snake River Near Heise, Idaho And Storage in Palisades-Jackson Reservoir



Source: Columbia River Water Management Group
Columbia River Basin 1969 Flood Regulations
(Portland, Oregon, 1969) Exhibit 15.

Figure 17

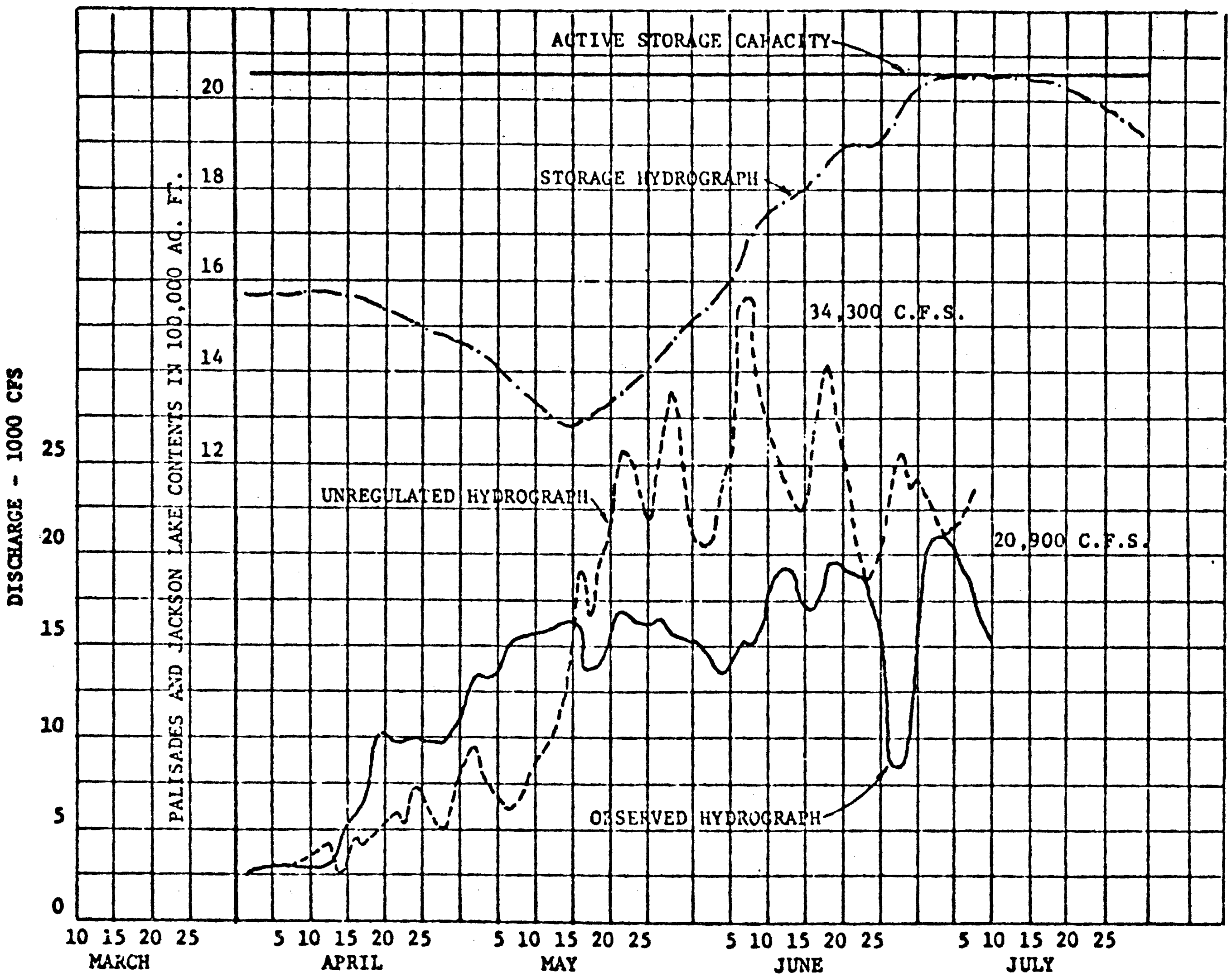
1965 Hydrograph of Snake River Near Heise, Idaho And Storage in Palisades-Jackson Reservoir



Source: Colorado River Water Management Group
Columbia River Basin 1965 Flood Regulation
(Portland, Oregon, 1965) Exhibit 10.

Figure 18

1964 Hydrograph of Snake River Near Heise, Idaho
And Storage in Palisades-Jackson Reservoir



Source: Columbia River Water Management Group
Columbia River Basin 1964 Flood Regulation
(Portland, Oregon, 1964) Exhibit 10.

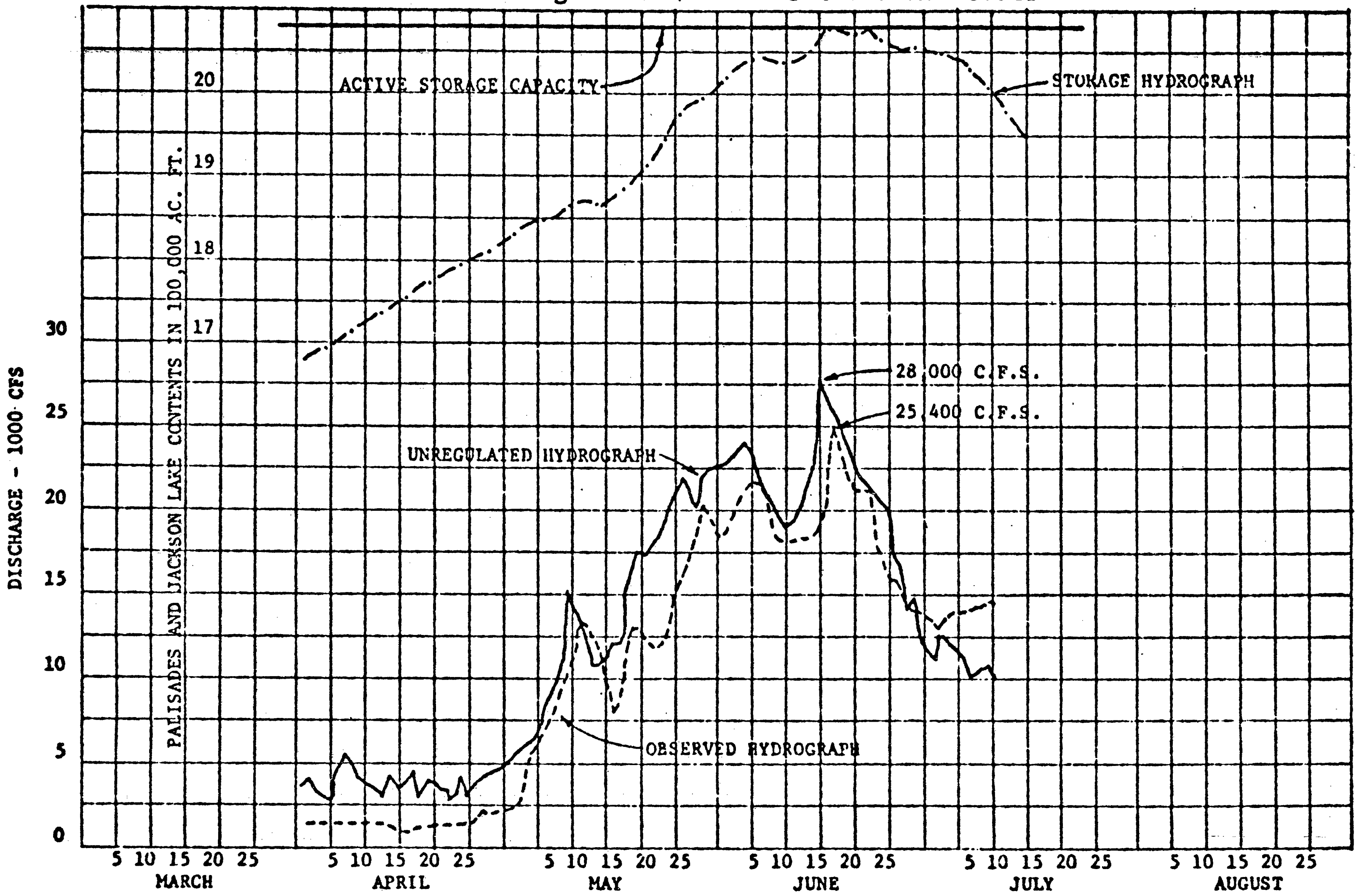
forecast on the 20 June that recession had not started would have prevented this flooding. In 1965 a good five-day forecast that the upturn of the inflow hydrograph on 5 July was more than a minor irregulatity would also have prevented the damage. In 1964 a good five-day forecast on 25 June would also have prevented the losses which followed.

In 1963 (see Figure 19), although the loss resulted from releases exceeding 20,000 cfs, the situation was entirely different from 1964 and 1965. In 1963 the runoff started in earnest about 23 May with the combined reservoirs containing about 1.95 million a-f. The releases exceeded 20,000 momentarily on 28 May, for 5 days between 3 June and 8 June and for 9 days between 15 June and 24 June. The peak occurred in this last period at 25,400 on 17 June. The reservoir was filled continuously from 1 April when it contained 1.67 million a-f until 16 June when it peaked at 2,273,220 a-f (capacity being 2,264,600 a-f). The problem in this year was one of inaccurate forecasts both in the seasonal total runoff and the short term forecasts. The Weather Bureau forecast on 1 April was 1,454,000 a-f and on 1 May 1,604,000 a-f. The actual runoff for the April 1 - July 31 period was 2,788,770 a-f. (The figures for the forecast were calculated from the Weather Bureau data which is the residual from indicated date to end of water year on 30 September.) On the basis of these erroneous forecasts, the reservoir was allowed to fill throughout the runoff season rather than being evacuated to provide some flood reservation space for control of the total seasonal runoff. However, if even a dependable thirty day forecast had been available on 15 May, the flow at Heise could have been kept below 20,000 assuming the reservoir was surcharged (i.e. filled above normal capacity). This could have been done by raising the discharge above the 7,500 cfs level as it was on the 15 May and holding it at the higher level. The final factor which made a bad situation worse was a 15 June rainpeak that coincided with the system fill. Had this rain been predicted 10 days in advance the releases could have been held at 21,500 for the following 10 days and the additional flooding prevented.

An example of how the reservoirs could have been operated to give better conditions for waterfowl nesting can be seen on the 1959 hydrographs (see Figure 20). The flow during March and April was very low

Figure 19

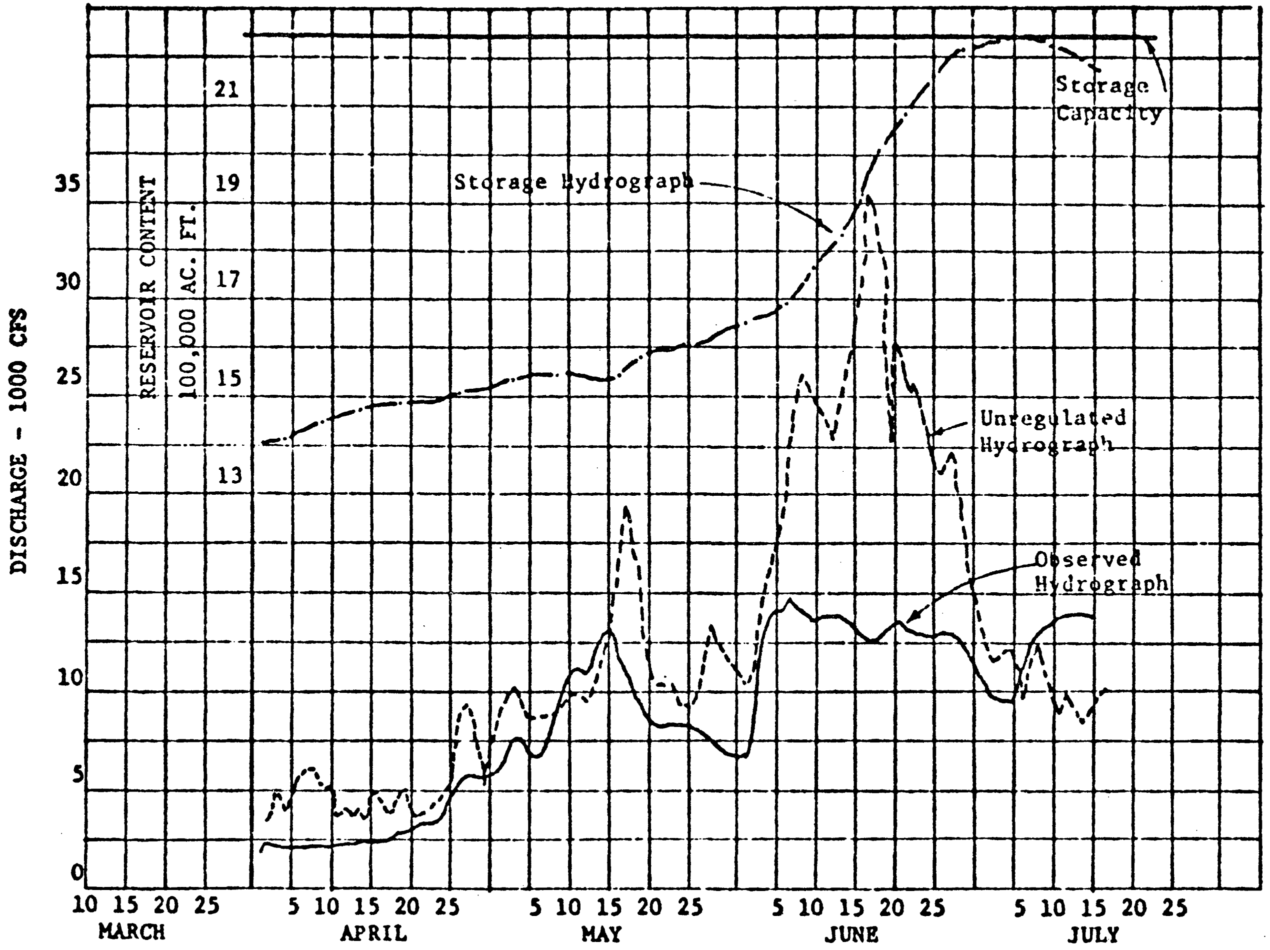
1963 Hydrograph of Snake River at Heise, Idaho And Storage in Palisades-Jackson Reservoir



Source: Columbia River Water Management Group
Columbia River Basin 1963 Flood Regulation
(Portland, Oregon, 1963) Exhibit 10.

Figure 20

1959 Hydrograph of Snake River Near Heise, Idaho
And Storage in Palisades-Jackson Reservoir



Source: Columbia River Water Management Group
Columbia River Basin 1959 Flood Regulation
(Portland, Oregon, 1959) Exhibit 8.

(April 1 the first day plotted was 2,500 cfs) inducing the waterfowl to nest in the flood plain. Discharges were at about 2,500 cfs until the last week in April when they began to rise, peaking at 12,500 cfs on the 15 May. The reservoirs peaked at over 2.2 million acre-feet in the second week of July. Since the reservoirs were actually surcharged hindsight reveals that larger releases could have been made in March (to force the birds higher) and the reservoir would still have been filled.

This methodology while satisfactory for identifying situations in which streamflow forecast improvements would have been helpful is not suitable for the estimation of average annual benefits. A more satisfactory methodology is presented in the following chapter.

FOOTNOTES

[1] Comprehensive surveys of the Basin, its economy and its water management problems have been performed by the Idaho Water Resources Board; The U.S., Dept. of the Army, Corps of Engineers and the U.S., Dept. of Interior Bureau of Reclamation; Pacific Northwest Basins Commission (Idaho Economic Base Study for Water Requirements, (2 vols.; Boise, Idaho, 1969); Upper Snake River Basin, (4 vols.; Walla Walla, Washington and Boise, Idaho, 1961); Columbia-North Pacific Region; Comprehensive Framework Study, (16 vols.; Vancouver, Washington: 1969)).

[2] Corps of Engineers and Bureau of Reclamation, Upper Snake River Basin, Vol. I: Summary Report, Table 2 following p. 2-6.

[3] U.S., Dept. of the Army, Corps of Engineers, U.S. Army Engineer District, Reservoir Regulation Manual for Palisades Reservoir (Walla Walla, Washington: 1958), Table 1.

[4] U.S., Dept. of Commerce, Bureau of Census, Census of Population: 1970, General Population Characteristics, Final Report PC(1)-B24, Idaho (Washington, D.C.: Government Printing Office, 1971).

[5] Idaho Water Resources Board, Potentially Irrigable Lands in Idaho (Boise, Idaho: 1970), Table 13, p. 23 and Table 14. p. 25.

[6] Idaho Water Resources Board, Economic Base Study, Table III-17, p. 129.

[7] Calculated from Ibid., Table IV-3, p. 148, citing unidentified Employment Security Data; and Ibid., Table V-32 and V-33, p. 269, citing State of Idaho Dept. of Employment.

[8] These data on Palisades and Jackson Reservoirs from Corps of Engineers, Palisades Reservoir Regulations, frontpiece.

[9] Glen Simmons, private interview held during a visit to the U.S. Bureau of Reclamation Project offices in Burley, Idaho, July, 1970.

[10] U.S., Dept. of the Army, Corps of Engineers, U.S. Army Engineer District, Design Memo 2: Flood Control Improvements, Heise-Roberts Extension (Walla Walla, Washington: 1965) and Corps of Engineers, tentative working papers dated January 1970.

[11] L. Peterson, Bureau of Sports Fisheries and Wildlife, interview in Boise, Idaho, July, 1970

[12] Henry C. Eagle, *Development of Snake River Irrigation* (Idaho Falls, Idaho: mimeo., undated), pp. 2-3.

[13] *Ibid.*, p. 5.

[14] *Ibid.*, p. 6.

[15] K. Higginson, Director of Idaho Dept. of Water Administration, private interview in Boise, Idaho, July, 1970.

[16] Corps of Engineers, *Palisades Reservoir Regulations*, p. 17.

[17] U.S., Dept. of Interior, Bureau of Reclamation, publicity release, November, 1969.

[18] U.S., Dept. of Interior, Bureau of Reclamation, *Final Report on the Allocation of Costs of Palisades Project* (Boise, Idaho: 1970), p. 5.

[19] Corps of Engineers, tentative working papers, January, 1970.

[20] Donald J. Street, Economist, Bureau of Reclamation, Boise, Idaho; Telephone interview, May, 1972 and U.S. Bureau of Reclamation, unpublished farmed budgets for the Upper Snake Basin.

[21] Richard Lindegrin, Bureau of Reclamation, private interview, Boise, Idaho, July, 1970.

[22] Note that most of the hydrographs are defined in terms of active storage, whereas the 1959 hydrograph is defined in terms of total storage:

Active Storage	2,047,000.	acre-feet
Dead Storage	217,600.	acre-feet
Total Storage	2,264,600.	acre-feet

CHAPTER XVI

ESTIMATION BY SIMULATION, SIMULATION RESULTS AND ANALYSIS

The Simulation Program

In order to estimate the potential benefits from improvements in streamflow forecasting, the operations of Palisades and Jackson Reservoirs were simulated according to the principles discussed in the preceeding chapters. It was necessary to build a simulated streamflow forecasting and reservoir operation model for this purpose since suitable models were not readily available.

The model was written in Fortran and consists of a Main program and fourteen Subroutines. Its basic functions are to make forecasts of both seasonal water supply and daily streamflow, to operate the reservoirs on the basis of the forecasts and predetermined decision rules and to maintain accounts of its actions. The forecasting routines permit the programmer to determine the accuracy of each forecast independently of the other. The operating routines establish the release each day on the basis of 1) whether or not the reservoir will overflow and 2) whether or not the required quantity of vacant storage space is available for flood control.

The general methodology of the operating program is based on the following considerations. First, the sequence of reservoir storages over the next thirty day forecasting period will depend on the initial storage, the sequence of inflows and the pattern of releases. The initial storage is a datum and the streamflow forecast routine has provided forecasts for the inflows during the period. The releases however are unknown. Second, the conservation operation must not constrain the flood control operation but if flood releases are not necessary only irrigation releases should be made and if flood releases are required they should not be larger than necessary. Third, only today's release decision must actually be implemented. Fourth, flood control releases may exceed the channel capacity only under certain specified conditions. These last three considerations limit the number of possible release patterns that need to be considered by the simulator. The strategy used to operate the reservoirs is discussed in the following paragraphs. Although the model considers both overflow and encroachment considerations, only encroachment decisions are discussed here since the scheme for overflow decisions is basically the same.

First, given today's storage and the inflow forecast for the next thirty days, the operations of the reservoirs are simulated on the basis of a daily normal outflow release today and releases at channel capacity for the next twenty-nine days. If the storage sequence resulting from this strategy does not exceed the maximum storage permitted by the flood regulations, today's release is established and implemented. If the resulting storage sequence does exceed the maximum permitted by the flood control regulations, a new simulation is performed utilizing releases at channel capacity for the entire thirty day period. If the new storage sequence does not exceed the limit set by the flood control regulations, today's release is established between the daily normal irrigation release and the channel capacity. The actual release is determined on the basis of a lead time adjustment embodying the number of days of lead time before the storage is in excess of that permitted by the flood control regulations. If the storage sequence generated by a pattern of thirty days of releases at channel capacity exceeds the storage level permitted by the flood control regulations, a release at channel capacity is implemented today. Following the implementation of any release, the model advances itself one calendar day, generates a new set of forecasts and repeats the decision process.

The description provided above is a simplified version of the basic decision processes embodied in the model. Although the procedures utilized involve only simple arithmetic operations, the complexity of the flood control regulations and the complications of operating Jackson and Palisades in series, require frequent transfer of control from the Main program to various Subroutines, from Subroutine to Subroutine and from location to location within the programs. These complications make the detailed discussion of the model in Appendix II very complex. The reader familiar with Fortran programming or especially interested in the construction of the model is advised to read the prose of Appendix II in conjunction with the flow charts and the Fortran statement listing.

The Simulation Runs and the Results

Seven sets of simulation runs were conducted utilizing this model. Table 47 summarizes the parameter values for each run. The parameter SDCAL is the standard deviation of the seasonal water supply forecast. ACCUR is the proportionality factor for the day-to-day forecast relating the accuracy of any given forecast to the accuracy of present daily streamflow forecasts. INIT is the initialization or "seed" value for the random number generator used in the forecasting routines. The values of 250 and 1 for SDCAL and ACCUR approximate the present levels of forecast accuracy whereas the values of 0. and 0. indicate perfect forecast accuracy.

TABLE 47

PARAMETERS FOR SNAKE RIVER SIMULATION RUNS

All runs in this table SP=1,417,600 CAPP=20,000*

RUN	INIT	SDCAL	ACCUR	FIRST YEAR	LAST YEAR
16	-	0	0	1910	1968
15	231	250	1	1910	1953
4				1958	1968
19	445	250	1	1910	1953
14				1958	1968
24	231	250	0	1910	1968
17	445	250	0	1910	1953
11				1958	1968
25	231	0	1	1910	1968
18	445	0	1	1910	1953
10				1958	1968

*SP is the Storage Capacity of Palisades Reservoir in acre-feet, CAPP is the downstream channel capacity in cubic feet per second.

In order to compare the simulation results generated by the runs defined in Table 47 three summary variables are defined. The variables are chosen to reflect the objectives of the operating rules and the water service area constituents. To summarize the flood control operations, the variable MAXR is defined. This variable presents the maximum release in excess of 20,000 cfs for each year. If releases do not exceed 20,000 cfs in a particular year, the variable is constrained to a value of zero for that year. The maximum release in the year is chosen to make the summary variable consistent with the Corps of Engineers flood damage data.

The objective of the conservation operation is to maximize the storage in the reservoir. To summarize the storage sequences resulting from the operations, variable MAXS is defined. This variable presents the maximum yearly storage in Palisades Reservoir.

A third area of concern is the amount of water released during flood releases (as opposed to the rate at which the release is made) which the irrigators must divert as "pre-irrigation water" or see "wasted" downstream below Milner. The variable XREL considers this aspect of the problem.

XREL takes a value of 0. acre-feet in years when Palisades is filled to capacity and in years when no releases in excess of daily irrigation demand are made. Otherwise it takes the value of the sum of the number of acre-feet of water released in excess of the daily irrigation demands.

Table 48 defines the statistical distribution of the summary variables for simulation runs. Tables 49 through 51 present the samples of MAXR, MAXS and XREL. Only the summary variables from the Palisades operation are analyzed because in both this model and the actual operation, Jackson Reservoir is almost allowed to operate itself.

As discussed in Chapter XV the quality of the data on flood damages makes construction of benefit and damages functions from this source difficult. The quality of the economic data for the irrigation projects is excellent but economic values derived from them are very crop and farm specific. This also makes general value estimation, as is desired here, difficult. For these reasons, the analysis below will concentrate on determining whether or not the simulation results can be considered samples from the same population of results or whether the different output runs constitute samples from different populations--i.e., the mechanisms which generated the two samples were different. If the simulation results were all generated by the same mechanism, the expected damages

TABLE 48

SUMMARY OF OUTPUT RESULTS

RUN	NO.	MEAN	VARIANCE	STD. DEV.	MINIMUM	MAXIMUM
Maximum Yearly Flood Release (cubic feet of water per second) (MAXR)						
16	50	7978	.1163D09	10790.	0.0	27610.
15,4	50	7976	.1277D09	11300.	0.0	27650.
19,14	50	5902	.1070D09	10100.	0.0	26000.
24	50	9624	.1221D09	11050.	0.0	26800.
17,11	50	5069	.9355D08	9672.	0.0	26000.
25	50	10510	.1344D09	11590.	0.0	29980.
18,10	50	7946	.1152D09	10730.	0.0	25330.
Maximum Yearly Storage (acre-feet of water) (MAXS)						
16	50	.1325D07	.1416D11	119000.	750900.	1418000.
15,4	50	.1328D07	.1439D11	119000.	750900.	1418000.
19,14	50	.1304D07	.1350D11	116200.	750900.	1418000.
24	50	.1330D07	.1445D11	120200.	750900.	1418000.
17,11	50	.1310D07	.1489D11	122000.	750900.	1418000.
25	50	.1349D07	.1349D11	118000.	750900.	1418000.
18,10	50	.1345D07	.1381D11	117500.	750900.	1418000.
Releases in Excess of Daily Irrigation Demand in Years When the Reservoir Failed to Fill (acre-feet of water) (XREL)						
16	50	.3826D06	.2155D12	.4642D06	0.0	.1558D09
15,4	50	.4662D06	.2376D12	.4875D06	0.0	.1693D07
19,14	50	.5069D06	.2757D12	.5251D06	0.0	.1742D07
24	50	.4808D06	.1952D12	.4418D06	0.0	.1558D07
17,11	50	.6843D06	.1444D13	.1201D07	0.0	.8252D07
25	50	.4876D06	.2281D12	.4776D06	0.0	.1700D07
18,10	50	.4582D06	.2493D12	.4493D06	0.0	.1697D07

TABLE 49

MAXIMUM YEARLY FLOOD RELEASE (MAXR)
(CFS)

Runs Numbered

YEAR	16	15,4	19,14	24	17,11	25	18,10
1910	0.	25279.	21000.	24958.	0.	29980.	23966.
1911	23160.	0.	0.	0.	0.	21140.	0.
1912	0.	0.	0.	0.	0.	22486.	22000.
1913	0.	26804.	0.	26804.	0.	22000.	21804.
1914	0.	20384.	24804.	20380.	24804.	24119.	22000.
1915	0.	0.	0.	20000.	0.	0.	0.
1916	0.	21000.	0.	21000.	0.	21714.	21000.
1919	0.	0.	0.	0.	0.	22661.	0.
1922	20147.	26000.	21000.	30000.	21000.	0.	20856.
1924	0.	0.	0.	0.	0.	0.	0.
1925	22000.	26000.	0.	26000.	0.	22000.	21000.
1926	0.	0.	0.	20000.	0.	0.	0.
1927	20976.	22000.	22000.	23402.	22428.	20297.	20944.
1928	22000.	24000.	22000.	24000.	22000.	22766.	22000.
1929	0.	0.	0.	0.	0.	0.	0.
1930	0.	0.	0.	0.	0.	0.	0.
1931	0.	0.	0.	0.	0.	0.	0.
1932	0.	0.	0.	0.	0.	0.	0.
1933	0.	0.	0.	0.	0.	0.	0.
1934	0.	0.	0.	0.	0.	0.	0.
1935	0.	0.	0.	0.	0.	0.	0.
1936	21842.	27646.	24879.	22000.	24879.	23353.	25332.
1937	0.	0.	0.	0.	0.	0.	0.
1938	21851.	0.	0.	0.	0.	21678.	0.
1939	0.	0.	0.	20000.	0.	0.	0.

TABLE49 (Continued)

YEAR	16	15.4	19.14	24	17.11	25	18.10
1940	0.	0.	0.	20000.	0.	0.	0.
1941	0.	0.	0.	20000.	0.	0.	0.
1942	0.	0.	0.	0.	0.	0.	0.
1943	22000.	22000.	0.	0.	0.	22000.	0.
1944	0.	0.	0.	20000.	0.	0.	0.
1945	0.	0.	0.	0.	0.	0.	0.
1946	0.	21691.	0.	21691.	0.	0.	21000.
1947	0.	0.	0.	0.	0.	0.	21000.
1948	22673.	23924.	0.	0.	0.	24000.	22352.
1949	22000.	0.	0.	0.	0.	22000.	21000.
1950	21440.	20564.	0.	21460.	0.	20634.	0.
1951	0.	0.	0.	0.	0.	0.	0.
1952	22804.	0.	22158.	0.	21443.	22287.	22174.
1953	0.	0.	0.	0.	0.	0.	0.
1958	22626.	22890.	23461.	20805.	22903.	26180.	0.
1959	0.	0.	0.	0.	0.	0.	0.
1960	0.	0.	0.	0.	0.	0.	0.
1961	0.	0.	0.	0.	0.	0.	0.
1962	0.	22804.	20336.	20804.	23000.	0.	0.
1963	22000.	0.	24000.	23691.	24000.	22000.	21405.
1964	0.	0.	0.	0.	0.	0.	0.
1965	22255.	24804.	22804.	22000.	0.	22255.	0.
1966	21405.	0.	20636.	21405.	21000.	23262.	22530.
1967	20111.	0.	26000.	20804.	26000.	20434.	0.
1968	27607.	21000.	0.	0.	0.	26118.	24961.

TABLE 50

MAXIMUM YEARLY STORAGE (MAXS)

Runs Numbered

YEAR	16	15,4	19,14	24	17,11	25	18,10
1910	1400457.	1417500.	1347379.	1417600.	1329644.	1417600.	1417600.
1911	1400457.	1409500.	1370455.	1401173.	1371665.	1414135.	1417255.
1912	1417599.	1386490.	1409490.	1397449.	1417599.	1417599.	1417599.
1913	1389913.	1301950.	1313525.	1301950.	1302468.	1381428.	1370408.
1914	1387323.	1333064.	1294310.	1333050.	1294810.	1378009.	1376390.
1915	1227025.	1227025.	1227025.	1227025.	1227025.	1227025.	1227025.
1916	1392274.	1386237.	1322376.	1392965.	1320139.	1406754.	1395211.
1919	1417597.	1417597.	1417590.	1417597.	1417592.	1409768.	1417590.
1922	1407032.	1393919.	1370923.	1352938.	1386441.	1417600.	1406056.
1924	1254803.	1254803.	1254803.	1254803.	1254803.	1254803.	1254803.
1925	1391733.	1363903.	1293411.	1364279.	1294378.	1379661.	1368669.
1926	1417599.	1417599.	1417599.	1417599.	1417599.	1417599.	1417599.
1927	1417599.	1391352.	1383213.	1417599.	1396424.	1417599.	1398576.
1928	1303131.	1332713.	1277565.	1328273.	1274909.	1313566.	1301791.
1929	1339192.	1277955.	1245714.	1277966.	1246478.	1377372.	1353072.
1930	1417600.	1417600.	1417600.	1417600.	1417600.	1417600.	1417600.
1931	1089265.	1089265.	1089265.	1089265.	1089265.	1089265.	1089265.
1932	1417593.	1394361.	1363739.	1395627.	1263739.	1417598.	1417598.
1933	1385263.	1347263.	1264447.	1321018.	1263084.	1382699.	1375585.
1934	1135049.	1135049.	1135049.	1135049.	1135049.	1135049.	1135049.
1935	1233513.	1229513.	1229513.	1229513.	1229513.	1233513.	1233513.
1936	1401510.	1413356.	1371792.	1417599.	1378600.	1383289.	1385783.
1937	1379624.	1379624.	1381965.	1379624.	1379624.	1379624.	1381965.

TABLE 50 (Continued)

YEAR	16	15,4	19,14	24	17,11	25	18,10
1938	1405956.	1352152.	1350194.	1353072.	1350141.	1391682.	1399630.
1939	1417595.	1417595.	1417593.	1417595.	1417593.	1417595.	1417594.
1940	1274124.	1274124.	1276830.	1274124.	1274642.	1274124.	1276830.
1941	1111024.	1111024.	1111234.	1111024.	1111284.	1111024.	1111284.
1942	1349730.	1230395.	1256449.	1276395.	1256449.	1351780.	1346229.
1943	1417600.	1401305.	1365679.	1417600.	1370325.	1397746.	1411694.
1944	1302430.	1234364.	1263719.	1284364.	1268719.	1302480.	1303428.
1945	1392193.	1191551.	1132473.	1199551.	1182488.	1327780.	1304029.
1946	1382364.	1406173.	1252539.	1406178.	1246890.	1382356.	1367019.
1947	1321580.	1245529.	1227103.	1245529.	1227384.	1328327.	1315306.
1948	1401347.	1417599.	1355915.	1417599.	1407524.	1394803.	1369546.
1949	1381125.	1341992.	1292244.	1342425.	1284300.	1378395.	1365662.
1950	1417600.	1400360.	1391303.	1407021.	1401304.	1417600.	1417600.
1951	1402900.	1342317.	1264323.	1342817.	1262002.	1391015.	1390468.
1952	1354462.	1417600.	1339592.	1417600.	1351610.	1351674.	1348339.
1953	1406964.	1237664.	1188888.	1237864.	1190829.	1406963.	1403767.
1958	1417600.	1417600.	1417600.	1417600.	1417600.	1417600.	1417597.
1959	1415843.	1330979.	1358173.	1368525.	1417600.	1415054.	1408778.
1960	1315133.	1319958.	1315133.	1315133.	1318737.	1315133.	1316354.
1961	750903.	750903.	750903.	750903.	750903.	750903.	750903.
1962	1405275.	1295284.	1379565.	1350923.	1417600.	1385645.	1385106.
1963	1417598.	1403530.	1417593.	1417598.	1417598.	1417598.	1417599.
1964	1400435.	1400729.	1365444.	1394706.	1369660.	1397302.	1382012.
1965	1405227.	1410706.	1414050.	1405296.	1405316.	1402926.	1411282.
1966	1417600.	1417599.	1417600.	1418173.	1417599.	1417600.	1417600.
1967	1417600.	1405143.	1383733.	1403904.	1411299.	1404511.	1408500.
1968	1417599.	1416700.	1353146.	1409287.	1358146.	1417599.	1417600.

TABLE 51

EXCESS RELEASES (XREL)

Runs Numbered

YEAR	16	15,4	19,14	24	17,11	25	18,10
1910	835772.	0.	949342.	0.	921078.	0.	847956.
1911	835772.	775425.	307404.	773947.	805162.	781570.	785970.
1912	0.	588070.	531250.	677110.	669847.	671106.	680777.
1913	871972.	1059939.	1059442.	1059939.	1059421.	980462.	992539.
1914	717315.	777350.	313356.	777841.	813856.	728912.	733092.
1915	271363.	263366.	0.	271868.	0.	259396.	0.
1916	345475.	359521.	917113.	849341.	915882.	856990.	849719.
1919	0.	0.	0.	21515.	24867.	521322.	26727.
1922	521066.	540412.	568374.	577394.	551598.	0.	550842.
1924	0.	0.	0.	0.	0.	0.	0.
1925	859192.	339488.	961606.	889118.	961606.	873860.	888484.
1926	551123.	0.	0.	551123.	213318.	550876.	215295.
1927	0.	1120323.	1140412.	1134873.	1112073.	1108580.	1113182.
1928	1501062.	1471476.	1523693.	1475916.	1529282.	1409624.	1502903.
1929	36722.	150180.	213844.	150180.	213844.	50772.	74020.
1930	0.	0.	0.	0.	0.	0.	0.
1931	50394.	54141.	0.	50992.	0.	54016.	0.
1932	0.	110511.	236360.	108472.	236360.	80266.	80270.
1933	0.	38000.	122130.	64245.	122180.	2564.	11040.
1934	20936.	20991.	0.	23563.	0.	21498.	0.
1935	0.	4000.	4000.	4000.	4000.	0.	0.
1936	916920.	967380.	959333.	953479.	951935.	935240.	933842.
1937	0.	3000.	5774.	8000.	5774.	0.	0.

TABLE 51 (Continued)

YEAR	16	15,4	19,14	24	17,11	25	18,10
1938	514426.	570745.	663333.	669826.	665758.	624220.	623026.
1939	0.	0.	0.	719420.	394805.	719434.	337907.
1940	336294.	334834.	0.	336294.	0.	337426.	0.
1941	331509.	315713.	0.	331509.	0.	331322.	0.
1942	24000.	92326.	141054.	96326.	141055.	22000.	42000.
1943	0.	1692912.	1741530.	0.	1718778	1700458.	1697255.
1944	411439.	428550.	77648.	475120.	77642.	389916.	0.
1945	0.	200652.	209888.	192652.	209888.	62192.	83326.
1946	1015314.	1013002.	1145070.	1013002.	1150070.	1016824.	1031584.
1947	733230.	307074.	326666.	807074.	8252100.	726482.	738452.
1948	533024.	0.	594264.	626579.	677143.	640052.	670023.
1949	542697.	584691.	633522.	583824.	639523.	545430.	560105.
1950	0.	1188625.	1199902.	1186206.	1186168.	0.	0.
1951	1312987.	1372213.	1453888.	1372218.	1453888.	1324878.	1328531.
1952	1230057.	0.	1291646.	0.	1281661.	1281776.	1283258.
1953	76366.	227690.	274723.	227690.	274728.	76650.	77706.
1958	0.	0.	0.	0.	0.	335906.	339562.
1959	35130.	188326.	92053.	81854.	274910.	35330.	50549.
1960	0.	0.	0.	0.	0.	0.	0.
1961	0.	0.	0.	0.	0.	0.	0.
1962	361225.	453343.	379877.	404520.	577455.	381956.	384371.
1963	0.	521880.	0.	452177.	472711.	448810.	446865.
1964	923127.	922936.	956888.	927624.	952671.	925020.	940102.
1965	1557754.	1563852.	1569702.	1557691.	1559948.	1560064.	1560118.
1966	0.	0.	0.	583981.	567429.	0.	0.
1967	0.	415137.	427073.	422368.	402878.	424028.	421256.
1968	0.	585884.	588165.	551328.	584165.	503926.	0.

and benefits of the operation must be the same for each level of forecast accuracy.[1]

To compare the distributions of the output generated by the above sets of simulations, Paired Comparison T-tests were performed on the sets of observations listed in Tables 49 through 51. The Paired Comparison T-test assumes that the observations were generated by the same mechanism with the exception of the simulation parameter in question. The ability to perform this test requires that the observations are individually identifiable in some way and that each observation may be paired with similar observations from another sample. In this case, the data are yearly observations on the variables discussed above, where it is known that the initial conditions at the beginning of each year were identical for each run and that the decision rules, the size of the reservoir and the downstream channel capacity were also identical in each case. The Paired Comparison T-test was chosen over a comparison of the means and standard deviations of the samples because the former requires only that the distribution of differences be approximately normally distributed. Although the results are not presented here, each of the samples of differences was plotted to see if the normality assumption was warranted. Given the large sample size, permitting an appeal to the Law of Large Numbers, the plots were sufficiently good approximations to a normal distribution to justify the use of the test.

The results of the Paired Comparison T-tests on the samples shown in Table 49 through Table 51 are presented in Table 52 through Table 54. Table 52 presents the results for variable MAXR (the Maximum Flood Release in excess of 20,000 cfs). As can be seen, none of the paired samples differ significantly. The other factor to notice in the table is that the sign of the mean in each case is opposite to what one would expect. In the six cases where the results of a run with an imperfect forecast are subtracted from a run with a perfect forecast, one hopes that the mean would be negative. In the other four cases, one hopes that the mean would be positive. This hope is based on the assumption that an improvement in forecasting would result in a sample containing fewer releases in excess of 20,000 cfs and that those in excess of that release rate would exceed it by a smaller amount. There are two possible

TABLE 52

MAXR PAIRED T-TEST RESULTS

Run No.	Parameter Values		
	SDCAL*	ACCUR**	INIT***
16	0	0	-
15,4	250	1	231
19,14	250	1	445
24	250	0	231
17,11	250	0	445
25	0	1	231
18,10	0	1	445

Paired Variable	No	Mean	Std. Dev.	T-Stat	Sig @ .95
16-15,4	50	2.140	117702.	.00129	No
16-19,14	50	2076.	10601.	1.3849	No
15,4-24	50	-5993.	27822.	-1.523	No
19,14-17,11	50	832.	4367.	1.347	No
15,4-25	50	-2531.	10924.	-1.639	No
19,14-18,10	50	-2044.	11308.	-1.278	No
16-24	50	582.	12836.	.0321	No
16-17,11	50	2980.	10567.	1.946	No
16-25	50	2260.	8994.	1.7770	No
16-18,10	50	31.	11722.	.0189	No

[*] SDCAL is the standard deviation of the seasonal water supply forecast.

[**] ACCUR is the porpotional daily forecast error parameter, zero implying perfect forecast.

[***] INIT is seed value for random number generator.

TABLE 53

MAXS PAIRED T-TEST RESULTS

Run No.	Parameter Values*		
	SDCAL	ACCUR	INIT
16	0	0	-
15,4	250	1	231
19,14	250	1	445
24	250	0	231
17,11	250	0	445
25	0	1	231
18,10	0	1	445

Paired Variable	No	Mean	Std. Dev.	T-Stat	Sig @ .95
16-15,4	50	278753.	1802850.	1.0933	No
16-19,14	50	302743.	1798380.	1.1904	No
15,4-24	50	-1477.	13044.	-0.812	No
19,14-17,11	50	-2719.	9880.	-1.946	No
15,4-25	50	-20453.	42665.	-3.386	Yes
19,14-18,10	50	-40847.	49395.	-5.847	Yes
16-24	50	227244.	1801709.	1.0882	No
16-17,11	50	44856.	58611.	5.4115	Yes
16-25	50	3084.	11859.	1.8393	No
16-18,10	50	6728.	15597.	3.051	Yes

*See Table 52for explanation of SDCAL, ACCUR, INIT.

TABLE 54

XREL PAIRED T-TEST RESULTS

Run No.	Parameter Values*		
	SDCAL	ACCUR	INIT
16	0	0	-
15,4	250	1	231
19,14	250	1	445
24	250	0	231
17,11	250	0	445
25	0	1	231
18,10	0	1	445

Paired Variable	No	Mean	Std. Dev.	T-Stat	Sig @ .95
16-15,4	50	-83644.	442933.	-1.3353	No
16-19,14	50	-124296.	378613.	-2.3124	Yes
15,4-24	50	-2955.	289095.	-0.072	No
19,14-17,11	50	-177406.	1052873.	-1.191	No
15,4-25	50	-17406.	317755.	-0.327	No
19,14-18,10	50	48706.	219089.	1.571	No
16-24	50	-98280.	369571.	-1.8804	No
16-17,11	50	-301702.	1107089.	-1.927	No
16-25	50	-105069.	365432.	-2.033	Yes
16-18,10	50	-75589.	335388.	-1.594	No

*See Table 52 for explanation of SDCAL. ACCUR, INIT.

reasons for the reversal of the signs. First, in the cases with imperfect information, positive forecast errors could cause releases in excess of daily normal irrigation releases but less than 20,000 cfs. These releases could prevent the reservoir from entering the critical state in which releases in excess of 20,000 cfs would be necessary. These erroneous releases are not reflected in the MAXR variable since even if they are the maximum release for the year they enter the MAXR sample as a zero (since they do not exceed 20,000 cfs). When perfect knowledge is available, these erroneous releases will not be made and the reservoir will enter the critical state more often (i.e. be near capacity storage or be near the maximum storage permitted by the flood control reservation diagram). If this effect is significant one would expect the sign of the mean of the XREL variable (the sum of the releases in excess of the daily normal irrigation demands in a year when the reservoir failed to fill) to indicate larger excess releases with larger forecast errors. Table 54 shows that this is the case. This in fact is the reason for the inappropriate sign on the mean of the differences of the variable MAXR (Maximum Release). Given perfect knowledge of inflows thirty days in advance, there is no reason why decision rules could not be formed that would prevent all releases in excess of 20,000 cfs. This was not done here because a major premise of this study is to investigate the results obtained if forecasts were improved while the present operating procedures are maintained. A second reason for not formulating a set of release rules specifically for the perfect knowledge case is the amount of work involved for what is in effect one simulation run.

There is a second possible reason for the inappropriate signs on the means on the variable MAXR. Negative forecast errors may be preventing the system from entering the critical state in which flood releases in excess of 20,000 cfs are required. Thus the results with perfect knowledge could more accurately reflect the required number of releases in excess of 20,000 cfs.

Table 53 presents the results of the Paired Comparison T-test on the samples of variable MAXS (the maximum storage each year). It is in this variable that the only truly significant differences between the pairs of samples are observed. In this case, it is interesting to note that while no significant differences are obtained by upgrading both the water supply and day-to-day forecasts from the present accuracy to perfect accuracy, significant results may be obtained by improving one or the other of the forecasts. After the one forecast has been improved, significant results can be obtained if the other forecast is improved.

The sample of differences generated by the improvement of the water supply forecast accuracy from a standard deviation of 250,000 acre-feet (SDCAL=250) to a standard deviation of zero acre-feet (the day-to-day forecast held at the present level of accuracy) was the only run that was significantly different with both seed value 231 and value 445. (It should be noted that three of the four significant runs utilized 445 as the seed value for the random number generator.) The fact that this run was significant with both seed values and the fact that the T-statistics were substantial indicates that this one level of forecast improvement provides the best potential for significant benefits. It will be noted that significant differences were observed in three of the four runs involving improvement in the seasonal forecasts and no change in the postulated day-to-day forecast accuracy.

Table 54 presents the results of the tests on the variable XREL (the sum of the releases in excess of daily normal irrigation demands in years when the reservoir failed to fill). In this case, it may be seen that in only two cases is there any indication of significance and that the results are only barely significant at that. It is interesting to note that the significant differences in reservoir storage discussed above are not reflected in significant reductions of releases in excess of normal irrigation demands as measured by the samples of the variable XREL. In years when the reservoir filled with the improved forecasts but had not filled with the erroneous forecast, the observation in the sample XREL changes to zero from a positive value. In the case of the present day-to-day accuracy and an improvement in the seasonal forecast, the reservoir filled in 9 additional years out of 100. With the improvement in the seasonal forecast on the assumption of an already perfect day-to-day forecast, the reservoir filled in an additional twenty-six years. The fact that the increase in the number of years the reservoir filled, and that the mean of the differences of XREL and the standard deviation of the distribution are so large indicate that with α set at .05 there is a high probability of β type errors being made. This problem will be discussed further in the conclusions of this report and inferences drawn concerning additional testing.

To estimate the average annual benefit from the improvement in forecast, we may utilize the mean difference of the various runs as presented in Table 53. As discussed in Chapter XV the average value of an acre-foot of water in the Upper Snake River area is in the range of \$5.00-\$10.00. Table 55 presents the mean differences as shown in Table 53 and the equivalent average annual benefit.

TABLE 55

BENEFITS FROM THE FORECAST IMPROVEMENTS

PARAMETERS		MEAN DIFFERENCE (acre-feet)	VALUE	
SDCAL	ACCUR		@ \$5.00	@ \$10.00
0	1	30,650*	\$153,250.	\$306,500.
250	1			
0	0	44,856	\$224,280.	\$448,560.
250	0			
0	0	6,728	\$ 33,640.	\$ 67,280.
0	1			

*Result of averaging the two significant runs for this level of improvement.

The results discussed to this point were generated on the assumption that the reservoirs and the operating criteria were maintained in approximately their present form. As is discussed in Appendix I, the operating rules and the reservoir configuration are interdependent in that the operating rules and reservoir size were adjusted during the project planning until simulations indicated that the flood regulation would be performed "adequately" 97% of the time. Adjustment of the operation regulations to obtain "adequate" performance included an adjustment of the flood control reservation curves by a factor of twice the standard deviation of the snow pack forecasts.

In the light of the streamflow forecast improvements postulated in this model, a recalculation of the flood control reservation curves to reflect these forecast improvements would be desirable. However, this is beyond the scope of this paper. Instead of such an adjustment, several runs were made on the assumptions that 1) the reservoir capacity of Palisades Reservoir was only 1,300,000 acre-feet and 2) that the critical channel capacity downstream of Palisades was only 15,000 cfs rather than the actual 20,000 cfs.

These assumption changes destroy the critical relationship between the operating rules and the reservoir configuration. In the first case whereas the rules were formulated to control floods using a maximum of 1,417,600 acre-feet of storage, only 1,300,000 acre-feet is now available. In the second case, the operating rules assumed that flood control space could be emptied at a rate of 20,000 cfs without damage. With the new assumption, this is no longer true. It must be admitted that these assumption changes are a crude approximation to the redesigned operating rules. However, these new assumptions do have significant effects on the output results.

The output of the runs involving the first change in assumptions are the most interesting of the two and will be discussed below. Table 56 summarizes the parameters for the simulation runs. Table 57 presents the summary results of the output. A comparison of the variable MAXR in Tables 49 and 57 for comparable runs (i.e. 16 vs. 21; 15,4 vs. 23; 19,14 vs. 26) reveals that the mean value of MAXR is greater with the smaller reservoir than with the larger. This result is of course to be expected.

TABLE 56

SUMMARY OF SIMULATION PARAMETERS

RUN NO.	SDCAL*	ACCUR**	INIT***	SP****(acre-feet)
21	0.	0.	-	1,300,000.
23	250.	1.	231	1,300,000.
26	250.	1	445	1,300,000.

*SDCAL is the Standard Deviation for the Seasonal Water Supply Forecast.

**ACCUR is the accuracy parameter for the day-to-day forecast.

***INIT is the initialization parameter for the random number generator.

****SP is the storage capacity of Palisades Reservoir.

TABLE 57

SUMMARY OF OUTPUT RESULTS - REDUCED STORAGE

RUN	NO.	MEAN	VARIATION	STD. DEV.	MINIMUM	MAXIMUM
Maximum Yearly Flood Release (cubic feet of water per second) (MAXR)						
21	50	12090.	.1284D09	11330.	0.0	27600.
23	50	9707.	.1353D09	11630.	0.0	27830.
26	50	7638.	.1287D09	11340.	0.0	30000.
Maximum Yearly Storage (acre-feet of water) (MAXS)						
21	50	.1260D07	.7648D10	87450.	750900.	1300000.
23	50	.1243D07	.7881D10	88780.	750900.	1300000.
26	50	.1241D07	.8036D10	89640.	750900.	1300000.
Releases in Excess of Daily Irrigation Demand in Years When the Reservoir Failed to Fill (acre-feet of water) (XREL)						
21	50	397800.	.2534D12	503400.	0.0	1675000.
23	50	447800.	.2694D12	519000.	0.0	1811000.
26	50	493100.	.3004D12	548100.	0.0	1817000.

Paired Comparison T-tests were once again performed on the samples generated at the different levels of information accuracy. The samples are shown in Table 58 through Table 60 and the results are shown in Table 61. Once again it will be seen that the sign of the mean of variable MAXR is counter to expectations. The reasoning and the justification for this result is presented above. The T-test results probably indicate only the need for a new set of decision rules in the event of perfect streamflow forecasts. It will be noted, however that of the two T-tests on MAXR, the first was not significant even though the standard deviation of the sample was relatively small. The second T-test was only just significant indicating that given the variation present more runs to generate large samples might be necessary to generate any significant differences.

The T-tests on variable MAXS once again indicate a truly significant difference between the samples of maximum storage. The fact that both T-tests show large T-statistics when the standard deviation is large indicates a high potential for significant benefits. The sign of the mean of the differences in MAXS is as would be expected.

The results on the test of XREL fail to show significance. However the standard deviation is large in each case indicating that larger sample sizes may be necessary for this variable. The sign of the mean conforms with a priori expectations.

One of the most interesting aspects of these runs with the reduced storage capacity is the number of years in which the reservoir was operated without flood loss. In the case of Run 23, the reservoir was operated without a release in excess of 20,000 cfs in 30 of the 50 years of the run. During Run 26 no flood releases were made in 36 years of the run. These results may not seem exceptional until one realizes that whereas Runs 23 and 26 were simulated with forecast parameters of SDCAL=250,000 and ACCUR=1, Run 16, made with perfect forecasts and a larger reservoir, avoided flood releases in only 32 of the 50 years of the run. It must be noted, however, that with the storage capacity of the reservoir reduced and perfect knowledge, the reservoir did not operate as well. In this case, the reservoir avoided flood releases in only 23 of the 50 years. A Paired Comparison T-test between Run 16 and Run 21

TABLE 58

MAXIMUM YEARLY FLOOD RELEASE* (MAXR)
(CUBIC FEET OF WATER PER SECOND)

Runs Numbered

YEAR**	RUN 21	RUN 23	RUN 26
1910	25066.	25279.	24956.
1911	22000.	0.	20804.
1912	23559.	0.	0.
1913	22000.	26804.	0.
1914	23691.	20804.	26804.
1915	0.	0.	0.
1916	22000.	20804.	0.
1919	0.	0.	0.
1922	21576.	26589.	0.
1924	0.	0.	0.
1925	22000.	26000.	22804.
1926	0.	0.	0.
1927	22000.	24000.	23605.
1928	23038.	24000.	22970.
1929	0.	0.	0.
1930	0.	0.	0.
1931	0.	0.	0.
1932	0.	0.	0.
1933	21091.	0.	0.
1934	0.	0.	0.
1935	0.	0.	0.
1936	23940.	27826.	26794.
1937	0.	0.	0.
1938	20804.	0.	0.
1939	0.	0.	0.
1940	0.	0.	0.
1941	0.	0.	0.
1942	20304.	0.	0.
1943	22000.	22000.	24000.
1944	0.	0.	0.
1945	0.	0.	0.
1946	0.	0.	0.
1947	21000.	0.	22000.
1948	22781.	23924.	22000.
1949	0.	21000.	24000.
1950	21439.	20585.	22804.
1951	20686.	20098.	0.
1952	22804.	0.	27077.
1953	22000.	0.	0.
1958	24861.	26180.	30121.
1959	0.	0.	0.
1960	0.	0.	0.
1961	0.	0.	0.
1962	0.	20804.	20463.

TABLE 58 (Continued)

YEAR	RUN 21	RUN 23	RUN 26
1963	22000.	21575.	20804.
1964	0.	0.	0.
1965	22285.	22000.	0.
1966	21405.	23262.	0.
1967	20423.	20804.	0.
1968	27604.	21000.	0.

[*] See Table 56 for definition of parameter values used in Runs #21, 23, 26.

[**] Years for which no observation shown were not simulated because of input data problems.

TABLE 59

MAXIMUM YEARLY STORAGE* (MAXS)
(ACRE-FEET OF WATER)

YEAR**	RUN 21	RUN 23	RUN 26
1910	1300000.	1300000.	1300000.
1911	1299989.	1279700.	1291775.
1912	1299999.	1269944.	1299999.
1913	1277430.	1193477.	1271509.
1914	1264392.	1233797.	1268354.
1915	1227025.	1277025.	1277025.
1916	1275172.	1270313.	1264624.
1919	1299997.	1299997.	1299997.
1922	1289368.	1234479.	1289396.
1924	1254803.	1254803.	1254803.
1925	1262703.	1244076.	1224154.
1926	1299999.	1299999.	1299999.
1927	1299999.	1299999.	1299999.
1928	1195936.	1211020.	1211493.
1929	1272747.	1246960.	1192986.
1930	1300000.	1259793.	1300000.
1931	1089265.	1089265.	1089265.
1932	1299998.	1278339.	1250729.
1933	1300000.	1233702.	1254752.
1934	1135049.	1135049.	1135049.
1935	1233513.	1225513.	1221513.
1936	1285803.	1296256.	1260725.
1937	1299999.	1299999.	1299995.
1938	1286948.	1253120.	1263949.
1939	1299995.	1299995.	1299995.
1940	1274124.	1274124.	1274124.
1941	1111024.	1111024.	1111024.
1942	1263159.	1263159.	1232807.
1943	1300000.	1284755.	1284335.
1944	1299999.	1284364.	1268719.
1945	1278826.	1138937.	1134308.
1946	1261010.	1291415.	1262562.
1947	1210204.	1136975.	1148383.
1948	1283739.	1299999.	1299999.
1949	1261441.	1215543.	1260556.
1950	1300000.	1282021.	1282004.
1951	1278413.	1238570.	1217696.
1952	1237495.	1300000.	1219131.
1953	1289337.	1215754.	1132359.
1958	1300000.	1300000.	1300000.
1959	1297455.	1282740.	1230499.
1960	1299997.	1299997.	1299997.
1961	750903.	750903.	750903.
1962	1285199.	1243071.	1262300.

TABLE 59 (Continued)

YEAR	RUN 21	RUN 23	RUN 26
1963	1299999.	1299999.	1299999.
1964	1281599.	1250433.	1249061.
1965	1287627.	1283637.	1280966.
1966	1300000.	1300000.	1299999.
1967	1287495.	1285334.	1282215.
1968	1299999.	1299999.	1299999.

[*] See Table 56 for definition of parameter values used in Runs #21, 23, 26.

[**] Years for which no observation shown were not simulated because of input data problems.

TABLE 60

RELEASES IN EXCESS OF IRRIGATION DEMAND DURING YEARS WHEN RESERVOIR FAILED TO FILL (XREL)*

YEAR**	RUN 21	RUN 23	RUN 26
1910	0.	0.	0.
1911	0.	899481.	0.
1912	0.	804613.	0.
1913	1084459.	1170643.	1092608.
1914	840273.	877093.	848512.
1915	325475.	325505.	325784.
1916	963075.	969158.	973624.
1919	0.	0.	0.
1922	638736.	696949.	643780.
1924	0.	0.	0.
1925	988240.	1009328.	1031770.
1926	0.	0.	0.
1927	0.	0.	1240758.
1928	1608262.	1593176.	1592704.
1929	166731.	216147.	276924.
1930	0.	227244.	0.
1931	235338.	239250.	239492.
1932	0.	225758.	232808.
1933	0.	151562.	130512.
1934	211072.	211072.	224860.
1935	0.	8000.	12000.
1936	1032733.	0.	1069810.
1937	0.	0.	0.
1938	732068.	769781.	751948.
1939	0.	0.	0.
1940	326444.	339290.	326574.
1941	336755.	276367.	337590.
1942	152493.	178944.	213916.
1943	0.	1810513.	1817288.
1944	0.	515640.	434046.
1945	113375.	253270.	258070.
1946	1138173.	0.	1153258.
1947	844622.	915640.	904228.
1948	750616.	0.	0.
1949	662380.	710715.	669600.
1950	0.	1311220.	1306026.
1951	1438703.	1476468.	1498202.
1952	1397235.	0.	1410716.
1953	192013.	249800.	333200.
1958	0.	0.	0.
1959	0.	167635.	169468.
1960	0.	0.	0.
1961	0.	0.	0.
1962	472469.	512373.	0.

TABLE 60 (Continued)

YEAR	RUN 21	RUN 23	RUN 26
1963	0.	0.	0.
1964	1040732.	1072068.	1072782.
1965	1675358.	1679355.	1583096.
1966	0.	0.	0.
1967	519939.	526886.	477616.
1968	0.	0.	0.

(units are acre-feet of water)

[*] See Table 56 for definition of parameter values for Runs #21, 23, 26.

[**] Years for which no observation shown were not simulated because of input data problems.

TABLE 61

PAIRED T-TEST RESULTS

RUN NO.	SDCAL	ACCUR	INIT
	PARAMETER VALUES		
21	0	0	-
23	250	1	231
26	250	1	445

PAIRED VARIABLE	NO.	MEAN	STD. DEV.	T-STAT	SIG. @ .95
Maximum Flood Release (cubic feet of water per second) (MAXR)					
21-23	50	2380.	9593.	1.574	No
21-26	50	4449.	11433.	2.752	Yes
Maximum Yearly Storage (acre-feet of water) (MAXS)					
21-23	50	16396.	32214.	3.598	Yes
21-26	50	19054.	34574.	3.897	Yes
Releases in Excess of Irrigation Demands During Years When Reservoir Failed to Fill (acre-feet of water) (XREL)					
21-23	50	-50063.	488256.	-.7250	No
21-26	50	-95318.	384618.	-1.752	No

TABLE 62

COMPARISON OF RUNS 16 AND 21* MAXIMUM YEARLY FLOOD RELEASE (cfs of water)

YEAR	RUN 16	RUN 21
1910	0.0	25066.
1911	23169.	22000.
1912	0.0	23599.
1913	0.0	22000.
1914	0.0	23691.
1915	0.0	0.0
1916	0.0	22000.
1919	0.0	0.0
1922	20147.	21576.
1924	0.0	0.0
1925	22000.	22000.
1926	0.0	0.0
1927	20976.	22000.
1928	22000.	23038.
1929	0.0	0.0
1930	0.0	0.0
1931	0.0	0.0
1932	0.0	0.0
1933	0.0	21091.
1934	0.0	0.0
1935	0.0	0.0
1936	21842.	23940.
1937	0.0	0.0
1938	21851.	20804.
1939	0.0	0.0
1940	0.0	0.0
1941	0.0	0.0
1942	0.0	20304.
1943	22000.	22000.
1944	0.0	0.0
1945	0.0	0.0
1946	0.0	0.0
1947	0.0	21000.
1948	22673.	22781.
1949	22000.	0.0
1950	21440.	21439.
1951	0.0	20636.
1952	22804.	22804.
1953	0.0	22000.
1958	22626.	24861.
1959	0.0	0.0
1960	0.0	0.0
1961	0.0	0.0
1962	0.0	0.0

TABLE 62 (Continued)

YEAR	RUN 16	RUN 21
1963	22000.	22000.
1964	0.0	0.0
1965	22255.	22285.
1966	21405.	21405.
1967	20111.	20423.
1968	27607.	27604.

*Runs 16 and 21 are both "perfect forecast" runs. They are differentiated by the assumption concerning storage capacity of Palisades. In Run 16, the capacity is 1,417,600 acre-feet. In Run 21, it is 1,300,000 acre-feet.

(both perfect knowledge runs) showed that there was a significant difference between the two runs. The results were:

Mean	Standard Deviation	T-statistic
-4109.	9666.	-3.006

A comparison of the two samples presented in Table 62 shows that the major deviation between the two occurs in the years when Run 23 made a flood release in excess of 20,000 cfs whereas Run 16 did not. During years when both runs made flood releases in excess of 20,000 cfs, little difference is seen in the sample observation of MAXR.

The above results show the sensitivity of the model to releases in excess of daily irrigation demand (DNOP) but less than the critical channel capacity. In the erroneous forecast situation with reduced storage capacity, the model avoided making releases in excess of 20,000 cfs by making more releases in excess of DNOP. In the perfect knowledge case however, where the erroneous forecasts did not lead to as many excess releases, we have more releases in excess of 20,000 cfs. Once again we see the trade off between flood control and conservation storage. The price of a smaller reservoir providing equivalent flood control protection is an increase in the size of the XREL variable.

The average annual benefits from the improvement in streamflow forecasting with the smaller reservoir are presented in Table 63. The benefits for the increased average storage are calculated as in Table 55 above.

TABLE 63

ANNUAL STORAGE BENEFITS REDUCED STORAGE CAPACITY CASE

PARAMETERS		MEAN DIFFERENCE	VALUE	
SDCAL	ACCUR	(acre-feet)	@ $5.00	@ $10.00
0 250	0 1	17800*	$89,400.	$178,000.

*Result of averaging the two significant runs for this level of improvement.

As discussed in Chapter XV in the discussion of the economic data for the Upper Snake River Basin, the available Corps of Engineers flood damage data is inadequate in that it does not discuss the damage relative to the length of the innundation or the marginal effects of reinnundating land several times a year. Thus it is not practical to estimate the possible benefits from these two sources. Nevertheless it is instructive to observe the frequency with which the releases were raised above 20,000 cfs in each year. Table 64 presents summary statistics for each run with respect to this observation. For example during Run 16, there were 32 years during which no releases were made in excess of 20,000 cfs, 10 years during which there was one "incident" of flooding, and 6 years in which there were 2 "incidents" of flooding and one year for each of 3 "incidents" and 4 "incidents." [2] The total number of days with releases in excess of 20,000 during run 16 was 46 i.e., an average of less than one day per year.

TABLE 64

FREQUENCY OF MULTIPLE INNUNDATIONS AND TOTAL NUMBER OF DAYS OF INNUNDATION

RUN NO.	NUMBER OF YEARS PER INCIDENT LEVEL						NO. OF DAYS IN EXCESS OF 20,000 cfs
	0	1	2	3	4	5	
16	32	10	6	1	1	0	46
15,4	33	13	3	0	1	0	40
19,14	37	11	2	0	0	0	24
24	34	11	5	0	0	0	34
17,11	40	9	1	0	0	0	23
25	27	9	7	5	2	0	78
18,10	32	9	3	4	2	0	50

Note: the sum of the cell values times the value of the number at the top of the column will not equal the total number of days in excess of 20,000 cfs.

The results of Table 64 seem to reflect the results discussed above with respect to the Paired Comparison T-test on variable MAXR. The runs with the greatest tendency to multiple innundations are Runs 16; 25; and 18,10. These are the runs in which a perfect knowledge seasonal forecast was in effect. Hence the reservoir decision routine made fewer releases in excess of DNOP which did not exceed 20,000 cfs. It will also be noted that these 3 runs had the largest total number of days with releases in excess of 20,000 cfs. Thus the sensitivity of the model to the number of releases in excess of DNOP is once again illustrated. It may be noted as well, that the results differ according to the seed value of the random number generator. Runs 15,4; 24; 25 were all performed with a seed value of 231. The others used a value of 445. It can be seen that there is a greater tendency to multiple incidents of releases in excess of 20,000 cfs with an initialization value of 231. This difference in the tendency reflects the differences in the sequence of random forecast errors generated by the random number generator. Without a more detailed analysis, it is not possible to state how the two sequences differed.

FOOTNOTES

[1] All of the statistical analysis reported here utilized the CONSTAT package developed by The University of Michigan Statistical Laboratory.

[2] An incident is defined as an occassion when the releases rise above 20,000 cfs (or 15,000 cfs during the special runs) for one or more days and then return to a level of less than 20,000 cfs (or 15,000 cfs) for one or more days.

CHAPTER XVII

CONCLUSIONS AND SUGGESTED IMPROVEMENTS IN METHODOLOGY

The conclusions of a study of this type must focus on three issues. First, do improved streamflow forecasts result in realizable benefits? Second, in the light of the experience derived during the foregoing investigation, are changes in the applied methodology needed? Third, is the methodology suitable for application to other situations for estimating the benefits in other basins?

Are There Benefits To Be Derived From Improved Forecasts?

Significant differences between the samples of maximum yearly storage in the reservoir were found with changes in forecast accuracy. Given the assumption that the water has significant economic value, economic benefit is derived from the forecast improvement. In areas in which water reliability relative to suitable land resources represent a major constraint (as for example in the semi-arid Southwest or in large areas in Mexico) these benefits might be large. However as was discussed in Chapter XV several authoratative persons in the Upper Snake River basin would say that increased yearly storage at the present time would result only in a need for a greater flood control draw down in the following year. Thus while statistically significant hydrologic changes may be identified as a result of the forecast improvement, economically significant changes do not necessarily result.

Significant differences were not observed in the case of the yearly maximum flood release or the summation of the yearly excess release from the reservoir. In both of these cases the variation of the sample and the small sample size could have caused type errors of the hypothesis of no significant differences not being rejected when it should have been. These problems will be discussed below. In the case of the yearly maximum flood release however the nature of the flood control operation would appear to minimize the possibility of benefits. As will be recalled from Chapter XLV, a flood loss caused by an error in forecasting required that the storage in the reservoir, the forecast and forecast error be in a critical relationship to each other. However as was discussed in the Reservoir Regulation Appendix, the parameter curves of the flood control reservation diagram are adjusted to minimize the frequency with which a Type 2 flood loss[1] could be caused by a forecasting error. The result is that the reservoir will operate adequately 97% of the time.

The probability of the system being in the critical state to cause a Type 1 flood loss is reduced by the fact that the simulation model raises the releases above the daily irrigation demand when an encroachment or overflow is forecasted during the thirty day period following the date of decision. This type of precautionary increase in releases will reduce the frequency of serious encroachment or overflow on the day of decision and hence reduce the frequency of releases in excess of 20,000 cfs.

Thus since the operating rules under conditions of imperfect forecasts are designed to reduce the losses caused by errors in the forecasts, it should not be surprising that benefits from forecast improvements are difficult to find. However, this statement applies only to presently constructed dams where the decision philosophy is not changed to take the new forecast accuracy into consideration. In the planning of the operating rules for new dams or in cases where the dedication of storage space in an existing reservoir is being adjusted to reflect the reduced inaccuracies in the forecasts, benefits become more significant. First, a smaller amount of space would be required for conditional flood control use. This space could be dedicated to conservation uses. In the case of new dams, the size of the dam could be reduced with resulting savings in construction and carrying costs.

The factor which reduced the probability of Type 1 flood losses discussed above would also tend to reduce the size of the releases in excess of the daily normal irrigation requirements. When encroachment or overflow is forecasted within the next thirty days, the releases are raised above daily irrigation demands on the basis of the size of the release needed to prevent the excess storage and the number of days before the excess storage is reached. The timing adjustment involves a quadratic proportionality factor which prevents the releases from being raised significantly above the daily irrigation demand until the event is sufficiently close to make the forecast of it relatively accurate.

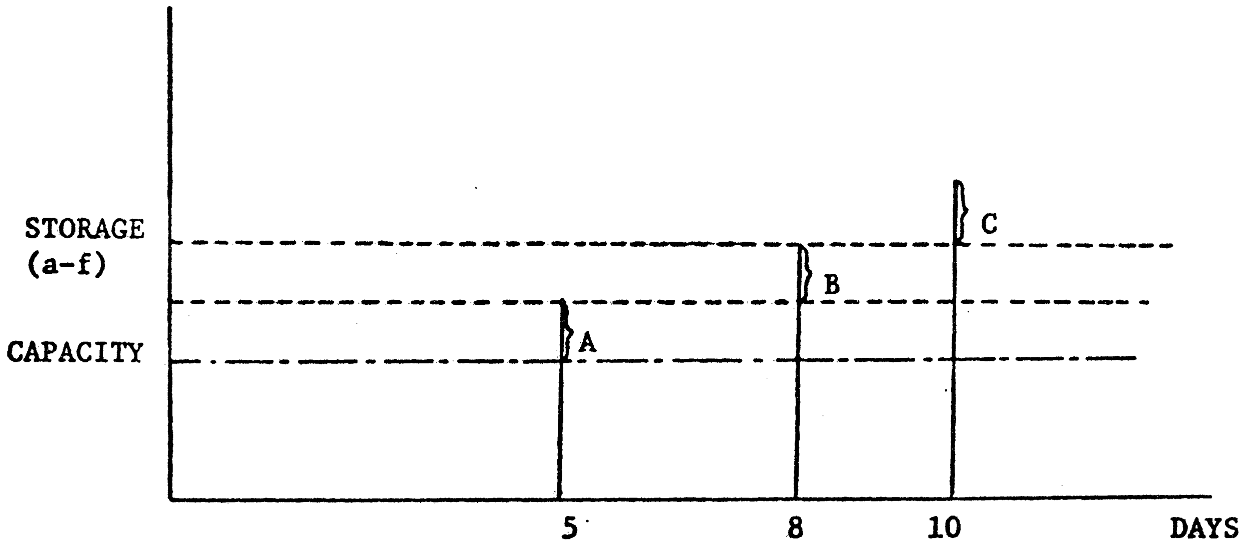
Deficiencies To Be Remedied Before Further Investigation

One of the major inadequacies of the model was discussed in Chapter XVI. When the model was formulated the importance of releases in excess of daily irrigation demands but not in excess of 20,000 cfs was seriously underestimated. As a result it was felt that the system would operate adequately under conditions of perfect information using the algorithm designed for the imperfect knowledge situation. As was seen above, the lack of erroneous forecasts indicating that excess storage would be present in the next thirty days resulted in the system more frequently entering the critical state in which excess storage was present on the decision day. This in turn resulted in releases in excess of 20,000 cfs occurring more frequently in the perfect knowledge case than they did in the case involving the lowest quality information. In future versions of the model, when perfect forecasts are available, projected encroachment or overflow should be handled in the following fashion. Assume first perfect knowledge as of March 1 of the seasonal water supply and perfect knowledge of the daily streamflow for the succeeding thirty days. Assume also that on each succeeding day accurate knowledge will be available concerning the daily streamflow for the next thirty days. The March 1st storage and the sum of the daily inflows in excess of the daily irrigation demands could be used to derive a series of resulting storages for the following thirty day period. If it is found that on the basis of daily irrigation demand releases the reservoir will overflow during the period, then the releases should be raised sufficiently to remove the excess. For each day the reservoir would overflow the excess storage to be disposed of will be known. The release on the preceding days must be raised sufficiently to remove that excess by the time it would occur. This is illustrated in Figure 21.

It should be noted that the suggested methodology considers only overflow, not encroachment of the flood control storage reservation. For the Palisades reservoir with a total monthly release capacity of 1,200,000 acre-feet, a flood control reservation would probably not be necessary given the perfect knowledge situation. Such a procedure would amount to the reservoir being operated as a single purpose "fill and spill" conservation reservoir. The only difference would be that rather than

Figure 21

Proposed Operating Rule



filling the reservoir as soon as possible and spilling all subsequent inflows the objective would be to fill the reservoir on the date of the maximum excess of thirty day period. Since the thirty day period advances one calendar day with the passage of each day, the final reservoir fill date will advance through the season until the day the inflows finally drop below the daily irrigation demands.

As discussed in Chapter XVI and mentioned earlier in this chapter, the large variance of some of the samples of differences could have caused α type errors in the testing for significant differences. In order to overcome this problem, larger samples of differences must be generated either by running the actual streamflow data through the model without reinitializing the random number generator so that another series of random errors with the same seed value is generated, or preferably by building a synthetic hydrology generator to produce longer records of streamflows. The procedure would then involve feeding the real and synthetic hydrologic records through the erroneous forecast generator and the operating algorithm to obtain a regulated and a storage hydrograph. The quality of the forecasts could be varied and samples of differences generated as they were above.[2]

Since benefits have been found in the perfect forecast situation, a useful modification to the model would involve the ability to adjust the degree of forecast accuracy within any given water year. As was discussed in the streamflow forecasting appendix, the major snowfall period ends in late March or early April. Thus improved March 1 and April 1 water supply forecasts require improved long-range precipitation forecasts. Improved water supply forecasts on May 1, June 1 and July 1 however may not depend significantly on the future precipitation because the major portion of the snow pack has already accumulated. However these forecasts would require improved knowledge of snow depth and water content over the entire basin and perfect knowledge of evapotranspiration rates etc. Since there are basically two different technologies involved in the different portions of the season, it is sensible to assume that advances in technology may be made in the one before the other. Thus the model should be adapted to permit improved forecasts after the majority of the snow pack is accumulated and less accurate forecasts before that time. This would also permit estimation of the relative marginal productivities of improvements in the two types of forecasting methodology.

Is The Methodology Adaptable To Other Basins?

The model presented above is adaptable to other basins. Some changes of the parameters used in the decision routines will of course be necessary to account for differences in reservoir size, downstream channel capacity and normal irrigation demands. The major adaptation of the decision routines lies in the restructuring of the flood control reservation matrix derived from the flood control reservation diagram. This however is to be expected since the diagrams are individually constructed for each reservoir. The streamflow forecasting routines will require adjustment to account for the differences in present levels of streamflow accuracy. Presumably the present standard deviation of the water supply forecasts will have to be adjusted as will the standard deviation and the autocorrelation coefficients for the day-to-day streamflow forecasts.

Before the simulation model is applied to a reservoir and a basin, however, the kind of advance investigations discussed above should be carried out. For instance reservoirs on the Missouri, the Rio Grande and the King's River in California were considered for application of the model but rejected after discussions with the operators and analysis of the operational hydrographs.

FOOTNOTES

[1] A Type 1 Flood Loss is a loss through unnecessary deliberate flooding. A Type 2 Flood Loss is a loss through failing to make a possible storage draw-down.

[2] Discussions of the construction of synthetic streamflow generators can be found in: H.A. Thomas Jr. and M.B. Fiering, "The Mathematical Synthesis of Streamflow Sequences," Ch. 12 of A. Maass et al., *Design of Water-Resource Systems* (Cambridge, Mass.: Harvard University Press, 1962).

APPENDIX I

RESERVOIR REGULATION PROCEDURES

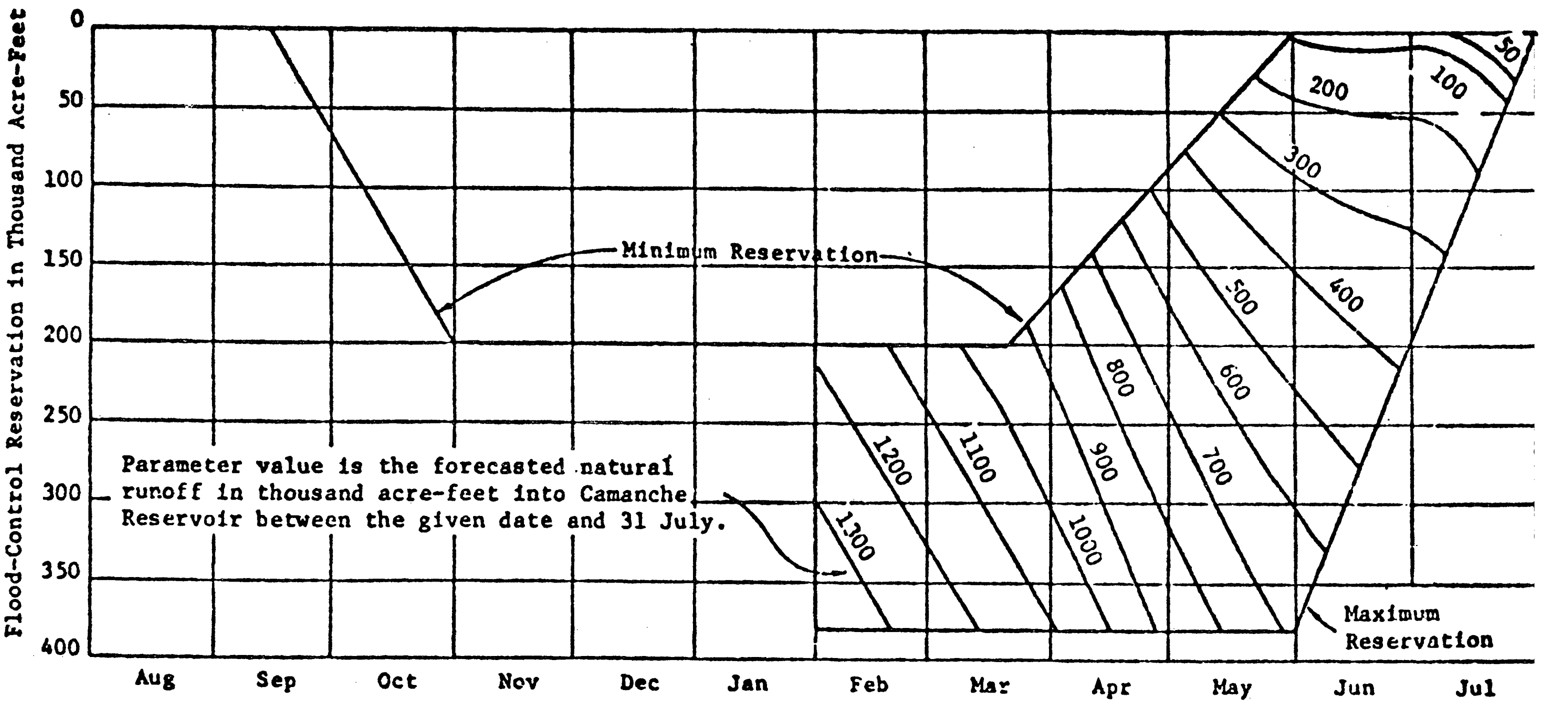
The purpose of this appendix is to familiarize the non-hydrologist reader with the methods of operating multiple purpose reservoirs. These reservoirs have joint use storage space which is allocated between flood control and conservation uses on the basis of conditional water supply forecasts. This appendix will introduce a simplified chart which provides the basic information for operating the reservoirs, discuss its derivation and utilize a simple example to illustrate the use of the chart. The Flood Control Reservation diagram for Palisades-Jackson Reservoir is presented at the end of the chapter. Although it appears much more complex it is basically identical to the examples discussed in detail. Hence the chart for the Palisades-Jackson Reservoir will not be analyzed.

As mentioned in the text, the fundamental purpose of a multiuse reservoir whose primary use is flood protection (i.e. most Federally funded reservoirs) is to be ready to moderate potentially dangerous flood flows whenever there is a significant probability of their occurrence. Water can be stored in the joint use space of a reservoir for other purposes as long as the flood control operation is not hindered. Water stored for conservation purposes is released upon demand by those holding the storage right. Thus the main operating decisions facing the operations staffs of the Bureau of Reclamation and the Corps of Engineers concern the amount of flood control space that ought to be available at any time and the size of the releases required to create additional space if it is required.

The 1944 Flood Control Act requires that all reservoirs constructed wholly or partially with Federal funds (except some TVA projects) should be operated for flood control purposes as required to prevent flood losses. Under the Act, the Secretary of War (presently the Secretary of the Army) through the Corps of Engineers is required to develop regulations for the use of such reservoir flood control space.[1] The operating regulations for this flood control space are summarized in a flood control reservation diagram (see Figure 22). The minimum reservation line on the chart indicates the minimum amount of vacant flood control space which must be kept available at all times to handle floods. During

Figure 22

Flood Control Reservation Diagram
Camanche Reservoir



Parameter value is the forecasted natural runoff in thousand acre-feet into Camanche Reservoir between the given date and 31 July.

Source: Adapted Chart 19, U.S. Corps of Engineers <u>Reservoir Criteria for Flood Control</u> Sacramento, Calif. Oct., 1959.

the snowmelt season, the maximum flood reservation that can be required is defined by the minimum flood control reservation plus the total amount of joint use storage space. The amount of flood control space required on any date can be read off the ordinate of that date and the forecasted parameter value.

An example of the use of the flood control reservation diagram in Figure 22 will be presented below, but first consider the derivation of the parameter lines.

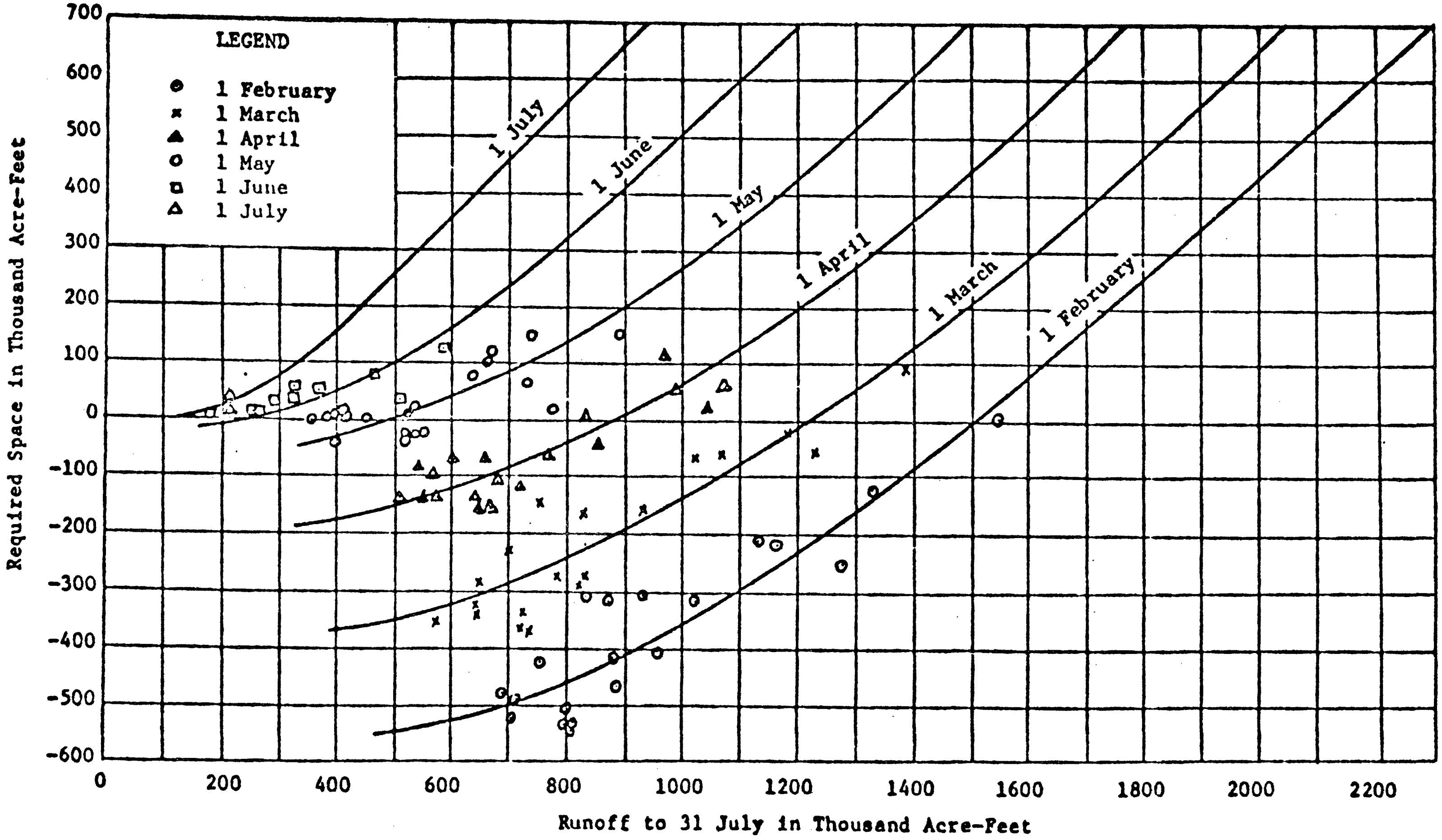
The objective in deriving the curves is to define the amount of storage space to be kept available for the control of floods of known or forecasted magnitude over a specified time interval. In calculating the amount of space required it is assumed that releases in excess of channel capacity will not be made. The amount of space required on any date will be the volume of inflow between the date in question and the date of maximum storage less the volume of water released from the reservoir. In order to derive parameter curves for the first day of the various months during the snow flood season, the historical record is routed through the reservoir and the amount of storage space required to control the runoff after the date in question is plotted for each year. A parameter line is then fitted through the scatter of points for the date in question.

For example in Figure 23 the postulated releases are downstream capacity releases through July 31. The positive values of required space indicate space that must be kept available in addition to the minimum flood control reservation. Years having negative values of required space indicate years in which the floods could have been controlled with less than the minimum flood control reservation. In Figure 23 it can be seen that in only one year did the flood between February 1 and the date of maximum storage require more space than the minimum reservation. On the other hand all of the observations scattered around the June 1 parameter line indicate that the amount of required space exceeded the minimum reservation.

Consider now the scatter of black dots around the May 1 parameter line. By following the 500,000 acre-foot ordinate vertically to the May 1 parameter line it may be seen that in six years of the period of

Figure 23

Snowmelt Runoff vs Required Space
Camanche Reservoir



Source: U.S. Dept. of the Army, Corps of Engineers, Reservoir Operation Criteria for Flood Control Ch. 14, Sacramento, 1959.

Note: Upward Extensions of Curves are Based on Full Releases Through 31 July.

record the runoff between May 1 and July 31 was between 500,000 and 600,000 acre-feet. On four of those six years the distribution of runoff was such that the flood was controlled by the minimum storage reservation, while in the other two years joint-use space was required in addition to the minimum specified flood protection reservation.

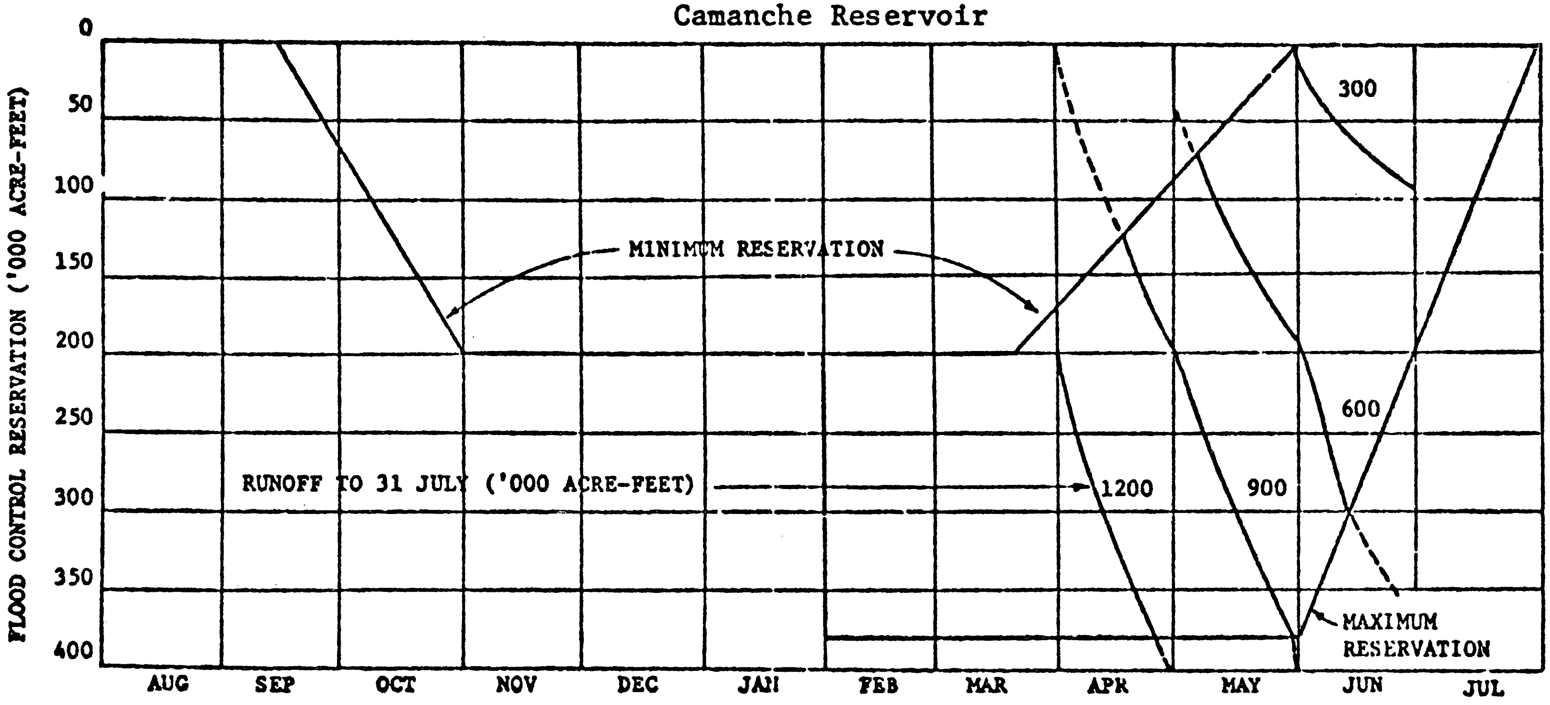
The parameter lines showing the flood control reservation required for a given runoff as the season progresses (see Figure 24) are obtained from Figure 23 by a simple transformation of the scales on the axes and the parametric value of the curves. Figure 24 shows only four parameter curves but the others can be obtained by plotting the proper values from Figure 24. (Figure 22 and Figure 24 are not identical, the difference will be explained below.)

This initial step permits specification of the amount of space required to control a known flood of known hydrograph between the date in question and the end of the flood season. However, the operation of the reservoir will be determined on the basis of forecasts of runoff and the curves in Figure 24 must be adjusted to make an allowance for errors in the seasonal runoff forecast and errors in the short or medium term forecast of the hydrograph. By calculating the standard error of the historical forecasts, we obtain an index of a portion of the uncertainty allowance that must be made. The standard error of the forecast is simply the square root of the quotient obtained from the sum of the squares of the forecast errors divided by the number of degrees of freedom. Research by Corps of Engineers personnel has indicated that the forecast error is often uncorrelated with the size of the runoff. Thus these forecast errors may be expressed in volumetric units (acre-feet) rather than in terms of a percentage of the forecast.[2] Improvements in streamflow forecasting will reduce this standard error and hence reduce one of the weighted components entering into the construction of the parameter curve.

Another source of uncertainty which must be allowed for in the construction of the diagram is the pattern in which the runoff will be produced from the snow pack, i.e. uncertainty in the short to medium term forecasts. The historical records show that identical snow packs on the same date can produce significantly different hydrographs. This

Figure 24

Illustrative Example, Mokelumne River Basin, California
Required Space to Control Snowmelt Runoff
Camanche Reservoir



Source: Chart 19, U.S. Corps of Engineers
<u>Reservoir Criteria for Flood Control</u>
Sacramento, Calif. Oct., 1959.

is due to variations in the meteorological conditions during the runoff - primarily in the temperature pattern. (See Chapter III on Snowmelt Runoff Forecasting.) If the weather warms up early in the season providing an unusually early flood, a large initial reservation is required because there will be less time for normal operational releases to empty the joint use space. This uncertainty can be estimated by calculating the standard error of the space runoff relationship derived in the first step of the procedure described above. If the relationship is plotted as in Figure 23, the deviation of the individual points from the curve will be calculated horizontally. Following the Corps of Engineers terminology, this standard error is called the "error in timing." An improvement in the short to medium term forecasts would reduce this standard error and again change the curves. The total uncertainty from these two sources is obtained by summing the squares of the individual errors and taking their square root. The Corps have called this the "standard error of estimate."

Before discussing how the parameters are adjusted to make allowance for these uncertainties one more concept must be introduced. This is the "latitude of operation" or the "contingency volume." In multiple purpose projects any unnecessary flood evacuation which results in wasted or mistimed project water downstream is inefficient and should be avoided. Thus flood releases should be delayed until as much uncertainty as possible has been removed. This will generally occur after the April 1 or the May 1 forecast. If releases are required before the April 1 forecast the need for them is continually re-evaluated as more and better information becomes available. If after initiating them they prove unnecessary or excessive, they are stopped or reduced as may be necessary. The latitude available in operating for snowmelt floods is equal to the maximum "zero damage" project release rate multiplied by the amount of time until the reservoir is expected to fill. This latitude of operation makes it possible to control anticipated floods without seriously risking the possibility of not filling the reservoir.[3]

The error allowance added to the parameter value of the historical flow will be some multiple (k) of the standard error of estimate. The size of the multiple will depend on the sensitivity of the operations to errors in forecast: the latitude of operation, the seriousness of losing control or of having to make planned overbank releases and the losses incurred if the reservoir is not filled. A detailed procedure is presented in the Corps manual but usually the value of $\underline{k}$ is twice the standard error of estimate. The runoff-space relationships resulting from making the above adjustments to the initial runoff-space relationships (Figure 24) are plotted as Figure 22 and define the space required to control the forecasted remaining runoff. (Note that the operation has been biased in favor of flood control by shifting the curves for the maximum probable underestimate of the actual streamflow.)

The frequency of inadequate operation of the reservoir can be calculated by using a table of exceedence values for a normal distribution. In an example presented by the Corps with a $\underline{k}$ for flood control of 2.0 and 25 degrees of freedom the operation would be inadequate 3.1% of the time. Thus, in 97 years out of 100 if flood releases are required the subsequent runoff will adequately be controlled. A similar index of the frequency of inadequate operation can be calculated for the conservation operation in years when flood control releases are required.

The Corps manual indicates that if a $\underline{k}$ of at least 2 is not obtained because of constraints on the latitude of operation then attempts should be made to increase the $\underline{k}$ either by increasing capacity, increasing the downstream channel capacity or by reducing the size of the standard error of estimate through improved forecast methodology.

To illustrate the use of the flood control reservation diagram, suppose that the date is April 1 and that the snow survey results show a forecasted runoff of 900,000 acre-feet. By reading off the flood reservation indicated by the intersection of the 900,000 a-f parameter line and the ordinate through April 1, Figure 22 indicates a required flood control reservation of about 215,000 a-f. If this amount of space is not available on this date, we must make releases sufficiently large that there is a negative net inflow and the storage behind the dam begins to decrease. Depending on the size of the inflow, this drafting release may or may not exceed the daily normal outflow required to fill the demands downstream. The flood control reservation chart does not indicate the size of the release to be made. It only indicates the maximum release which is based on the downstream channel capacity. The decision concerning the rate of release will depend on the short to medium term forecast. If the encroachment is small and the short term forecast indicates that inflows will not increase rapidly for some time, the release may be set to draw the encroached space down gradually. This will minimize the amount of water unnecessarily released if subsequently an error in the forecast becomes apparent. On the other hand, if the short term forecast indicates massive inflows in the near future, the reservoir would be drafted at the maximum allowable rate. (It should be noted that in some reservoirs the flood control regulations specify that if the flood control space is encroached the draft must be made at the channel capacity rate. The regulations for the Pine Flat Reservoir on the King's River in California do make such a stipulation. The Palisades-Jackson regulations do not.)

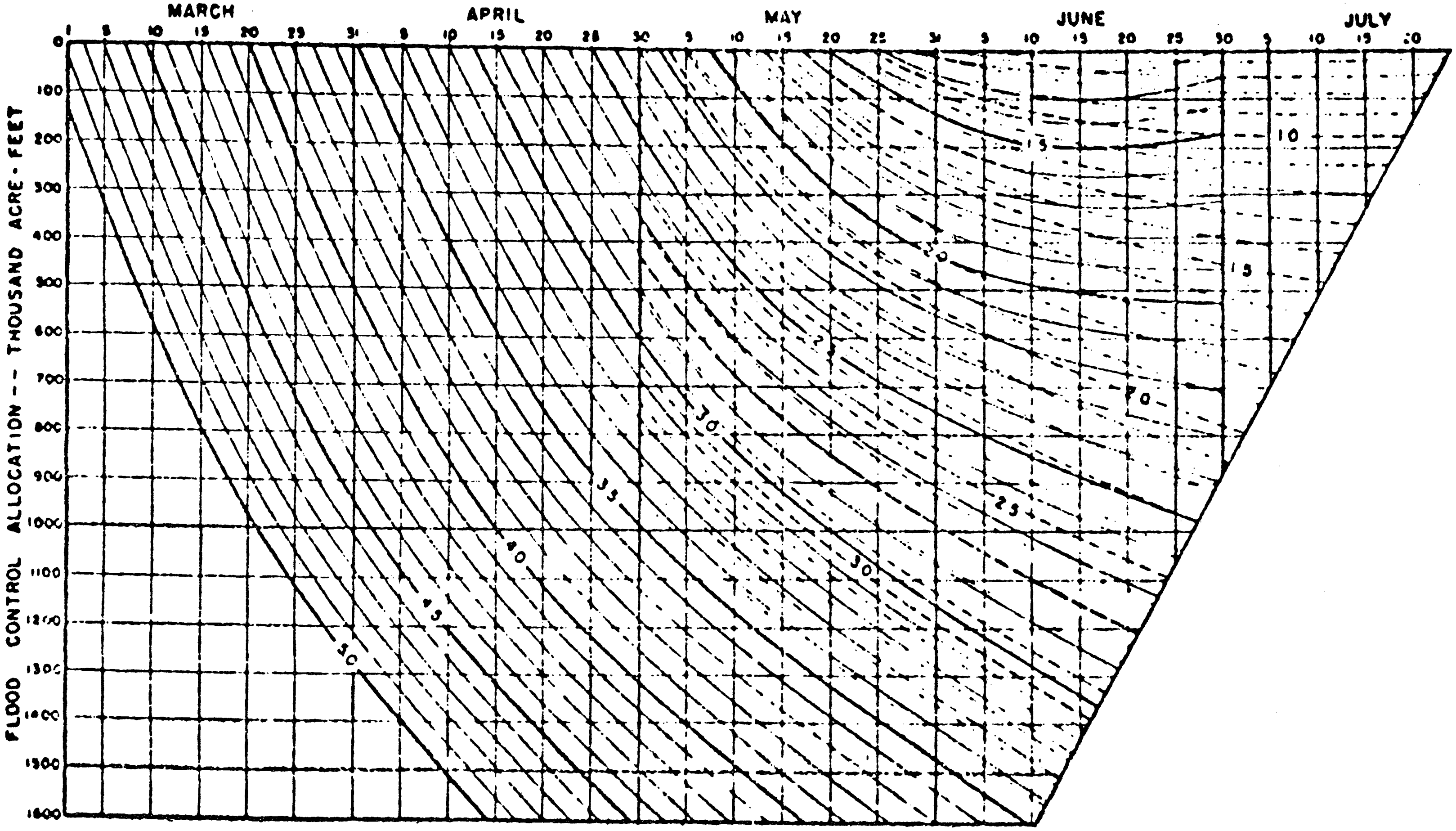
As time passes after the beginning of the flood draft, two forces will be at work. The draft will be reducing the storage in the reservoir, while the passage of time and the accompanying streamflow will be reducing the forecast size of the remaining season runoff. These two forces jointly work to remove the encroachment.

As the season progresses further, the forecast of runoff between now and July 31 decreases and the flood control reservation decreases. This means that the maximum storage permitted without assumed encroachment increases and that the reservoir can be filled. This leads to the objective of having the reservoir full at the end of the spring snowmelt runoff season. In terms of the reservoir operation jargon, the amount of joint storage space committed to flood control decreases as the season progresses and the amount of the joint storage space committed to conservation increases. At the end of the season the entire joint use storage space is committed to conservation. (Note that in this reservoir, there is no minimum required flood control space for the months of June, July, August and part of September but this is not always the case.)

The Palisades-Jackson Flood Control Reservation Diagram is illustrated in Figure 25. The dashed parameter lines are used when the inflow has exceeded 20,000 cfs.

Figure 25

Flood Control Reservation Diagram
Palisades Reservoir



Source: U.S. Dept. of the Army, Corps of Engineers
Reservoir Regulation Manual for Palisades Reservoir
(Walla Walla, Washington: 1958), Appendix B, Plate B-1.

For use in the simulation model discussed in Appendix II, this chart was converted to a matrix of flood storage reservation. In the model the matrix is denoted FLDCTL. The notes and supplementary regulations accompanying the Flood Storage Reservation Diagram in the Palisades Regulation Manual were adopted to fit the model and are included in the discussion presented in Appendix II.

FOOTNOTES

[1] Corps of Engineers, Reservoir Regulation, p. 28.

[2] Harold A. Keith, Corps of Engineers, Sacramento California, personal research notes.

[3] This discussion is an adaptation and elaboration of: U.S. Dept. of the Army, Corps of Engineers, U.S. Army Engineer District, Reservoir Operation Criteria for Flood Control (Sacramento California; 1959), pp. 20-23.

APPENDIX II

THE SNAKE RIVER SIMULATION MODEL[1]

This appendix describes the computer simulation model developed for the purpose of estimating the benefits from improved streamflow forecasts. The discussion below should be read in conjunction with the flow charts and the Fortran statement listing at the end of the Appendix.

The computer simulation model of Palisades and Jackson Reservoirs on the Upper Snake River consists of a main program and fourteen subroutines. (A simplified flow chart for MAIN is shown in Figure 26.) The functions of these various programs can be divided into three classes. The first function is to make daily streamflow forecasts and seasonal water supply forecasts for the Upper Snake Basin. The second and principal function is to operate Palisades and Jackson Reservoirs as independent and interdependent entities on the basis of the forecasts provided by the forecasting routines. The third function is an accounting role to summarize the key parameters of the operating plan: the maximum release greater than 20,000 cfs from Palisades and 7,000 cfs from Jackson, the number of incidents of releases greater than these levels and the duration of each incident, the maximum storage in each reservoir and the excess of the releases over the daily irrigation demand if each reservoir has failed to fill.

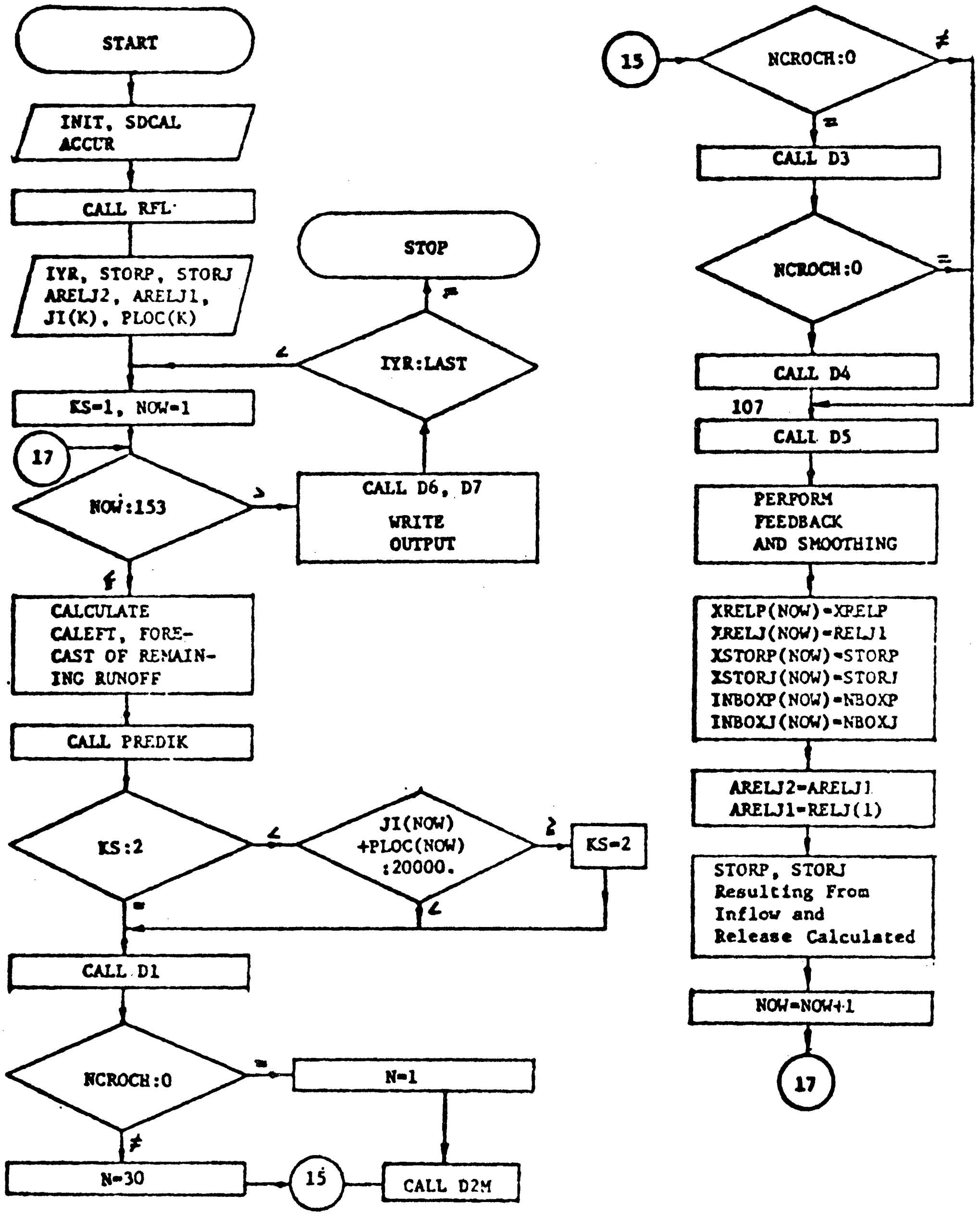
The Forecasting Routines

The water supply and daily streamflow forecasts utilized by the decision routines of the program are not based on primary hydrologic or meteorologic variables such as temperature or snow pack depth or water content and rainfall. Instead the historical flows from the period of record are viewed as the population of hydrologic events for the system. The forecasting subroutine provides forecasts of these events. The accuracy of the forecast is established by the programmer to suit the simulation in question.

The daily forecast (generated each day for the following thirty days) has three components. The first is the actual streamflow that occurred on each day. The second is a systematic error generated by an autocorrelated error scheme. The third component is a random element

Figure 26

MAIN Program



generated by a random number generator. The forecasting equation for the daily flow (contained in Subroutine PREDIK) is:

PP1(K) = PLOCT(K) . (Z(K) + 1)

where PLOCT (K) is the actual streamflow which occurred on day K and Z(K) is determined by the following scheme. If K = 1 (i.e. we are forecasting today's inflow) Z(1) = 0.0 If K = 2 (i.e. tomorrow's inflow is forecasted) Z(2) = a random deviate. For days 3 through 30 of the forecast period:

Z(K) = RHO1 . Z(J-1) + RHO2 . Z(J-2) + (a random deviate).

Z(J-1) is the value of Z on the previous day while Z(J-2) is the value of Z two days previously. In all cases reported below, RHO1 = .8 and RHO2 = 0.0, but other values could have been used. RHO1 and RHO2 were determined by comparing forecasts of the Snake River flows made by the Corps of Engineers Streamflow Synthesis and Reservoir Regulation model (SSARR) with the actual streamflows. The sample of the errors was fitted by several autoregressive schemes. The values of RHO1 = .8 and RHO2 = 0.0 gave the best fit.

The water supply forecast routine is located in MAIN. In this case the forecast routine first calculates the historical remaining season runoff from the date in question to the end of July. (Calendar time in the model is designated by year and by a variable named NOW which ranges from 1 to 153. This corresponds to the period from March 1 to July 31). Then a random term for the seasonal forecast is added to the sum of the actual remaining season runoff for the year.

In both cases the random variate is generated by an IBM function subroutine known as GRAND. With this routine, numbers are generated from a normal distribution having zero mean and a standard deviation specified by the user. The user also provides a "seed" value from which the routine commences. In the simulations reported here the "seed" values are 231 and 445. Given the seed value, the routine selects a random value each time GRAND is called. The routine advances a pointer each time a value is generated and it moves through a list following the initial value. If the same seed value and standard deviation are provided and GRAND is called the same number of times in each simulation run, the list of random numbers generated will be identical. However the program may call GRAND differing numbers of times in successive years. Therefore the random number portion of the forecast may not be identical in each year even though the random number generator was the same in each case.

The Reservoir Operating Routines

The basic operating procedures for the reservoirs are relatively simple. The prime determinants of the size of the release are: 1) whether or not the reservoir will spill over the top of the dam in an uncontrolled fashion, 2) whether or not the amount of vacant storage space is adequate in view of the forecasted inflow and the prespecified maximum storage levels (i.e. whether or not the flood control reservation will become encroached) and 3) the amount of irrigation water that downstream irrigators have requested to be released during periods when flood releases are not being made. In order to discuss the first two considerations above, some background information about the reservoirs must be presented.

Jackson Dam and Reservoir lie upstream from Palisades Dam and Reservoir. (Jackson Reservoir has a storage capacity of 847,000 acre-feet while Palisades Reservoir has a capacity of 1,417,600 acre-feet.) In the reach of the river between the two reservoirs, numerous tributaries enter the mainstream but no significant diversions occur. Thus any water released from Jackson Dam constitutes an inflow to Palisades Reservoir. There is a lag between the release of water at Jackson and its inflow at Palisades. The travel time is a function of the size of the release at Jackson and is calculated in Subroutine D2M. On questions of whether or not reservoirs will overflow the top of the dams, the two situations are treated separately with separate decision rules and maximum releases. To calculate the amount of vacant storage space, the two reservoirs are treated as one unit. The amount of vacant storage space is the sum of the capacity of Palisades (variable SP in the programs) + the capacity of Jackson (variable SF) minus the sum of the storage in Palisades (STORP and the storage in Jackson (STORJ). In that event that insufficient storage space is available in the combined reservoir, water is released from Palisades in order to increase the total vacant storage space in the combined unit. Obviously releases from

Jackson are not appropriate in this case, since the released water has nowhere to go but into the Palisades Reservoir and the release from Jackson does not create vacant space in the total system. (Because of this interdependency between the two reservoirs, the flood control regulations specify that two-thirds of the vacant storage space in the total system must be in Palisades. If this rule is violated then as much inflow into Jackson as is possible must be stored while Palisades is drawn down until the proper ratio is attained. This decision is taken in Subroutine D5 and is indicated on the output printout by NBOXP=12.)

We will now consider the basic decisions in the order in which the program makes them. Each decision will be identified by Subroutine and identifying parameter which is also indicated on the output printout. We will distinguish the basic release decisions (i.e. those releases determined by the forecasted inflows) from the various smoothing or, feedback decisions to be discussed below.

The first decision made each day is whether or not the entire system is encroached (i.e. insufficient flood control storage space is available). This process is completed in Subroutine D1. On the basis of the forecast of remaining season runoff for the given day, the required amount of vacant flood control space is calculated in Subroutine RFL.[2] Subroutine D1 then compares the required vacant flood control space (variable STOMIN) with the actual available vacant storage space. If the vacant space is deficient the reservoir system (both Palisades and Jackson) is encroached and releases must be raised above inflows. The flood control regulations require immediate commencement of releases at maximum channel capacity from Palisades (CAPP=20,000 cfs) if the calendar date is before June 1 (i.e. the value of variable NOW is less than 93). In the output, the indication of this release is NBOXP=1.

If NOW is greater than 93 (i.e., the day's date is later than June 1) the flood control regulations permit releases greater than 20,000 cfs under certain conditions. The release may be raised by 1000 cfs. If NOW is greater than 93, D1 calculates the appropriate release and indicates the decision by NBOXP=2. In both cases of NBOXP=1 and NBOXP=2 the release from Jackson is the daily normal outflow (denoted as DNOJ). The indicator in the output for this release is NBOXJ=1 or NBOXJ=2 to be compatible with the decision indicator for the release from Palisades. In either case it is necessary to check whether or not the DNOJ (Daily Normal Outflow at Jackson) release will cause the Jackson Reservoir to overflow the dam on this day. If it will, the DNOJ release is increased by a quantity sufficient to prevent the overflow and NBOXJ=39.

If the system is not encroached at the beginning of the day in question, the subroutine calculates whether or not Jackson Reservoir will overflow the dam on the basis of today's storage (STORJ), a forecast of the inflows for the next thirty days (PJ(L), L=1,30) and a hypothetical release pattern (as discussed below). (Figure 27 presents the flow chart for this portion of D1.) The methodology of this decision is the basis of the investigation of whether or not Palisades Reservoir will overflow in the future and whether or not the combined system will become encroached during the up-coming thirty day decision period. For this reason, the process will be considered in detail here and treated more lightly in the other similar decision problems.

The basic problem under consideration is the quantity of water to be released today. Past releases are beyond control and tomorrow's decisions do not overly concern us because the decision process carried out today will be duplicated tomorrow. Only two of the possible releases today are specified a priori. There are the daily normal outflow release (DNOJ) which is calculated from SUBROUTINE DNOJ and the maximum release from Jackson unless the reservoir will overflow today. The maximum release (indicated by variable name CAPJ) is 7,000 cfs, the downstream channel capacity below the dam. If we find that on the basis of today's storage (STORJ), the forecasted inflow (PJ) and a given assumed release pattern, a release exceeding CAPJ will be required on some future day of the 30 day forecast period to prevent the reservoir from overflowing on that day, it is reasonable to raise today's release above the hypothesized level to try and prevent the overflow. (Obviously today's release will not be greater than CAPJ in this case.)

Since today's release need not be raised above the DNOJ unless releases greater than CAPJ will be needed to prevent overflow in the future, it seems appropriate to investigate the time path of storages based on

Figure 27

Subroutine D1
Not Encroached on DAY1

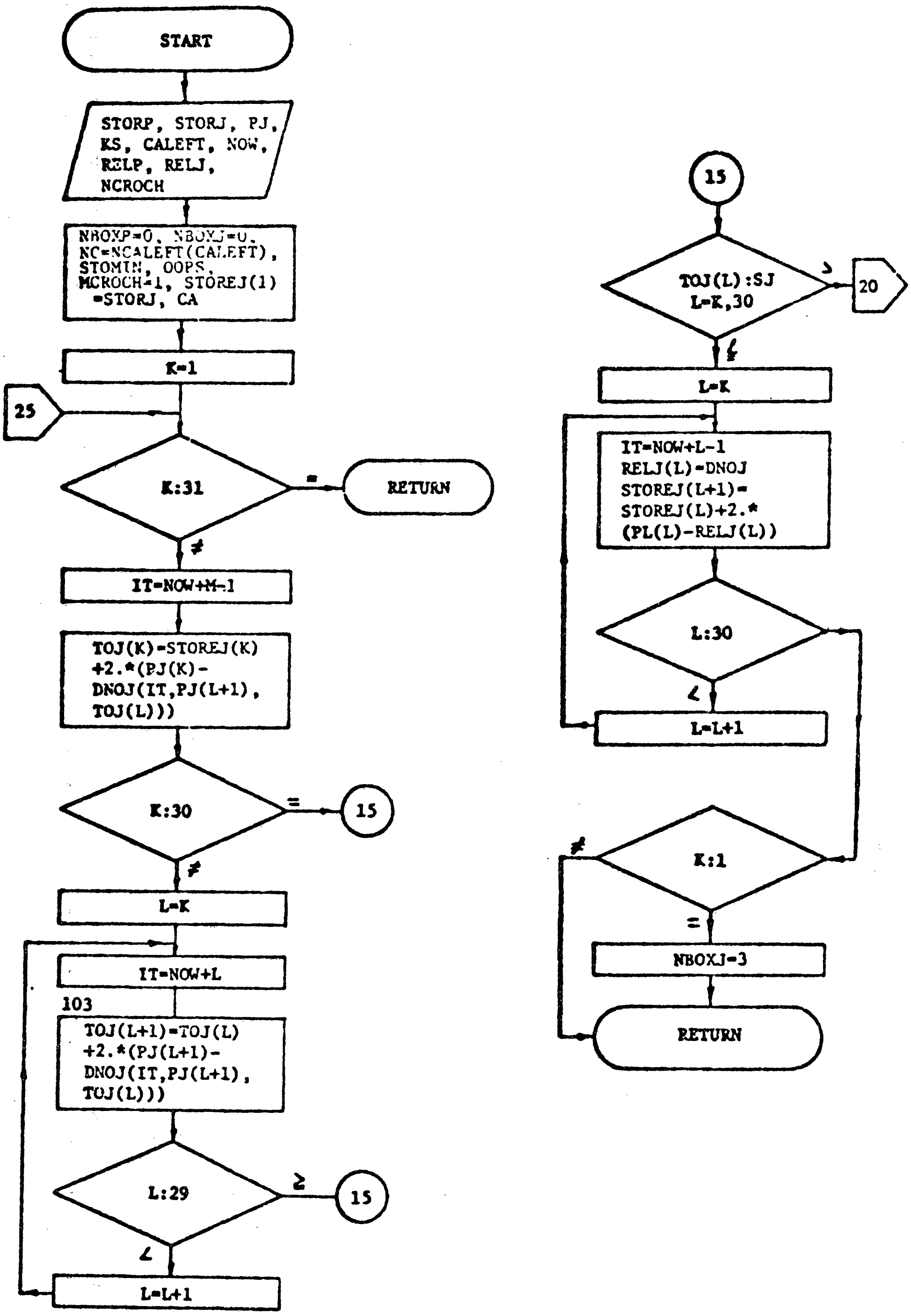
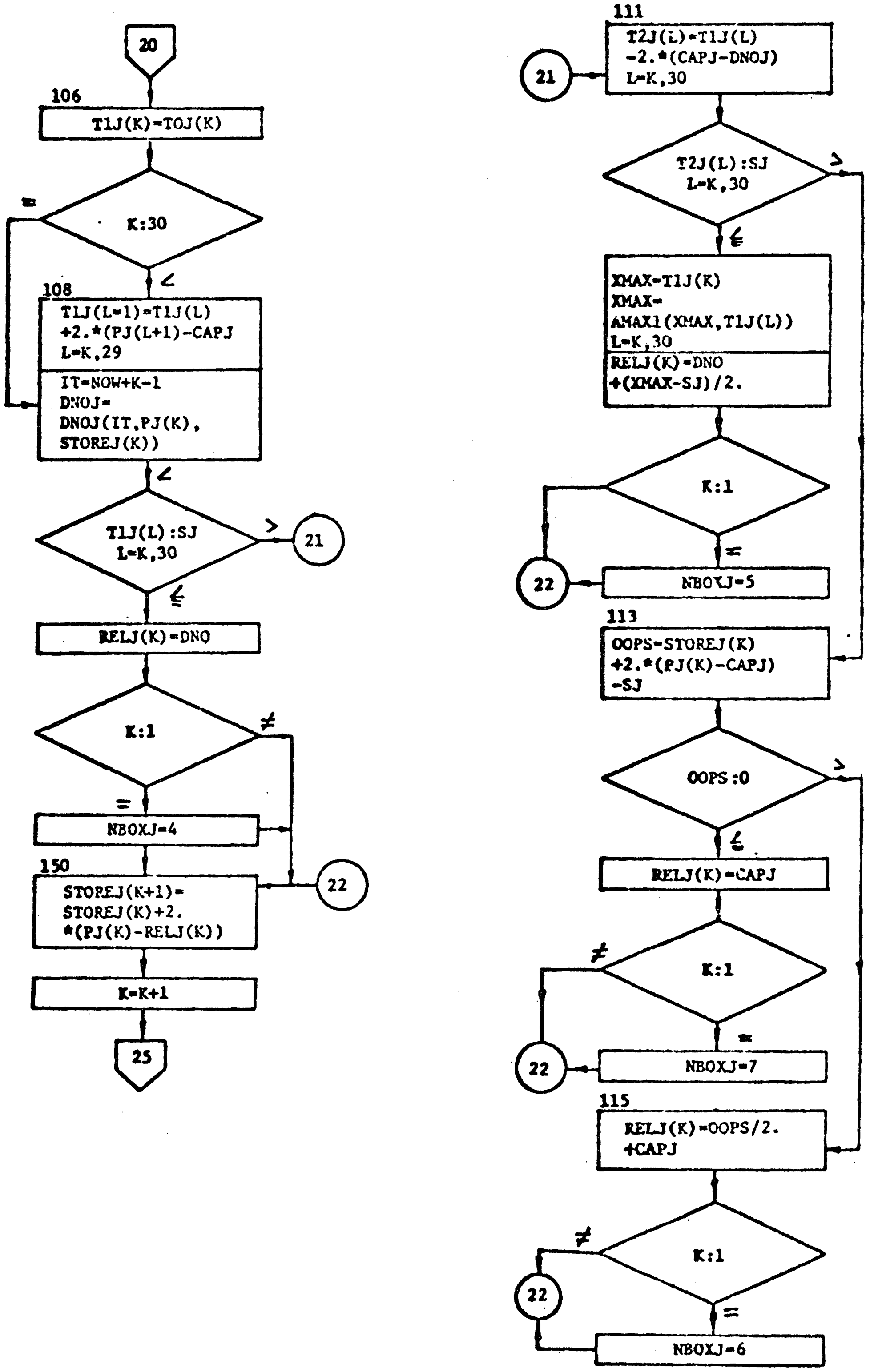


Figure 27 (Cont'd)



STORJ, PJ and a release pattern of DNOJ today and hypothetical releases of DNOJ each day for the remainder of the 30 day period. If the resulting storages (variable name TOJ (K), K=1,30) do not exceed SJ (the storage capacity of Jackson Reservoir) during the 30 day period, then DNOJ is the proper release for today and NBOXJ=3. If, however, TOJ(K) exceeds SJ for some K, then some RELJ's should be raised above DNOJ. We already noted above that RELJ for any day can exceed CAPJ only if the reservoir will overflow on that day. Hence the maximum RELJ to prevent an overflow in the future is CAPJ. We now construct another series of hypothetical storages based on STORJ, PJ, and hypothetical releases of DNOJ(today) + CAPJ for the remaining days of the 30 day period. This set of storages has the variable name T1J(K).[3] Once again if T1J(K) does not exceed SJ for any K then today's release need only be DNOJ and NBOXJ=4. If, however, T1J(K) does exceed SJ for some K then today's release must be raised above DNOJ. Once again we construct a new storage series with today's release raised to the maximum (CAPJ) and the rest of the 30 days' releases set hypothetically at CAPJ.

If T2J(K), the new storage sequence still exceeds SJ at any K we check to see if it will overflow today. If it will, the release is set at an amount sufficient to prevent the overflow from occurring and NBOXJ=6. (The difference between a release sufficient to prevent an overflow from occurring and simply letting the overflow occur is that in the former the flow of the river downstream of the dam is still under the operator's regulation, although the choice of operation is severely restricted.) If the reservoir will not overflow the top of the dam today, the release is CAPJ and NBOXJ=7.

If the T2J(K) series does not exceed the Jackson storage capacity (denoted as SJ) the proper release for today is greater than DNOJ but less than or equal to CAPJ. If the reservoir did not have a conservation storage function this consideration would not arise and we would simply release CAPJ. Because the reservoir does have such a purpose, we do not wish to release more water than necessary to maintain flood control. To determine the release, the maximum acre-footage of excess water is calculated and converted to cfs. This release rate when added to DNOJ gives today's release and NBOXJ=5 in this case.

If Jackson Dam and Reservoir were not the upstream dam of a two dam system, the program would pass through Subroutine D1 only once for each NOW. We have already seen that SUBROUTINE D2M routes Jackson releases downstream to Palisades and in effect determines a large portion of the Palisades inflow. Since a procedure similar to that described above will be carried on at Palisades for both overflow and encroachment considerations, we require 30 specific hypothetical releases from Jackson Dam for SUBROUTINE D2M to route downstream. (Recall that in the above discussion the hypothetical releases for days 2, 30 in the 30 day forecast period were either DNOJ or CAPJ. In only a few cases would these two release patterns be an adequate hypothetical release pattern for the purposes of D2M.) The procedure discussed above is iterated up to 30 times to generate specific hypothetical releases from Jackson Reservoir (see Figure 27). Each time through the routine, the storage parameters are up-dated according to the real or hypothetical release of the preceeding days. The forecasts PJ(K) are made for the period K=L,30 with L being incremented one each time through the routine. These hypothetical releases do not cause NBOXJ (the indicator of the decision location in the program) to be set. In only one case is D1 iterated only once. This occurs when the TOJ series (the series of hypothetical storages in Jackson Reservoir) does not exceed SJ (the storage capacity of Jackson) on any day during the 30 day period and all of the releases are set to DNOJ. When this is done the program exists from the SUBROUTINE D1 and returns to MAIN. If some TOJ does exceed SJ on the first iteration the program continues to iterate until TOJ does not exceed SJ for the remaining days or until the thirtieth iteration is reached upon which it automatically returns to the MAIN program. (This special role of the TOJ series is the reason for having two storage series which set RELJ (1) equal to DNOJ (daily normal irrigation release). The subscript (1) used here in connection with the RELJ name indicates that we are considering the actual release from Jackson Reservoir rather than one of the hypothetical releases which are also denoted by RELJ.)

When control is passed back to the MAIN program, it checks to see what decision SUBROUTINE D1 has made concerning the encroached or unencroached condition of the system. If the system is currently unencroached, MAIN passes the 30 hypothetical releases from Jackson to D2M which calculates the inflows to Palisades. These are passed to D3 through

MAIN. If the system is currently encroached then only RELJ (1) (today's release from Jackson Reservoir) is passed through D2M to D3.

SUBROUTINE D3 investigates whether or not Palisades Reservoir will overflow the Dam. Once again the parameters are the present storage (STORP (NOW)), the forecasted inflow (PP(J) and a hypothetical release pattern (RELP(K) K=1,30). The forecasted inflows consist of the tributary inflows between Jackson and Palisades as forecasted in MAIN as discussed above, and the calculated mainstream flow resulting from releases at Jackson over the previous few days as calculated by D2M.

As mentioned above the decision process for the overflow in Palisades is very similar to that discussed in connection with SUBROUTINE D1. In this case, the series of storages are denoted T1P(M) and T2P(M) where the first is based on an assumed release pattern of daily normal outflow the first day (DNOP) and hypothetical releases of channel capacity (CAPP= 20000 cfs) over days two to thirty. The second is based on CAPP releases over all 30 days of the forecast period. In the event that TIP(M) does not exceed SP for any M=1,30 then D3 makes no decision and returns immediately to MAIN. If T1P(M) and T2P(M) both exceed SP (the storage capacity of Palisades Reservoir) for some M, the first step is to determine whether or not the reservoir will overflow today. If it will not, RELP=CAPP, NBOXP=8 and control returns to MAIN. If the reservoir will overflow today the release is set at CAPP plus a sufficient amount to prevent the overflow and NBOXP=14. If T2P(M) does not exceed SP for any M then once again a release greater than DNOP but less then or equal to CAPP will prevent the reservoir from overflowing. In this case a more sophisticated mechanism is utilized for determining the release than was the case at Jackson. Here the maximum amount of "excess storage" (the maximum amount of additional storage space required to prevent overflow) is calculated and the date noted. The release is the sum of DNOP (daily normal outflow from Palisades Reservoir) plus the product of a proportionality factor and the difference between the release required to prevent the maximum "excess storage" and DNOP. The equation is:

RELP = DNOP + PROP (NOW) . (RELP-DNOP)

NBOXP=13 for this decision. The proportionality factor PROP is an inverse quadratic function of the number of days before the maximum excess storage occurs. Two functions are actually included in the program and may be chosen by the programmer at will. The actual quadratic forms were chosen by trial and error to get "reasonable" results. At this point in the decision routine the control returns to MAIN.

If SUBROUTINE D3 has not made a release decision for Palisades the MAIN programme calls SUBROUTINE D4 which considers whether or not the entire system will become encroached within the next 30 days. (If D3 did make a Palisades release decision, D4 is passed over.) SUBROUTINE D4 operates in a fashion very similar to that od D1 and D3. (Figure 28 illustrates the basic decision algorithm and the smoothing function.) There are some differences however. The initial storage for the sequence of hypothetical storages is the sum of the storage in Palisades (STORP) and the Jackson storage (STORJ). The forecasted inflow to the system is the forecast of inflow to Jackson (PJ(M)) and the tributary inflow into Palisades (PP1(M)). Note that the inflow into Palisades from releases at Jackson is not considered. The releases at Jackson are also not considered. The series of hypothetical storages are denoted STOREO(M), STOREL(M) and STORE2(M). They differ from those used in D1 and D3 in that they are total system storages and they are the beginning of the day storage rather than the end of the day storage as were the T-P series.

The STOREO(M) series of hypothetical storages is based on the assumption of DNOP releases for M-1,10 and CAPP releases for M=11,30.[4] This series is used to calculate a series indicating vacant storage space, denoted as ASPACO(M). This series is compared with the amount of vacant storage space required for flood control purposes as indicated by SUBROUTINE RFL.[5] The required amount of space is indicated by the variable name TEST(M). If ASPACO (the amount of available space) exceeds TEST (the required amount of space) for all M=1, 30, the RELP is set at DNOP, NBOXP is set to 45 and control is returned to MAIN. If ASPACO does not exceed TEST for all M, then STORE1(M) and ASPAC1(M) series are calculated based on the assumption of a DNOP release on the first day and CAPP (downstream channel capacity) releases for the rest of the period. If ASPAC1 exceeds TEST for all M, then a release adjusted by a proportionality factor as in D3 is made. The proportionality factors are identical in D1 and D3 and the release is once again based on the shortage of

Figure 28

Subroutine D4
Basic Decision Routine and Smoothing Function

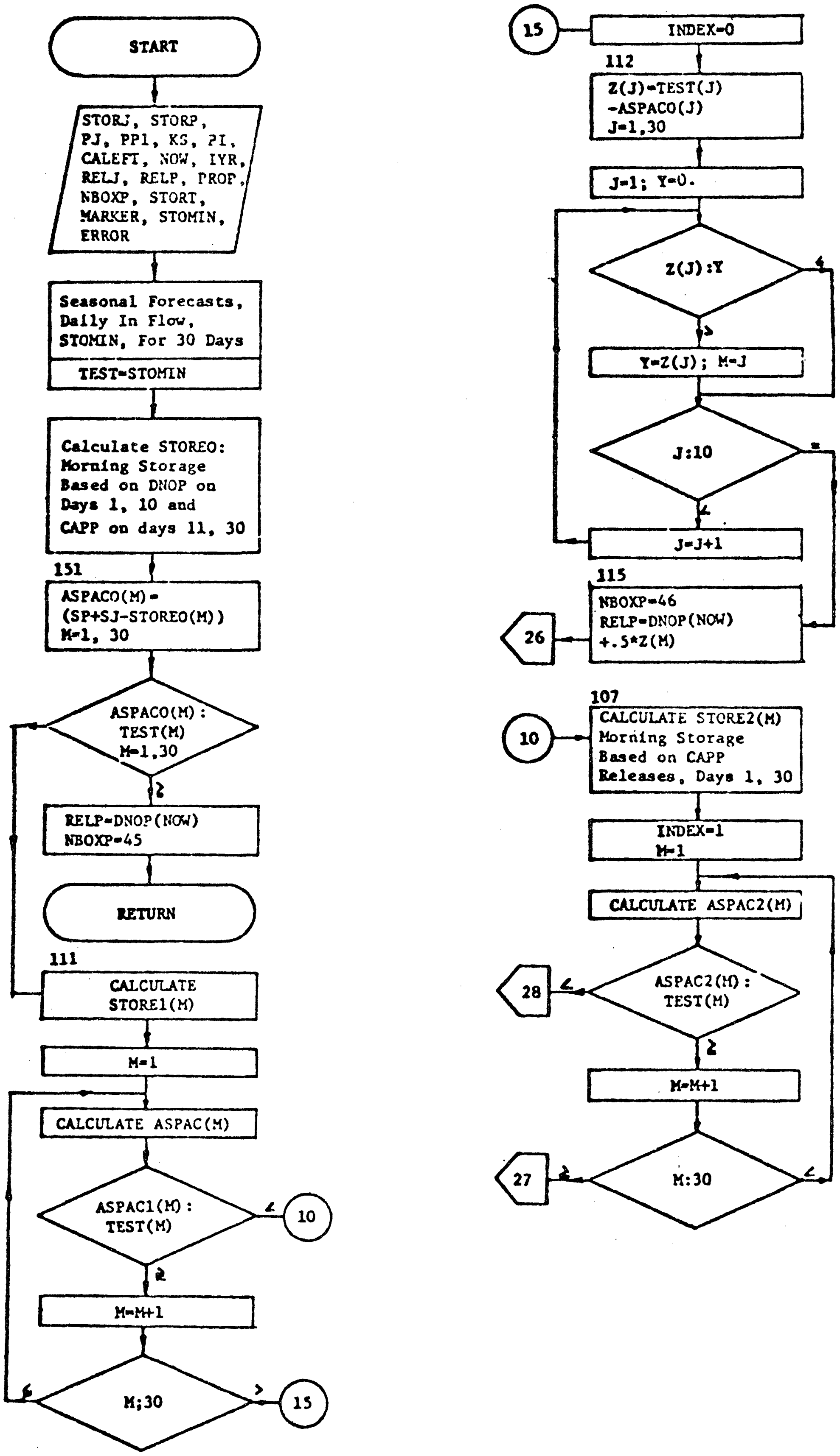
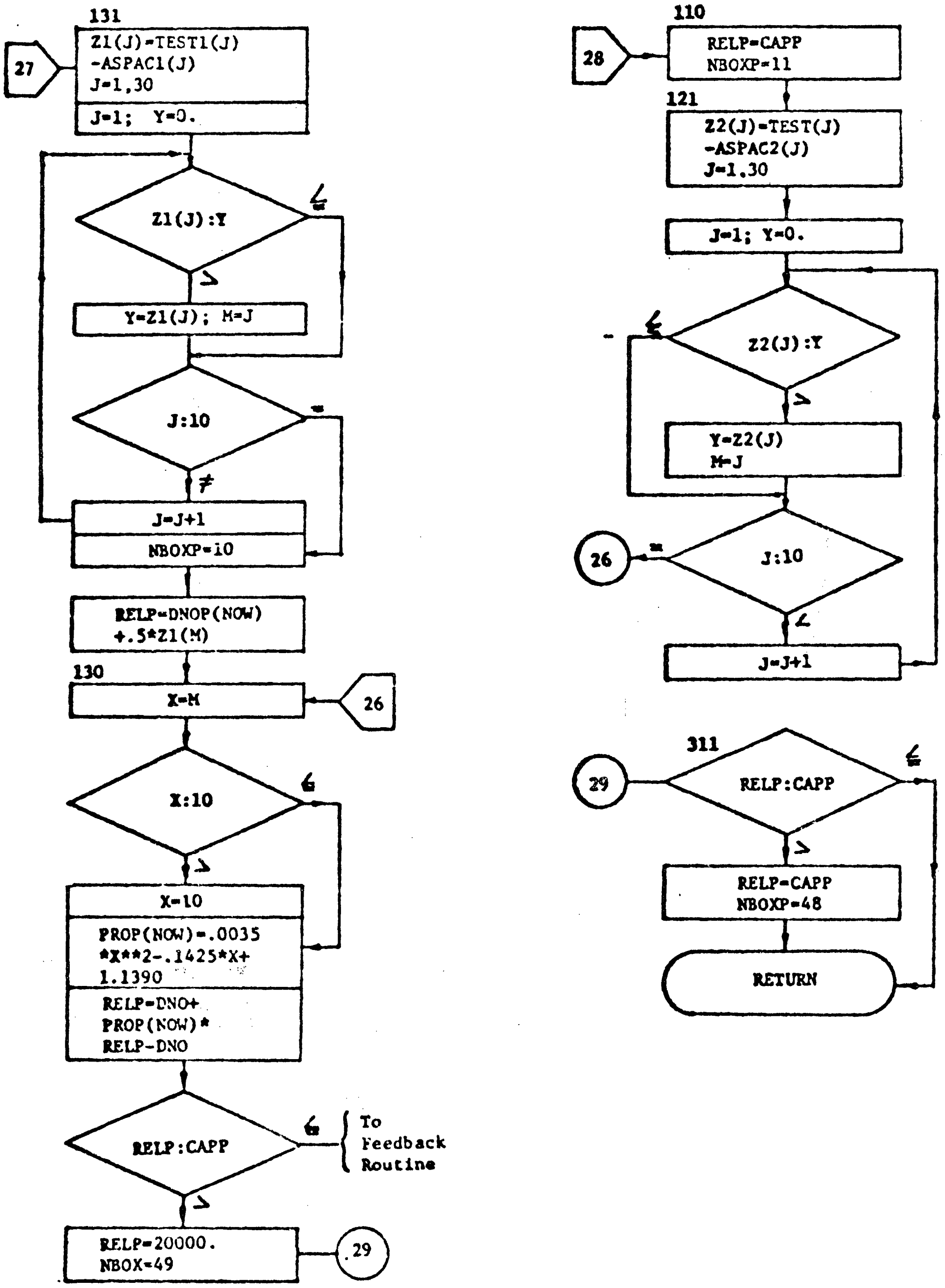


Figure 28 (Cont'd)



available space with respect to ASPACO on the maximum day and the number of days before that excess is reached. The decision location indicator (NBOXP) is set to 46 in this case. In the basic decision procedure control would return to MAIN at this point.

If ASPAC1 is less than TEST for some M, then STORE2(M) and ASPAC2(M) series are calculated. (These are respectively the sequence of storages based on the assumption of channel capacity releases for each of the 30 days and the sequence of available storage space based on the same assumption concerning releases.) If ASPAC2(M) is greater than TEST for all M, then a release based on the proportionality factor is again made. This time the release utilizes the maximum shortage of available space with ASPAC1 and the time lead before the occurrence. The proportionality factors are calculated by the same method as above and once again the programmer has the choice of which two quadratic equations to use. NBOXP is set to 10 in this case and once again in the basic decision model control is returned to MAIN.

The MAIN program checks to see if the total available storage in the combined reservoir is greater or less than the forecasted remaining season runoff. If it is not, MAIN scans the forecasted daily inflow for the next 30 days to determine whether or not it exceeds 20,000 cfs per day. If it does not and if the first test succeeds then SUBROUTINE D5 is passed over. If the forecasted inflow does exceed 20,000 cfs on one or more days, the MAIN program ascertains whether or not releases are being made because the system is presently encroached or Palisades is about to overflow. If either of these situations holds, D5 is passed over. If by the above D5 has not been passed over, D5 will be called at the programmer's discretion. As mentioned above, if D5 is called and the available storage space is not the proper ratio Palisades is released at channel capacity Jackson releases only irrigation demands and NBOXP=12. Control is returned to MAIN at this point if D5 was called.

This constitutes the basic decision package for the operation of the Jackson Dam and Reservoir and Palisades Dam and Reservoir on the Upper Snake River in Wyoming and Idaho. This program was run at several different levels of forecast accuracy and the basic objectives of maintaining releases at levels below CAPJ (downstream channel capacity - Jackson) and CAPP (downstream channel capacity - Palisades) and of filling or nearly filling the dam were adequately met. Although this decision system is not a completely faithful model of the actual operation on the river, some comparisons with the actual operation results were made. While recognizing that the value of comparisons is reduced by the deviation of the above decision criteria from those actually used, it can be said that given similar levels of information accuracy our program seems to operate the system with fewer losses in both high and low water years. In one way, however, the above basic program is deficient. The releases are very mechanistic and the resulting outflow hydrograph is far too rough and discontinuous to be tolerated on an actual river (particularly one with a great deal of water-related recreation carried on along its banks). The reason that the actual outflow hydrograph is much smoother is, of course, because the actual operations are controlled by a reasoning being who filters incoming information through a screen of experience. Such a learning model was considered for inclusion in this decision program but was rejected as being too complex for the benefits obtained. Instead it was decided to utilize a series of flow rate increase and decrease constraints (with suitable exception possibilities for emergency cases) and a feedback mechanism so that the program would consider the effect of today's decision on tomorrow's state of nature.

If the prime consideration were to construct a reservoir operation model, a learning through doing aspect should be included because of the potentialities for greater operating efficiency. This type of model does have a deficiency in that vast quantities of additional computer storage would be required to store the wealth of data on the effects of preceding decisions given various states of nature. As it is, the smoothing and feedback functions included in the model are very inefficient computationally in that there are numerous transfers of control but no additional computer storage is required. In terms of the quality of the operating model, for the level of sophistication required in this situation, however, the present methodology appears to be adequate.

The flow rate change constraints will be considered first since they are the simplest in nature. These constraints are located[6] in MAIN following all of the decision-making subroutines but before the accounting subroutines and the output producing statements of the MAIN program. The basic method is to set a maximum change in the release from one day to the next. The name of this maximum is CMAS for releases from Palisades and CMAXJ for releases from Jackson. CMAX is 2,000 cfs if the most recent releases from Jackson. CMAX is 2,000 cfs if the most recent release (RELP1) was greater than 10,000 cfs and 20% of REPL1 if RELP1 was less than 10,000 cfs.

The first step in the process is to determine whether or not the change in the release is positive or negative. If it is negative and if the forecasts for the next 30 days exceed 20,000 cfs for one or more days, the following process ensues. If RELP (the release from Palisades) is greater than 20,000 cfs and RELP1-RELP is greater than CMAX, then the previous RELP (established by D1 or D3 or D4 above) is cancelled, a new release order is issued (RELP=20,000) and a new indicator is set (IMBOXP=60). If RELP is less than 20,000 cfs and RELP1-RELP exceeds CMAX (either 2,000 cfs or .2(RELP1) depending on whether RELP1 is less than 10,000 cfs) the previous RELP is once again cancelled and a new one issued (RELP=RELP1-CMAX and IMBOXP=61).

If the change in the rate of release is positive, before the increase in the release rate is constrained, it must be determined whether or not the program is trying to make an emergency release of some kind. The following table indicates emergency releases and the reason for the release.

NBOXP = 8 Palisades will overflow today
NBOXP = 13 Palisades will overflow in the future
NBOXP = 14 Palisades will overflow today
NBOXP = 1 System encroached today

In addition any release previously adjusted by the proportionality factor where PROP = 1 (the problem occurs today) is considered an emergency release. All of the above releases are exempted from the CMAX constraint.

If RELP-RELP1 exceeds CMAX, then the old RELP is cancelled. The release from Palisades is set to RELP1 + CMAX and the decision location indicator (NBOXP) is set to 62. Again CMAX is 2,000 cfs or .2(RELP1) unless NBOXP=12 (indicating that the available storage space in Palisades and Jackson is not in the proper proportion in which case CMAX= 5,000. (This last CMAX was determined strictly on a trial and error basis. The reason it is different from the others results from difference in the state of nature when NBOXP=12 decisions are made. They are not emergency releases like the others so they should not be exempted. The release has to be allowed to change faster than 2,000 cfs per day however because a NBOXP=12 release requires normal 2,000 cfs CMAX release would make available storage space in the two reservoirs too slow.)

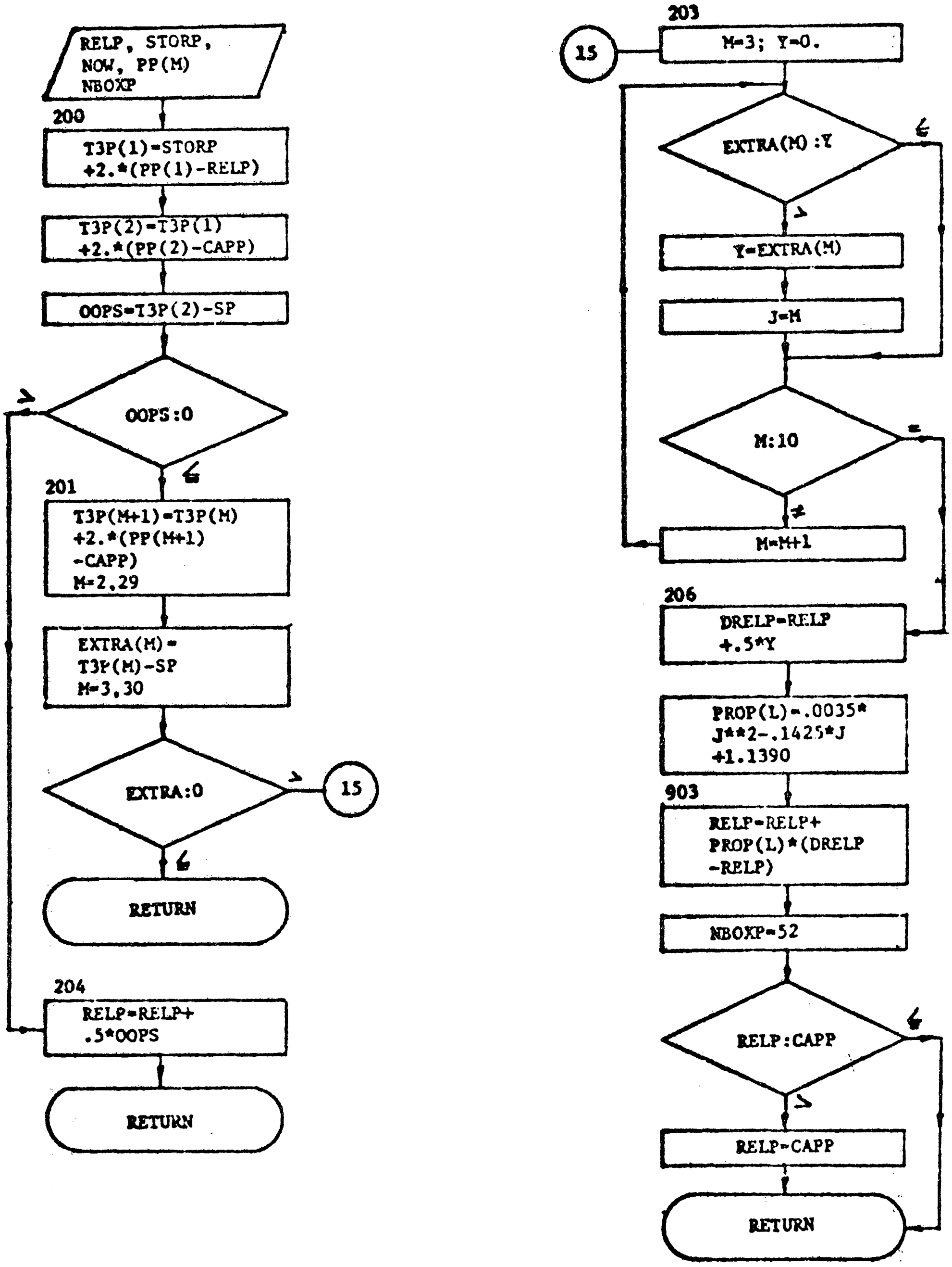
A similar procedure is followed to constrain the rate of change of releases from Jackson. CMAXJ=1,500 cfs and the various other parameters are changed to fit the new situation. The only emergency release exempted in the case of Jackson is a NBOXJ=6 release which indicates that Jackson releases are IMBOXJ=60, 61, 62, where the reasoning parallels that for the identically numbered indicator at Palisades.

The feedback mechanism built into SUBROUTINES D3 and D4 has a more fundamental reason for its existence than the cosmetic changes it makes in the release pattern. It will be recalled that the methodology of the basic decision process consisted of testing various hypothetical release patterns. These patterns consisted of the daily normal outflow from Palisades Reservoir (DNOP) or the channel capacity downstream of Palisades Dam (CAPP) for the rest of the period. If the DNOP release caused a violation of a storage constraint, and a CAPP release did not the release was set between DNOP and CAPP to minimize the release without violating the storage constraint. It was found that this method worked adequately for today's release. While it functioned reasonably well for the hypothetical releases of the following days, this method could blind the program to some critical situations which were developing in the future. For this reason a feedback mechanism was built into the two subroutines named above.

The basic idea behind the two feedback systems is identical with the only differences arising through the differences in SUBROUTINES D3 and D4. The system in D3 will be outlined here. (See Figure 29 for a simplified flow chart of this feature.) Using the RELP calculated by the basic routine of the subroutine, a new series of storages is calculated. These are known as T3P(M). T3P(1) is calculated on the basis

Figure 29

Subroutine D3
Feedback Routine



of RELP and the remainder of the series assumes CAPP releases. The program then checks to see if T3P(M) will exceed SP for the range M=2,30. If it discovers that the Reservoir will overflow the Dam on day M=2, RELP is increased by the full amount required to prevent the overflow. If it is discovered that the reservoir will overflow the Dam on a later day the release today to prevent the future overflow is calculated and then it is adjusted by the quadratic proportionality factor. Once again the release is determined by

RELP = RELP + PROP(L) . (DRELP-RELP) where DRELP is the release today to prevent the maximum future excess storage.[7]

As mentioned above the methodology in D4 is the same except that instead of using a new storage sequence a new ASPAC (the amount of space available in Palisades for flood control) series is used to be consistent with the basic procedure.

The above discussion outlines all of the routines with the exception of the accounting routines and the output printing section of the MAIN program which are straightforward. Their Fortran listings on the following pages should present no difficulty to the reader.

MAIN Program

```
C    INIT IS THE INITIAL NO. FOR GRAND, FORMAT = I7
C    LAST IS THE LAST YEAR OF SIMULATION, FORMAT = I5
C    CONSER IS A CONSERVATISM PARAMETER TO BOOST FORECAST,
C      FORMAT = F4.0
C    SDCAL IS THE STD DEV OF THE CALCULATED REMAINING RUNOFF,
C      FORMAT = F8.0
C    ACCUR IS THE STD DEV FOR THE DAILY FORECAST FORMAT=F8.0
C    RUNNO IS THE RUN NUMBER, FORMAT=I4
C    D5 IS BYPASSED IF ID5=0, CALLED IF ID5=1, FORMAT I1
      INTEGER RUNNO, DELAY,ADJUST,ERROR
      REAL JI,JIT,MAXR,MAXS
      DIMENSION JI(213),PLOC(213),PJ(30),PP1(30),RELJ(30),
     1      PI(30),XRELP(153),XRELJ(153),XSTORP(153),
     2      XSTORJ(153),INBOXP(153), INBOXJ(153), PP(30),
     3      JIT(30),PLOCT(30),PIT(30),RELJT(30),TEST(153),
     4      PROP(153),STORT(153),IMBOXP(153),IMBOXJ(153),
     5      NOD(20),NODJ(20),I(20),PP1T(30),ERROR(153)
      COMMON FLDCTL(29,45,2), STAND(213)
      READ(5,503) INIT,LAST,CONSER,SDCAL,ACCUR,RUNNO, ID5,
     1·     MARKER,DELAY,ADJUST
  503 FORMAT(I7/I5/F4.0/F8.0/F8.0/I4/I1/I1/I2/I1/I1/F8.0.
     1     /F6.0)
'F6.0)'
      WRITE(6,504) RUNNO,LAST,CONSER,SDCAL,ACCUR,MARKER,
     1      ID5,INIT,DELAY,ADJUST
  504 FORMAT(1H1,'SNAKE RIVER SIMULATION  RUN NO=',I3,
     1      ' 1910-',I4,'  CONSER=',F3.0,'SDCAL=',F7.0,
     2      ' ACCUR=',F7.0,' MARKER=',I1,' ID5=',I1,
     3      ' INIT=',I5,' DELAY=',I2,'ADJUST=',I1)
      WRITE(6,515) ICONST,SP,CAPP
  515 FORMAT (6X,' ICONST=',I1,'SP=',F9.0,'CAPP=',F7.0)
      CALL GRAND1(INIT)
      CALL REL
      READ(1,506)(STAND(J),J=1,213)
  506 FORMAT(10F8.0)
  100 READ(4,500) IYR,STORP,STORJ,ARELJ2,ARELJ1
  500 FORMAT(I4,4F8.0,F6.0)
      STORP=STORP*1000.
      READ(2,501)(JI(K),K=1,213)
      READ(3,501)(PLOC(K),K=1,213)
```

MAIN Program (continued)

```
      KS=1
      NOW=1
  501 FORMAT(/(10F8.0))
      STORT(NOW)=STORP+STORJ
      DO 901 M=1,153
      IMBOXP(M)=0
      IMBOXJ(M)=0
      ERROR(M)=0
  901 PROP(M)=99.
  102 CALEFT=0.
      DO 103 K=NOW,153
 103  CALEFT=CALEFT+JI(K)+PLOC(K)
      CALEFT=CALEFT*2.
C  CALCULATES FORECAST OF REMAINING SEASON RUNOFF BY
C   CALCULATING ACTUAL REMAINING SEASON RUNOFF AND
C   ADDING RANDOM ELEMENT
      IF (NOW.EQ.1) GO TO 911
      IF (NOW.LT.DAY+DELAY) GO TO 910
      DAY=NOW
      CALEFT=CALEFT+GRAND(SDCAL,0.)
      GO TO 910
  911 DAY=NOW
      CALEFT=CALEFT+ GRAND(SDCAL,0.)
  910 DO 110 K=1,30
      IT=NOW+K-1
      JIT(K)=JI(IT)
  110 PLOCT(K)=PLOC(IT)
      CALL PREDIK (NOW,JIT, PLOCT, CONSER,ACCUR,PJ,PP1)
      IF(KS.EQ.2) GO TO 104
      IF(JI(NOW)+PLOC(NOW).LT.CAPP) GO TO 104
      KS=2
  104 CALL D1(STORJ,STORP,PJ,KS,CALEFT,NOW,RELP,RELJ,
     1        NCROCH,NBOXP,NBOXJ,IYR,STOMIN,STORT,ADJUST,
     2        ICONST,ERROR,SP,CAPP)
      TEST(NOW)=STOMIN
      IF(NCROCH.EQ.0) GO TO 105
      N=30
      GO TO 106
  105 N=1
  106 CALL D2M(ARELJ2,ARELJ1,RELJ,PI,N)
```

MAIN Program (continued)

```
      DO 109 J=1,30
  109 PP(J)=PP1(J)+PI(J)
      CALL D3(STORP,PP,NOW,RELP,NCROCH,NBOXP,PROP,MARKER,
     1        SP,CAPP)
      IF(NCROCH.EQ.0) GO TO 107
      IF (MCROCH.EQ.0) GO TO 107
      CALL D4(STORJ,STORP,PJ,PP1,KS,CALEFT,NOW,RELJ,
     1        PI,RELP,NBOXP,IYR,PROP,STORT,MARKER,
     2        STOMIN,ERROR,SP,CAPP)
      TEST(NOW)=STOMIN
  107 IF (ID5.EQ.1) GO TO 801
      GO TO 116
  801 IF((SP-STORP).GE.CALEFT) GO TO 116
      IF(NOW.LE.75) GO TO 112
      DO 113 J=1,30
      IF(PP1(J).GE.CAPP) GO TO 112
  113 CONTINUE
      GO TO 116
  112 IF (NCROCH.EQ.0) GO TO 116
      IF (MCROCH.EQ.0) GO TO 116
      CALL D5(STORJ,STORP,RELP,NBOXP,SP,CAPP)
  116 IF (NOW.EQ.1) GO TO 117
      J=NOW
      RELP1=XRELP(J-1)
      IF (KS.EQ.1) GO TO 903
      DO 902 L=1,30
      IF (PP1(L).LT.CAPP) GO TO 119
  902 CONTINUE
  903 CMAX=2000.
      IF (RELP.GE.RELP1) GO TO 119
      IF (ICONST.EQ.1) GO TO 119
      IF (RELP1.LE.CAPP) GO TO 122
      IF (RELP1-RELP.LE.CMAX) GO TO 111
      IF (RELP.GT.CAPP) GO TO 111
      RELP=CAPP
      IMBOXP(NOW)=60
  122 IF (RELP1.LT.10000.) CMAX=.2*(RELP1)
      IF ((RELP1-RELP).LE.CMAX) GO TO 111

      RELP=RELP1-CMAX
      IMBOXP(NOW)=61
```

MAIN Program (continued)

```
      GO TO 111
  119 CMAX=2000.
      IF (NBOXP.EQ.8) GO TO 111
      IF (NBOXP.EQ.13) GO TO 111
      IF (PROP(NOW).EQ.1.) GO TO 111
      IF (NBOXP.EQ.14) GO TO 111
      IF (NBOXP.EQ.1) GO TO 111
      IF (RELP-RELP1.LE.CMAX) GO TO 111
      IF (NBOXP.EQ.12) CMAX=5000.
      RELP=RELP1+CMAX
      IMBOXP(NOW)=62
  111 IF (RELJ(1).LE.1500.) GO TO 117
      CMAXJ=1500.
      J=NOW
      RELJ1=XRELJ(J-1)
      IF (RELJ(1).GE.RELJ1) GO TO 118
      IF (ICONST.EQ.1) GO TO 118
      IF (RELJ1.LE.7000.) GO TO 123
      IF (RELJ1-RELJ(1).LE.CMAXJ) GO TO 117
      IF (RELJ(1).GT.7000.) GO TO 117
      RELJ(1)=7000.
      IMBOXJ(NOW)=60
  123 CONTINUE
      IF (RELJ1-RELJ(1).LE.CMAXJ) GO TO 117
      RELJ(1)=RELJ1-CMAX
      IMBOXJ(NOW)=61
      GO TO 117
  118 IF (NBOXJ.EQ.6) GO TO 117
      IF (RELJ(1)-RELJ1.LE.CMAXJ) GO TO 117
      RELJ(1)=RELJ1+CMAXJ
      IMBOXJ(NOW)=62
  117 CONTINUE
      XRELP(NOW)=RELP
      XRELJ(NOW)=RELJ(1)
      XSTORP(NOW)=STORP
      XSTORJ(NOW)=STORJ
      INBOXP(NOW)=NBOXP
      INBOXJ(NOW)=NBOXJ
      ARELJ2=ARELJ1
      ARELJ1=RELJ(1)
```

MAIN Program (continued)

```
      STORP=STORP+2.*(PI(1)+PLOC(NOW)-RELP)
      STORJ=STORJ+2.*(JI(NOW)-RELJ(1))
      J=NOW+1
      STORT(J)=STORT(NOW)+2*(PLOC(NOW)+JI(NOW)-RELP)
  900 NOW=NOW+1
      IF (NOW.LE.153) GO TO 102
      DO 200 J=1,153
      IF (ERROR(J).EQ.0) GO TO 200
      IF(XRELP(J).LE.20000.) GO TO 200
      XRELP(J)=20000.
      INBOXP(J)=98
  200 CONTINUE
      CALL D7 (XSTORJ,XRELJ,NODJ,MAXRJ,MAXSJ,XRELJJ,L,PJ)
C   OUTPUT AND FORMAT STATEMENTS INSERTED AT THIS POINT
C    AS DESIRED.
      IF(IYR.GE.LAST) STOP
      GO TO 100
      STOP
      END
```

SUBROUTINE D1

```
      SUBROUTINE D1(STORJ,STORP,PJ,KS,CALEFT,NOW,RELP,
     1   RELJ,MCROCH,NBOXP,NBOXJ,IYR,STOMIN,STORT,
     2   ADJUST,PP1,ERROR,SP,CAPP)
C    D1 EXAMINES WHETHER OR NOT SYSTEM IS ENCROACHED. IF IT
C        IS, D1 FIXES RELP AND RELJ(1), SETS MCROCH=0,
C        AND RETURNS. IF SYSTEM IS NOT ENCROACHED,
C        RELJ(L),L=1,30 ARE CALCULATED AND NCROCH=1.
C        IF NCROCH=1, PROGRAM ITERATES LOOP FROM 101
C        THIRTY TIMES TO CALCULATE RELJ(1)'S TO FEED INTO
C        PALISADES AS INFLOWS. ACTUAL REL=RELJ(1) ON
C        FIRST ITERATION ONLY. THIS IS ONLY TIME NBOXJ SET.
      DIMENSION PJ(30),RELJ(30),CA(30),STOREJ(31),TOJ(40),
     1   T1J(40),PJT(30),T2J(40),STORT(153),PP1(30),
     2   P(30),ERROR(153),ITEST(31),STOM1(31),STOM2(31)
      INTEGER ERROR
      REAL OOPS
      DATA CAPJ,SJ,ITEST,STOM1STOM2/7000.,847000.,1,5,
     2   10,15,20,25,31,36,41,46,51,56,61,66,71,76,
     3   81,86,92,97,102,107,112,117,122,127,132,137,
     4   142,147,153,140.,330.,580.,800.,980.,1100.,
     5   1290.,1400.,1500.,1550.,1600.,1590.,1550.,
     6   1580.,1530.,1560.,1580.,1580.,1600.,1600.,
     7   1600.,1520.,1400.,1200.,1060.,800.,0.,0.,0.,
     8   0.,0.,140.,330.,580.,800.,980.,1100.,1290.,
     9   1400.,1500.,1600.,1590.,1550.,1580.,1530.,
     1   1560.,1580.,1580.,1600.,1600.,1540.,1430.,
     2   1200.,1060.,800.,680.,480.,300.,120.,0.,0./
      NBOXP=0
      NBOXJ=0
      NC=NCALEF(CALEFT)
      CALL STO(STOMIN,NOW,NC,KS)
      IF (STOMIN.GE.0) GO TO 120
      IF (KS.GT.1) GO TO 920
      DO 926 M=2,31
      IF (NOW.LT.ITEST(M)) GO TO 924
  926 CONTINUE
      STOMIN=STOM1(31)*1000.
      GO TO 921
  924 STOMIN=STOM1(M-1)*1000.
      GO TO 921
```

SUBROUTINE D1 (continued)

```
  920 DO 925 M=2,31
      IF (NOW.LT.ITEST(M)) GO TO 927
  925 CONTINUE
      STOMIN=STOM2(31)*1000.
      GO TO 921
  927 STOMIN=STOM2(M-1)*1000.
  921 ERROR(NOW)=1
  120 CONTINUE
  928 OOPS=STOMIN-SP-SJ+STORT(NOW)
  300 IF (OOPS.GT.100) GO TO 100
      MCROCH=1
      STOREJ(1)=STORJ
      CA(1)=CALEFT
      DO 102 L=1,29
  102 CA(L+1)=CA(L)-PJ(L)*2.
      K=1
  101 IF(K.EQ.31) RETURN
      IT=NOW+K-1
      TOJ(K)=STOREJ(K)+2.*(PJ(K)
     1   -DNOJ(IT,PJ(K),STOREJ(K)))
      IF(K.EQ.30)GO TO 104
      DO 103 L=K,29
      IT=NOW+L
  103 TOJ(L+1)=TOJ(L)+2.*(PJ(L+1)-DNOJ(IT,PJ(L+1),TOJ(L)))
  104 DO 107 L=K,30
      IF(TOJ(L).GT.SJ) GO TO 106
  107 CONTINUE
      DO 105 L=K,30
      IT=NOW+L-1
      RELJ(L)=DNOJ(IT,PJ(L),STOREJ(L))
  105 STOREJ(L+1)=STOREJ(L)+2.*(PJ(L)-RELJ(L))
      IF(K.EQ.1) NBOXJ=3
C   TOJ SERIES LESS THAN SJ. THUS RELJ=DNOJ FOR ALL DAYS
C        K,30. NO FURTHER ITERATIONS NECESSARY.
C        THEREFORE EXIT FROM SUBROUTINE.
      RETURN
  106 T1J(K)=TOJ(K)
      IF(K.EQ.30) GO TO 117
      DO 108 L=K,29
```

SUBROUTINE D1 (continued)

```
  108 T1J(L+1)=T1J(L)+2.*(PJ(L+1)-CAPJ)
  117 IT=NOW+K-1
      DNO=DNOJ(IT,PJ(K),STOREJ(K))
      DO 109 L=K,30
      IF(T1J(L).GT.SJ) GO TO 110
  109 CONTINUE
      RELJ(K)=DNO
      IF(K.EQ.1) NBOXJ=4
      GO TO 150
  110 DO 111 L=K,30
  111 T2J(L)=T1J(L)-2.*(CAPJ-DNO)
      DO 112 L=K,30
      IF(T2J(L).GT.SJ) GO TO 113
C   INVESTIGATES WHETHER STORAGE AT THE END OF KTH DAY
C        EXCEEDS CAPACITY STORAGE.
  112 CONTINUE
      XMAX=T1J(K)
      DO 114 L=K,30
  114 XMAX=AMAX1(XMAX,T1J(L))
      RELJ(K)=DNO+(XMAX-SJ)/2.
      IF(K.EQ.1) NBOXJ=5
      GO TO 150
  113 OOPS=STOREJ(K)+2.*(PJ(K)-CAPJ)-SJ
C    STOREJ(5)= STORAGE AT BEGINNING OF KTH DAY.
      IF(OOPS.GT.0.)GO TO 115
      RELJ(K)=CAPJ
      IF(K.EQ.1) NBOXJ=7
      GO TO 150
  115 RELJ(K)=OOPS/2.+CAPJ
C   THIS  HYPOTHETICAL RELEASE EXCEEDS  CAPJ BECAUSE IT
C        IS THE RELEASE FOR THE DAY THE RESERVOIR
C        GOES OUT OF CONTROL.
      IF(K.EQ.1) NBOXJ=6
  150 STOREJ(K+1)=STOREJ(K)+2.*(PJ(K)-RELJ(K))
      K=K+1
      GO TO 101
  100 MCROCH=0
      IF(NOW.GT.93) GO TO 116
      IF (ADJUST.EQ.1) GO TO 301
      DO 302 L=1,30
      P(L)=PJ(L)+PP1(L)
```

SUBROUTINE D1 (continued)

```
      IF (P(L).GE.CAPP) GO TO 301
  302 CONTINUE
      RELP=DNOP+.3*(CAPP-DNOP)
      NBOXP=44
      RELJ(1)=DNOJ(NOW,PJ(1),STORJ)
      NBOXJ=44
      GO TO 151
  301 RELP=CAPP
      NBOXP=1
      NBOXJ=1
      GO TO 151
  116 ATWO=CAPP+OOPS/5.
      IF (ADJUST.EQ.1) GO TO 303
      DO 304 L=1,30
      P(L)=PJ(L)+PP1(L)
      IF (P(L).GE.CAPP) GO TO 303
  304 CONTINUE
      RELP=DNOP+.3*(ATWO-DNOP)
      RELJ(1)=DNOJ(NOW,PJ(1),STORJ)
      NBOXP=43
      NBOXJ=43
  303 RELP=AMIN1(30000.,ATWO)
      RELJ(1)=DNOJ(NOW,PJ(1),STORJ)
      NBOXP=2
      NBOXJ=2
  151 IF (STORJ+2.*(PJ(1)-DNOJ(NOW,PJ(1),STORJ)).LE.SJ)
     1   RETURN
      RELJ(1)=DNOJ(NOW,PJ(1),STORJ)+.5*(STORJ+2.*(PJ(1)
     1   -DNOJ(NOW,PJ(1),STORJ))-847000.)
      NBOXJ=39
      RETURN
      END
```

SUBROUTINE D3

```
      SUBROUTINE D3(STORP,PP,NOW,RELP,NCROCH,
     1   NBOXP,PROP,MARKER,SP,CAPP)
C    D3 CALCULATES RELEASE FROM PALISADES IF DAM MAY
C        GO OUT OF CONTROL (NCROCH=0) OR PASSES
C        RELEASE DECISION TO D4 IF DAM WILL NOT GO
C        OUT OF CONTROL (NCROCH=1).
      DIMENSION PP(30),T1P(30),T2P(30),PROP(153),PPT(30),
     1   T3P(30),EXTRA(30),PPI(30),ASTORP(153)
      REAL OOPS
  302 DNO=DNOP(NOW)
      T1P(1)=STORP+2.*(PP(1)-DNO)
      DO 100 M=1,29
  100 T1P(M+1)=T1P(M)+2.*(PP(M+1)-CAPP)
  303 DO 101 M=1,30
      IF(T1P(M).GT.SP) GO TO 102
  101 CONTINUE
      NCROCH=1
      RETURN
  102 NCROCH=0
      DO 103 M=1,30
  103 T2P(M)=T1P(M)+2.*(DNO-CAPP)
  304 DO 104 M=1,30
      IF(T2P(M).GT.SP) GO TO 105
  104 CONTINUE
      XMAX=T1P(1)
      DO 106 M=2,30
  106 XMAX=AMAX1(XMAX,T1P(M))
      DO 112 M=1,30
  112 IF (XMAX.EQ.T1P(M)) J=M
      GO TO 108
  105 OOPS=STORP+2.*(PP(1)-CAPP)-SP
      IF(OOPS.GT.0.) GO TO 107
      RELP=CAPP
      NBOXP=8
      RETURN
  107 RELP=.5*OOPS+CAPP
      NBOXP=14
      GO TO 200
  108 RELP=DNO+.5*(XMAX-SP)
      IF (MARKER.EQ.1) GO TO 900
      IF (J.GT.10) J=10
```

SUBROUTINE D3 (continued)

```
      PROP(NOW)=.0035*J**2-.1425*J+1.1390
      GO TO 905
  900 IF (J.GT.15) J=15
      PROP(NOW)=.0054*J**2-.1570*J+1.1526
  905 RELP=DNO+PROP(NOW)*(RELP-DNO)
      NBOXP=13
  200 T3P(1)=STORP+2.*(PP(1)-RELP)
C   STATEMENT 200 COMMENCES FEEDBACK ADJUSTMENT TO RELEASES
C        DETERMINED BY NBOXP = 8,14,13.
      T3P(2)=T3P(1)+2.*(PP(2)-CAPP)
      OOPS=T3P(2)-SP
      IF (OOPS.GT.0) GO TO 204
C   ADJUST RELP BY FULL AMOUNT REQUIRED TO KEEP IN CONTROL
C        ON (NOW+1).
      DO 201 M=2,29
  201 T3P(M+1)=T3P(M)+2.*(PP(M+1)-CAPP)
      DO 202 M=3,30
      EXTRA(M)=T3P(M)-SP
      IF (EXTRA(M).GT.0) GO TO 203
  202 CONTINUE
      RETURN
  204 RELP=RELP+.5*OOPS
      RETURN
  203 M=3
      Y=0.
  207 IF (EXTRA(M).LE.Y) GO TO 205
      Y=EXTRA(M)
      J=M
  205 IF (MARKER.EQ.1) GO TO 901
      IF (M.EQ.10) GO TO 206
  901 IF (M.EQ.15) GO TO 206
      M=M+1
      GO TO 207
  206 DRELP=RELP+.5*Y
C   DRELP=RELEASE REQUIRED TO PREVENT OVERFLOW ON
C        DAY (NOW+M-1) M=2,29.
      L=NOW
      IF (MARKER.EQ.1) GO TO 902
      PROP(L)=.0035*J**2-.1425*J+1.1390
```

SUBROUTINE D3 (continued)

```
  902 PROP(L)=.0054*J**2-.1570*J+1.1526
      GO TO 903
  903 RELP=RELP+PROP(L)*(DRELP-RELP)
C   RELP=RELEASE IN LIGHT OF POSSIBILITY OF OVERFLOW
C         2 OR MORE DAYS AHEAD. IT IS DRELP ADJUSTED
C         BY A PROPORTIONALITY FACTOR.
      NBOXP=52
      IF (RELP.LE.CAPP) RETURN
      RELP=CAPP
      RETURN
      END
```

SUBROUTINE D4

```
      SUBROUTINE D4(STORJ,STORP,PJ,PP1,KS,CALEFT,NOW,
     1   RELJ,PI,RELP,NBOXP,IYR,PROP,STORT,MARKER,STOMIN,
     2   ERROR,SP,CAPP)
C    D4 CALCULATES TODAY'S RELEASE FROM PALISADES
C        BASED ON ENCROACHMENT CONSIDERATIONS.
C    THE STORE(M) SERIES IS STORAGE AT THE BEGINNING OF LEAD
C        DAY M (FROM NOW-1).
C    STORE1(M) IS HYPOTHETICAL STORAGE AT BEGINNING OF
C        DAY M IF DNOP IS RELEASED FOR M=1 AND
C        CAPP FOR ALL DAYS THEREAFTER.
C    STORE2(M) IS HYPOTHETICAL STORAGE BEGINNING OF DAY
C        M IF CAPP RELEASED FOR ALL DAYS PRECEEDING M.
C    THE T J(M) AND T P(M) SERIES ARE SIMILAR TO THE
C        STORE SERIES EXCEPT THEY ARE MEASURED AT THE END OF
C        DAY M WITH THE APPROPRIATE RELEASE DURING DAY M.
      DIMENSION STORE1(30),STORE2(30),PJ(30),PP1(30),
     1   CA(30),NC(30),PJT(30),PP1T(30),KC(30),TEST(30),
     2   Z(30),ASPAC1(30),ASPAC2(30),STORE0(30),ASPAC0(30),
     3   PROP(153),RELJ(30),PI(30),STORT(153),Z1(30),
     4   Z2(30),APSAC(30),ZED(30),ERROR(153),ITEST(31),
     5   STOM1(31),STOM2(31)
      INTEGER ERROR
      DATA CAPJ,SJ,ITEST,STOM1STOM2/7000.,847000.,1,5,
     2   10,15,20,25,31,36,41,46,51,56,61,66,71,76,
     3   81,86,92,97,102,107,112,117,122,127,132,137,
     4   142,147,153,140.,330.,580.,800.,980.,1100.,
     5   1290.,1400.,1500.,1550.,1600.,1590.,1550.,
     6   1580.,1530.,1560.,1580.,1580.,1600.,1600.,
     7   1600.,1520.,1400.,1200.,1060.,800.,0.,0.,0.,
     8   0.,0.,140.,330.,580.,800.,980.,1100.,1290.,
     9   1400.,1500.,1600.,1590.,1550.,1580.,1530.,
     1   1560.,1580.,1580.,1600.,1600.,1540.,1430.,
     2   1200.,1060.,800.,680.,480.,300.,120.,0.,0./
      CA(1)=CALEFT
      DO 101 M=1,29
      CA(M+1)=CA(M)-2.*(PJ(M)+PP1(M))
      IF (CA(M).LE.0) GO TO 918
  101 CONTINUE
      MEND=30
```

<u>SUBROUTINE</u> <u>D4</u> (continued)

```
      GO TO 919
  918 MEND=M
  919 DO 102 M=1,MEND
  102 NC(M)=NCALEF(CA(M))
      IF (KS.EQ.2) GO TO 103
      DO 900 M=1,30
      IF ((PJ(M)+PP1(M)).GE.CAPP) GO TO 901
      KC(M)=1
      GO TO 900
  901 DO 903 J=M,30
  903 KC(J)=2
      GO TO 902
  900 CONTINUE
      GO TO 902
  103 DO 104 M=1,MEND
  104 KC(M)=2
  902 DO 105 M=1,MEND
      IT=NOW-1+M
      CALL STO(STOMIN,IT,NC(M),KC(M))
  105 TEST(M)=STOMIN
      DO 198 M=1,MEND
      IF (TEST(M).GE.0) GO TO 198
      IF (KC(M).GT.1) GO TO 920
      IT=NOW-1+M
      DO 930 J=1,31
      IF (IT.LT.ITEST(J)) GO TO 931
  930 CONTINUE
      TEST(M)=STOM1(J)*1000.
      GO TO 934
  931 TEST(M)=STOM1(J-1)*1000.
      GO TO 934
  920 IT=NOW-1+M
      DO 932 J=1,31
      IF (IT.LT.ITEST(J)) GO TO 933
  932 CONTINUE
      TEST(M)=STOM2(J)*1000.
      GO TO 934
  933 TEST(M)=STOM2(J-1)*1000.
```

SUBROUTINE D4 (continued)

```
934 ERROR(NOW)=4
198 CONTINUE
922 STOMIN=TEST(1)
925 CONTINUE
927 STOREO(1)=STORT(NOW)
    DO 150 M=1,10
150 STOREO(M+1)=STOREO(M)+2.*(PJ(M)+PP1(M)-DNOP(NOW))
    DO 155 M=11,29
155 STOREO(M+1)=STOREO(M)+2.*(PJ(M)+PP1(M)-CAPP)
    DO 151 M=1,30
151 ASPACO(M)=(SP+SJ-STOREO(M))
    DO 156 M=1,30
    IF(ASPACO(M).LT.TEST(M)) GO TO 111
156 CONTINUE
    RELP=DNOP(NOW)
    NBOXP=45
    RETURN
111 STORE1(1)=STORT(NOW)
    STORE1(2)=STORE1(1)+2.*(PJ(1)+PP1(1)-DNOP(NOW))
    DO 100 M=2,29
100 STORE1(M+1)=STORE1(M)+2.*(PJ(M)+PP1(M)-CAPP)
    DO 106 M=1,30
    ASPAC1(M)=(SP+SJ-STORE1(M))
    IF(ASPAC1(M).LT.TEST(M)) GO TO 107
106 CONTINUE
    INDEX=0
    DO 112 J=1,30
112 Z(J)=TEST(J)-ASPACO(J)
    J=1
    Y=0.
113 IF(Z(J).LE.Y) GO TO 114
    Y=Z(J)
    M=J
114 IF (MARKER.EQ.1) GO TO 910
    IF(J.EQ.10) GO TO 115
910 IF (J.EQ.15) GO TO 115
    J=J+1
    GO TO 113
115 NBOXP=46
700 RELP=DNOP(NOW)+.5*Z(M)
    GO TO 130
107 STORE2(1)=STORT(NOW)
    DO 108 M=1,29
```

SUBROUTINE D4 (continued)

```
108 STORE2(M+1)=STORE2(M)+2.*(PJ(M)+PP1(M)-CAPP)
    INDEX=1
    DO 109 M=1,30
    ASPAC2(M)=(SP+SJ-STORE2(M))
    IF (ASPAC2(M).LT.TEST(M)) GO TO 110
109 CONTINUE
    DO 131 J=1,30
131 Z1(J)=TEST(J)-ASPAC1(J)
    J=1
    Y=0.
133 IF(Z1(J).LE.Y) GO TO 132
    Y=Z1(J)
    M=J
132 IF (MARKER.EQ.1) GO TO 911
    IF(J.EQ.10) GO TO 140
911 IF (J.EQ.15) GO TO 140
    J=J+1
    GO TO 133
140 NBOXP=10
    RELP=DNOP(NOW)+.5*Z1(M)
    GO TO 130
110 RELP=CAPP
    NBOXP=11
307 DO 121 J=1,30
121 Z2(J)=TEST(J)-ASPAC2(J)
    J=1
    Y=0.
123 IF(Z2(J).LE.Y) GO TO 122
    Y=Z2(J)
    M=J
122 IF (MARKER.EQ.1) GO TO 912
    IF (J.EQ.10) GO TO 130
912 IF (J.EQ.15) GO TO 130
    J=J+1
    GO TO 123
130 X=M
701 IF (MARKER.EQ.1) GO TO 913
    IF (X.LE.10) GO TO 306
    X=10
    GO TO 306
913 IF (X.LE.15) GO TO 306
    X=15
```

SUBROUTINE D4 (continued)

```
  306 IF (MARKER.EQ.1) GO TO 914
      PROP(NOW)=.0035*X**2-.1425*X+1.1390
      GO TO 309
  914 PROP(NOW)=.0054*X**2-.1570*X+1.1526
  309 TPROP=PROP(NOW)
  197 DNO=DNOP(NOW)
      RELP=DNO+PROP(NOW)*(RELP-DNO)
  310 IF (RELP.LE.CAPP) GO TO 302
      RELP=CAPP
      NBOXP=49
      GO TO 809
  302 ASPAC(2)=ASPAC1(1)+2.*(RELP-PP1(1)-PJ(1))
C     STATEMENT 302 STARTS FEEDBACK SECTION
      IF (INDEX.EQ.0) GO TO 805
      IF(ASPAC(2).GT.TEST(2)) GO TO 805
      ZEE=TEST(2)-ASPAC(2)
      RELP=RELP+.5*ZEE
  805 DO 801 M=2,30
      ASPAC(M+1)=ASPAC(M)+2.*(CAPP-PP1(M)-PJ(M))
  801 ZED(M)=TEST(M)-ASPAC(M)
C    TESTS TO SEE IF FEEDBACK ADJUSTED RELP(NOW) WILL
C         PREVENT ENCROACHMENT DURING THE REMAINDER OF
C         THE PERIOD.
      DO 807 M=2,30
      IF (ZED(M).GT.0) GO TO 808
  807 CONTINUE
      GO TO 809
  808 M=2
      Y=0.
  800 IF (ZED(M).LE.Y) GO TO 803
      Y=ZED(M)
      J=M
  803 IF (MARKER.EQ.1) GO TO 915
      IF (M.EQ.10) GO TO 804
  915 IF (M.EQ.15) GO TO 804
      M=M+1
      GO TO 800
  804 DRELP=RELP+.5*Y
C    DRELP IS RELEASE REQUIRED TO PREVENT FUTURE
C         ENCROACHMENT BASED ON NOW'S FORECAST OF
C         FUTURE INFLOWS.
```

SUBROUTINE D4 (continued)

```
      L=NOW
      IF (MARKER.EQ.1) GO TO 916
      PROP(L)=.0035*J**2-.1425*J+1.1390
      GO TO 917
  916 PROP(L)=.0054*J**2-.1570*J+1.1526
  917 RELP=RELP+PROP(L)*(DRELP-RELP)
      NBOXP=47
  809 CONTINUE
  311 IF (RELP.LE.CAPP) RETURN
      RELP=CAPP
      NBOXP=48
  303 RETURN
      END
```

SUBROUTINE STO

```
      SUBROUTINE STO(STOMIN,NOW,NC,KS)
C    STO CALCULATES MINIMUM STORAGE REQUIREMENT FOR FLOOD
C        CONTROL. IF APPROPRIATE DATA  DOES NOT EXIST
C        IN FLDCTL MATRIX, STOMIN=-1.
      READ(1,100) (((FLDCTL(I,J,K),J=1,40),I=1,29),K=1,2)
  100 FORMAT(5X,15F5.0/5X,15F5.0/5X,10F5.0)
      DIMENSION ITEST(29)
      COMMON FLDCTL(29,45,2), STAND(213)
      DATA ITEST/1,5,10,15,20,25,31,36,41,46,51,56,
     1    61,66,71,76,81,86,92,97,102,107,112,117,
     2    122,127,132,137,142/
      DO 103 J=2,29
      IF(NOW.LT.ITEST(J)) GO TO 101
  103 CONTINUE
      STOMIN=FLDCTL(29,NC,KS)
      RETURN
  101 STO1=FLDCTL(J-1,NC,KS)
      STO2=FLDCTL(J,NC,KS)
      IF (STO1.LT.0) GO TO 102
      IF (STO2.LT.0) GO TO 102
      XNUM=NOW-ITEST(J-1)
      DENOM=ITEST(J)-ITEST(J-1)
      STOMIN=STO1+(XNUM/DENOM)*(STO2-STO1)
      RETURN
  102 STOMIN=AMIN1(STO1,STO2)
      RETURN
      END
```

<u>FUNCTION</u> <u>TT(REL)</u>

```
      FUNCTION TT(REL)
C    THIS FUNCTION COMPUTES THE TIME IN FRACTIONS OF A DAY
C         TAKEN BY A RELEASE OF SIZE RELJ AT JACKSON
C         TO TRAVEL TO PALISADES.
      DIMENSION TIME(17),TEST(17)
      DATA TIME/1.427,1.240,1.104,1.010,.937,.885,.840,
     1   .812,.792,.771,.750,.740,.729,.715,.702,
     2   .698,.687/TEST/2000.,3000.,4000.,5000.,
     3   6000.,7000.,8000.,9000.,10000.,11000.,
     4   12000.,13000.,14000.,15000.,16000.,17000.,
     5   18000./
      IF (REL.LT.TEST(1)) GO TO 100
      DO 101 J=2,17
      IF(REL.LT.TEST(J)) GO TO 102
  101 CONTINUE
      IF(REL.EQ.TEST(17)) GO TO 103
      TT=.5
      RETURN
  103 TT=TIME(17)
      RETURN
  100 TT=TIME(1)
      RETURN
  102 TT=TIME(J-1)-((REL-TEST(J-1)/1000.)*
     1   (TIME(J-1)-TIME(J))
      RETURN
      END
```

FUNCTION DNOP (NOW)

```
      FUNCTION DNOP(NOW)
C    THIS SUBROUTINE CALCULATES THE DAILY NORMAL OUTFLOW
C         FROM PALISADES AS A FUNCTION OF THR DAY,
C         (NOW), NUMBERED CONSECUTIVELY FROM MARCH 1
C         BASED ON THE AVERAGE RELEASES FROM 1959,1960,1961.
      INTEGER TEST
      DIMENSION DNO(5),TEST(5)
      DATA DNO/1841.,2724.,9691.,12804.,13107./
      DATA TEST/31,62,93,124,165/
      DO 100 J=1,5
      IF(NOW.LE.TEST(J)) GO TO 101
  100 CONTINUE
  101 DNOP=DNO(J)
      RETURN
      END
```

```
      SUBROUTINE RFL
C   RFL READS THE FLOOD CONTROL MATRIX.
      COMMON FLDCTL(29,45,2), STAND(213)
      READ (1,100)(((FLDCTL(I,J,K),J=1,45),I=1,29),K=1,2)
  100 FORMAT(5X,15F5.0)
      DO 200 I=1,29
      DO 200 J=1,45
      DO 200 K=1,2
  200 FLDCTL(I,J,K)=FLDCTL(I,J,K)*1000.
      RETURN
      END
```

SUBROUTINE D2M

```
      SUBROUTINED2M(ARELJ2,ARELJ1,RELJ,PI,N)
C     MODIFIED D2 FOR CALCULATION OF TRIBUTARY INFLOWS
C    D2M CALCULATES INFLOWS AT P RESULTING FROM RELEASES AT J.
C     N IS DIMENSION OF RELJ AND PI
      DIMENSION RELJ(30),PITEMP(32),PI(30)
      REAL LAG
      NP2=N+2
      DO 100 M=1,NP2
  100 PITEMP(M)=0.
      LAG=TT(ARELJ2)
      IF(LAG.GT.1.) PITEMP(1)=(LAG-1.)*ARELJ2
      LAG=TT(ARELJ1)
      IF(LAG-1.) 101,102,103
  101 PITEMP(1)=PITEMP(1)+LAG*ARELJ1
      GO TO 104
  102 PITEMP(1)=PITEMP(1)+ARELJ1
      GO TO 104
  103 PITEMP(1)=PITEMP(1)+(2.-LAG)*ARELJ1
      PITEMP(2)=(LAG-1.)*ARELJ1
  104 K=1
      NP1=N+1
  105 IF(K.EQ.NP1) GO TO 200
      LAG=TT(RELJ(K))
      IF(LAG-1.) 106,107,108
  106 PITEMP(K)=PITEMP(K)+(1.-LAG)*RELJ(K)
      PITEMP(K+1)=PITEMP(K+1)+LAG*RELJ(K)
      GO TO 109
  107 PITEMP(K+1)=PITEMP(K+1)+RELJ(K)
      GO TO 109
  108 PITEMP(K+1)=PITEMP(K+1)+(2.-LAG)*RELJ(K)
      PITEMP(K+2)=PITEMP(K+2)+(LAG-1.)*RELJ(K)
  109 K=K+1
      GO TO 105
  200 DO 201 M=1,N
  201 PI(M)=PITEMP(M)
      RETURN
      END
```

SUBROUTINE PREDIK

```
      SUBROUTINE PREDIK(NOW,JIT,PLOCT,CONSER,ACCUR,
     1   PJ,PP1)
      REAL JIT
      DIMENSION JIT(30),PLOCT(30),PJ(30),PP1(30),Z(30)
      XNOW=NOW
      RHO1=.8
      RHO2=0.0
      SD=ACCUR*SQRT(0.00010*XNOW)
      ADD=CONSER*SD
      Z(1)=0.0
  102 Z(2)=GRAND(SD,0.0)
      DO 100 J=3,30
  100 Z(J)=RHO1*Z(J-1)+RHO2*Z(J-2)+GRAND(SD,0.0)
      DO 101 K=1,30
      PJ(K)=JIT(K)*(Z(K)+1.)*(ADD+1.)
  101 PP1(K)=PLOCT(K)*(Z(K)+1.)
      RETURN
      END
```

```
      FUNCTION NCALEF(CALEFT)
C   NCALEF CONVERTS CALEFT TO THE APPROPRIATE  INTEGER
C          FOR LOOKING UP STOMIN.
      Y=51.-CALEFT/100000.
      IY=Y
      YI=IY
      NCALEF=IY
      IF((Y-YI).GT..5) NCALEF=NCALEF+1
      IF(NCALEF.GT.44)NCALEF=44
      IF(NCALEF.LT.1) NCALEF=1
      RETURN
      END
```

SUBROUTINE D5

```
      SUBROUTINE D5(STORJ,STORP,RELP,NBOXP,SP,CAPP)
C    D5 CALCULATES RELEASES FROM PALISADES BASED ON
C         DISTRIBUTION CONSIDERATIONS. IF PALISADES
C         DOESN'T HAVE AT LEAST 2/3 OF THE EMPTY STORAGE,
C         RELP=CAPP, IF IT IS NOT AT LEAST THAT HIGH ALREADY.
      DATA SJ/847000./
      IF(RELP.GE.CAPP) RETURN
      IF((SP-STORP).GE.(1.5*(SJ-STORJ))) RETURN
      IF (STORP.LT.800000.) RETURN
      IF (NBOXP.EQ.45) RETURN
      IF (NBOXP.EQ.46) RETURN
      RELP=CAPP
      NBOXP=12
      RETURN
      END
```

```
      FUNCTION DNOJ(NOW,PJONE,STORJ)
      DIMENSION UPPER(5),ITEST(4)
      COMMON FLDCTL(29,45,2), STAND(213)
      DATA ITEST/31,61,92,122/,XLOW/5./,UPPER/400.,3000.,
     1   3000.,7000.,3000./
      DNOJ=(STORJ-STAND(NOW+1))/2.+PJONE
      IF(DNOJ.LT.XLOW) GO TO 100
      DO 101 J=1,4
      IF(NOW.LE.ITEST(J)) GO TO 102
  101 CONTINUE
      MO=5
      GO TO 103
  102 MO=J
  103 IF(DNOJ.GT.UPPER(MO)) GO TO 104
      RETURN
  100 DNOJ=XLOW
      RETURN
  104 DNOJ=UPPER(MO)
      RETURN
      END
```

SUBROUTINE D6

```
      SUBROUTINE D6(XSTORP,XRELP,NOD,MAXR,MAXS,
     1   XREL,K,SP,CAPP)
C   D6 PROVIDES A YEARLY SUMMARY OF MAXIMUM RELEASE, # OF DAYS
C        WHEN RELEASE EXCEEDED CAPP, # OF SERIES WITH RELEASES
C        IN EXCESS OF CAPP, AND AMOUNT OF WATER RELEASED
C        IN EXCESS OF DNOP IN YEARS WHEN PALISADES FAILED TO
C        FILL.
      REAL MAXR,MAXS
      DIMENSION XSTORP(153),XRELP(153),NOD(20)
      DO 111 K=1,20
  111 NOD(K)=0
      K=0
      MAXR=0.
      MAXS=0.
      DO 100 NOW=1,153
  110 IF(MAXS.GE.XSTORP(NOW)) GO TO 102
      MAXS=XSTORP(NOW)
      IF (NOW.EQ.1) GO TO 100
  102 IF (XRELP(NOW).LE.CAPP) GO TO 100
  101 J=NOW
      IF(XRELP(J-1).GT.CAPP) GO TO 105
      K=K+1
  105 NOD(K)=NOD(K)+1
  106 IF(MAXR.GE.XRELP(NOW)) GO TO 100
      MAXR=XRELP(NOW)
  100 CONTINUE
      XREL=0.
      IF (MAXS.EQ.SP) RETURN
      DO 108 NOW=1,153
      IF(XRELP(NOW).LE.DNOP(NOW)) GO TO 108
  109 XREL=XREL+2.*(XRELP(NOW)-DNOP(NOW))
  108 CONTINUE
      RETURN
      END
```

SUBROUTINE D7

```
      SUBROUTINE D7(XSTORJ,XRELJ,NODJ,MAXRJ,MAXSJ,
     1   XRELJ,L,PJ)
C   D6 IS THE ACCOUNTING ROUTINE FOR JACKSON RESERVOIR.
      REAL MAXRJ,MAXSJ
      DIMENSION XSTORJ(153),XRELJ(153),NODJ(20),PJ(153)
      DO 211 L=1,20
  211 NODJ(L)=0
      L=0
      MAXRJ=0.
      MAXSJ=0.
  210 DO 200 NOW=1,153
      IF (MAXSJ.GE.XSTORJ(NOW)) GO TO 202
      MAXSJ=XSTORJ(NOW)
      IF (NOW.EQ.1) GO TO 200
  202 IF (XRELJ(NOW).LE.7000.) GO TO 200
  201 K=NOW
      IF (XRELJ(K-1).GT.7000.) GO TO 205
      L=L+1
  205 NODJ(L)=NODJ(L)+1
  206 IF(MAXRJ.GE.XRELJ(NOW)) GO TO 200
      MAXRJ=XRELJ(NOW)
  200 CONTINUE
      XRELJJ=0.
      IF(MAXSJ.EQ.847000.) RETURN
      DO 208 NOW=1,153
      IF (XRELJ(NOW).LE.DNOJ(NOW,PJ(NOW),XSTORJ(NOW)))
     1   GO TO 208
  209 XRELJJ=XRELJJ+2.*(XRELJ(NOW)-
     1   DNOJ(NOW,PJ(NOW),XSTORJ(NOW)))
  208 CONTINUE
      RETURN
      END
```

FOOTNOTES

[1] The early stage of the computer programming for the model discussed in this chapter was done by Mr. George Moore of The University of Michigan's School of Natural Resources. He also consulted on the model in later stages.

[2] Subroutine RFL is discussed below in this appendix.

[3] The apparent redundancy between TOJ and T1J is explained below.

[4] The different assumptions for days M=1,10 and M=11,30 are made to improve the model's responsiveness to forecasted encroachment early in the decision period.

[5] Subroutine RFL is a subroutine which takes the date of decision, the forecast for the remaining season runoff as of that date and a parameter k and looks up the appropriate STOMIN (the required amount of vacant storage) in a 29 x 45 x 2 matrix. The subroutine contains an interpolation scheme since the matrix does not contain an element for each of the 153 days of the flood season. The parameter k takes a value of one or two, depending on whether or not the average inflow has already exceeded 20,000 cfs and whether or not it is forecasted to do so in the next thirty days.

[6] The constraint routine starts with statement #903 of MAIN.

[7] NBOXP=47 or 48 (if RELP constrained to 20,000 cfs) for D4, while NBOXP + 52 for D3.

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