Journal of Hydrology, 68 (1984) 461—472
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

PRELIMINARY STUDY OF THE DIVERSION OF 283 $m^3 s^{-1}$ (10,000 cfs) FROM LAKE SUPERIOR TO THE MISSOURI RIVER BASIN

J.W. BULKLEY, S.J. WRIGHT and D. WRIGHT

Department of Civil Engineering, University of Michigan, Ann Arbor, MI 48109 (U.S.A.)

(Accepted for publication October 25, 1982)

ABSTRACT

Bulkley, J.W Wright, S.J. and Wright, D., 1984. Preliminary study of the diversion of 283 $m^3 s^{-1}$ (10,000 cfs) from Lake Superior to the Missouri River basin. In: G.E. Stout and G.H. Davis (Editors), Global Water: Science and Engineering — The Ven Te Chow Memorial Volume. J. Hydrol., 68: 461—472.

Trans-basin diversion is an established practice in this country. The High Plains Study authorized by the U.S. Congress in 1976 examined large-scale intra-basin diversion to replenish the depleted groundwater resources of the Ogallala aquifer. A portion of this intra-basin diversion could come from the Missouri River basin. This study presents the preliminary engineering associated with a large-scale diversion of Lake Superior water out of the Great Lakes and into the Missouri River basin in order to replace intra-basin water diverted for recharge of the Ogallala aquifer. The magnitude of the diversion is 283 $m^3 s^{-1}$ (10,000 cfs). The first cost of the conveyance structure is estimated at US \$19.6 billion. The total length is estimated at 984 km and the total static lift including friction losses, static head, and pumping plant losses is 1130 m. It is estimated that eighteen pumping plants will be required to lift the water from Lake Superior and transport it to the Missouri Basin. This study estimated an energy requirement to move this water equivalent to the annual energy production from seven 1000-MW plants. Initial costs of these power plants is estimated at \$ 7 billion.

INTRODUCTION

Trans-basin diversion of water is an established practice in a number of important regions of the U.S.A. Certain of these diversion programmes had their original plans formulated in the 19th century — for example, the diversion of Lake Michigan water at Chicago was planned in the late 1800's and put into operation in the early part of this century. The diversion of water from the Connecticut River basin to supply the City of Boston had been planned in the late 1800's and implemented over the past 50 years. A portion of New York City's water supply is diverted from the Delaware River basin. The City of Denver uses a trans-basin diversion to bring water across the Continental Divide from the Colorado River basin to meet Denver's water needs. The City of Los Angeles obtains its water from the Great Basin, the Colorado Basin, and the Sacramento Basin. While these diversions have all been for municipal purposes, trans-basin diversions have

0022-1694/83/\$03.00

been implemented for agricultural purposes as well. Water from the Colorado River basin has been diverted for agricultural purposes into the South Platte Basin and Arkansas River basin. The Central Valley of California has received trans-basin waters for agricultural purposes.

Historically, a number of plans for large-scale trans-basin diversion have been proposed, but are not currently being implemented. One idea would be to divert water from the Columbia River System to the Colorado River. One of these plans would be to transport 93 m^3 s^{-1} (3300 cfs*) from the Snake River in Idaho. A second plan would divert 586 m^3 s^{-1} (20,718 cfs) from the main stream of the Columbia River. The Texas Water Plan proposed to divert 665 m^3 s^{-1} (23,400 cfs) from the Mississippi River and east Texas. Finally, the North America Water and Power Alliance (N.A.W.P.A.) was conceived in 1964. It proposed to bring water from Alaska and Canada for delivery to the Great Basin, Lake Superior, Texas and Mexico. N.A.W.P.A. included plans to divert a flow of 4300 m^3 s^{-1} (151,933 cfs) for the purpose of power generation and agricultural development (N.W.C., 1973, pp. 317—334).

More recently, the U.S. Congress in 1976 in Section *193* of Public Law *94-587* authorized the High Plains Study to investigate large-scale transport of waters to replenish the depleted groundwater resources of the Ogallala aquifer. More than 60,000 km^2 ($15 \cdot 10^6$ acres) of irrigated farm land in a six-State High Plains region, extending from west Texas to Nebraska, depend on water from the Ogallala aquifer (H.P.A., 1982). If major transport of water were to take place to enable the continuation of the irrigation agriculture economy of the High Plains region, a portion of the waters transported would come from the Missouri River. The Great Lakes are recognized as a potential source of fresh water which could, in theory, be utilized in a productive way through trans-basin diversion to arid and semi-arid regions of the High Plains.

Most recently, the identification of major large-scale trans-basin diversion of waters in this country as a solution to water-short regions has been made in the context of the greenhouse effect resulting from increased carbon dioxide in the earth's atmosphere. Certain analyses suggest that the increase in temperature resulting from the greenhouse effect may alter the water balance in certain critical regions, i.e. increase the evaporation losses, for example, in the Colorado River basin and accordingly, it is time now to think through the elements of large-scale water diversion (Revelle, 1982).

It should be noted that diversions into and out of the Great Lakes already are taking place. Two diversions into Lake Superior provide 159 m^3 s^{-1} (5600 cfs) of flow primarily for hydropower generation. The diversion at Chicago takes 91 m^3 s^{-1} (3200 cfs) from Lake Michigan and diverts it into

---

* 1 cfs = 1 $ft.^3$ s^{-1} = 0.028316 m^3 s^{-1}.

the Illinois River via the Sanitary and Ship Canal. This flow thus joins the Mississippi River. The Welland Canal diverts 266 m^3 s^{-1} (9400 cfs) from Lake Erie to Lake Ontario. The combined effect of these diversions is to decrease the level of Lake Michigan—Lake Huron by 0.64 cm (0.25 in) and to decrease the level of Lake Erie by 10.16 cm (4.0 in). These changes are small in comparison to the effect of natural factors (precipitation, evaporation, and runoff) on lake-level fluctuations — Lake Michigan—Lake Huron 174 cm (5.7 ft.) and Lake Erie 210 cm (6.9 ft.) (I.J.C., 1981).

Given the interest in large-scale diversion and given the presence of the Great Lakes, the largest body of surface fresh water in the world, it is appropriate to undertake a preliminary study in order to identify the magnitude of effort — both in terms of initial capital and in terms of energy requirements in order to provide Great Lakes water for use in the High Plains Region.

OBJECTIVES

The primary objective of this study was to develop preliminary quantitative estimates of the first costs and the annual operation and maintenance costs required for a diversion of 283 m^3 s^{-1} (10,000 cfs) from Lake Superior to the Missouri River basin. It should be noted that the water transfer element of the High Plains—Ogallala Aquifer Study (Pearson, 1981) projects diversions from two locations on the Missouri River to locations in western Nebraska, western Kansas, and eastern Colorado. The maximum combined diversion from the Missouri River at Ft. Randall, South Dakota, and St. Joseph, Missouri, would be $9.84 \cdot 10^9$ m^3 $yr.^{-1}$. A continuous diversion of 283 m^3 s^{-1} from Lake Superior would equal $8.93 \cdot 10^9$ m^3 $yr.^{-1}$. Accordingly, the 283-m^3 s^{-1} flow represents a replacement of Missouri River water which would be diverted for agricultural purposes.

Table I shows the elements contained within this study, which are

TABLE I

Study elements

(1) Route corridor
(2) Representative components of conveyance system
(3) Estimate number of pumping plants
(4) Estimate gross energy requirements
(5) Estimate first costs to build the system
  (a) Land acquisition
  (b) Cost of canals and conduits
  (c) Cost of pumping plants
  (d) Necessary equipment
  (e) Power plants

necessary to provide the quantitative estimates of the first costs and annual operating and maintenance costs for the Lake Superior diversion. It should be emphasized that the estimates provided by this study are of a preliminary nature and are intended to provide a general framework upon which general water-management decisions can be based. Study time constraints and objectives precluded a detailed assessment of the particulars, for example, of a route selection. The information contained herein is intended to address general feasibility questions associated with the potential diversion.

A secondary objective arose later near the end of the study. This involved an alternative water diversion scheme; namely a coal slurry pipeline from Lake Superior to Wyoming. This case was limited to water and energy requirements for the return water line. This was intended primarily to serve for purposes of comparison with the magnitude of the previously described diversion. Quantitative estimates were made for the return water line only, due to time constraints involved with the original study.

DESIGN PROCEDURE

In order to obtain numerical values for the study objectives, a preliminary design of the conveyance system must be prepared. In principle, this involves an optimization of conduit and channel sizes along possible routes in order to arrive at a least cost alternative. This, of course, requires a very detailed analysis, which is unsuited for the types of preliminary estimates desired. Consequently, information from other existing and proposed water projects was synthesized to obtain realistic designs that could be included in the energy and cost estimates. As a first step, information was collected for the existing and currently operational California State Water Project (Golze, 1965; Dewey, 1966; D.W.R., 1968, 1974; Frederiksen, 1969; Jansen, 1972). It came to the attention of the study team that the U.S. Army Corps of Engineers in conjunction with the U.S. Department of Commerce and the High Plains Study Council had recently completed a study of major water transfers to resupply the Ogallala aquifer from the Missouri River basin and the Arkansas—White—Red River basin. The design manual (U.S.A.C.E., 1980) (hereafter referred to as the cost and design manual), was obtained and utilized for the present study. By using this information, the data are reasonably current, and allows for a certain degree of consistency between the U.S. Army Corps of Engineers projects to transfer water to the Ogallala aquifer and this study project. Much useful information was obtained from the cost and design manual in that several empirical relations which are based upon the design experience of the Corps could be utilized to arrive at approximate sizes for the various conveyance elements. These could then be readily utilized for the remainder of the analysis.

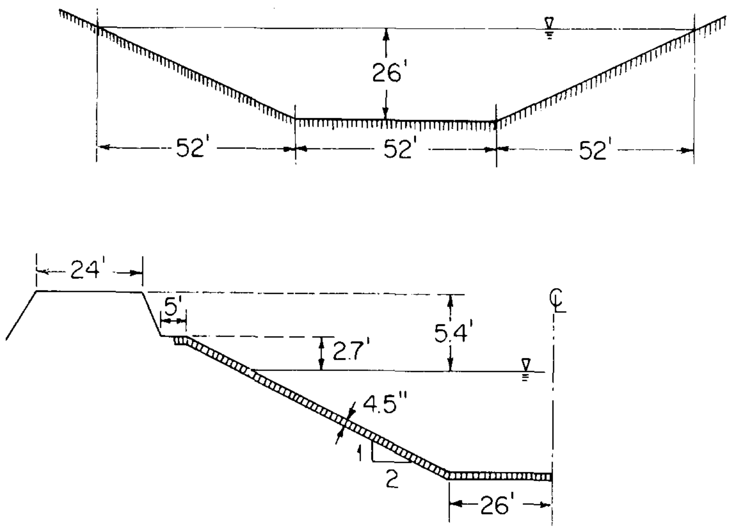

Fig. 1. Cross-section of concrete lined canal ($1' = 30.48$ cm; $1'' = 2.54$ cm).

Conveyance structure elements

As mentioned above, the cost and design manual provided the guidance necessary to select conveyance elements sufficient to pass the design flow of 283 m^3 s^{-1}. A typical open-channel section is recommended in the cost and design manual for the specified diversion is indicated in Fig. 1. Using this cross-section, a Manning's coefficient of roughness, n, of 0.016, and the design flow results in a computed slope of 0.0000391 for the open-channel portions of the system. The closed-conduit cross-sections are dictated by assuming a friction head loss of 1 m per 1000 m and a maximum conduit diameter of ~ 6 m. These two criteria result in several parallel conduits being required wherever force main pumping is required. The cost and design manual gives an empirical formula for determination of conduit diameter (one can derive a similar relation from the Hazen—Williams formula with a C-value of 100 and the specified friction loss):

$$D = (0.981\,Q)^{0.375}$$

where Q is to be given in ft.^{3} s^{-1} and D in ft. Use of this formula results in a requirement of four flow conduits, each with a required diameter of 5.7 m. This along with the open-channel cross-section, constituted the system design information upon which subsequent computations are based.

Route corridor selection

The first step in the determination of possible routes was to choose the origin and destination of the conveyance system. Since the present study considered only the possibility of a Lake Superior diversion, the extreme western end of Lake Superior was the origin. The destination became the Missouri River at Yankton, South Dakota, which was determined to be the closest location where the existing channel could take the entire diversion flow.

Once the origin and destination were selected, the original routes (North and South Routes in Fig. 2) were indentified. These two routes minimized the distance between the diversion origin and destination. In addition, the

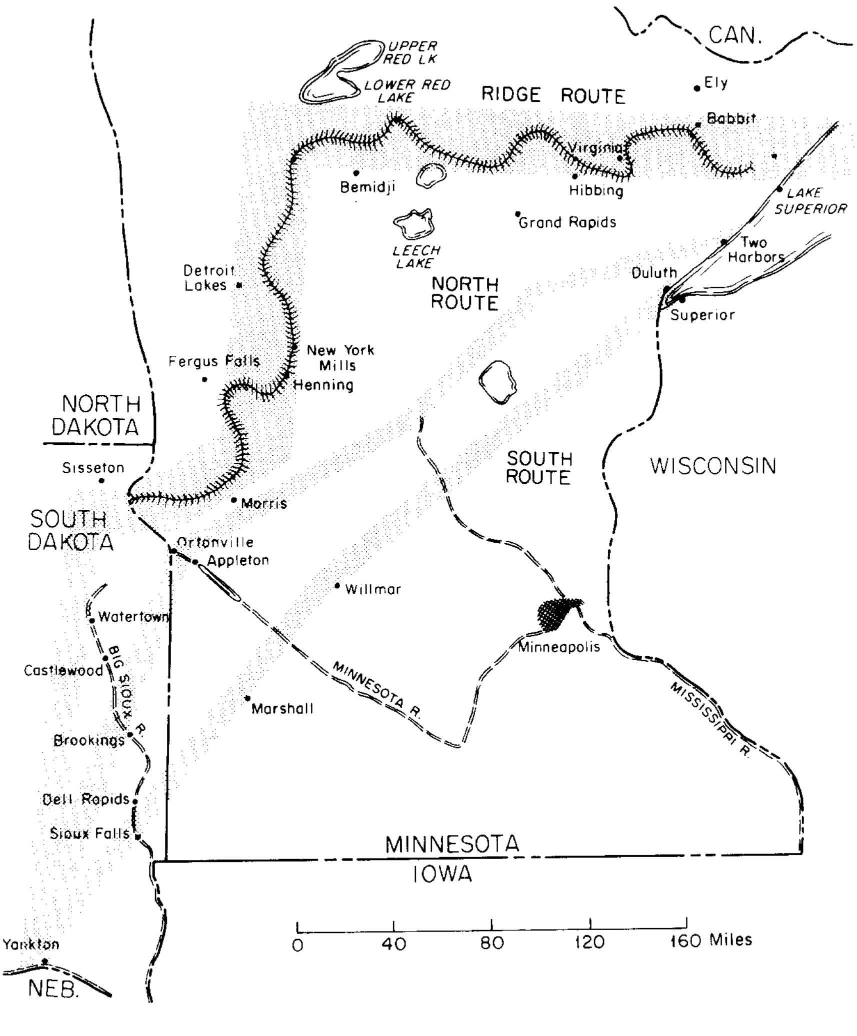

Fig. 2. Map of proposed diversion (1 mile = 1.609 km).

North Route follows the elevation contours as determined from U.S. Geological Survey's 1:250,000 maps with 15.2-m (50 ft.) contours. The South Route followed an existing railway line on the assumption that this route would be of minimum elevation changes. After preliminary calculations, both of these routes were eliminated from further consideration because of excessive pressurized-conduit pumping requirements which would be necessary to lift the water out of the Mississippi River basin and into the Missouri River basin. Consequently, the Ridge line route, which is also shown in Fig. 2, was identified as a more feasible alternative. The Ridge Route takes maximum advantage of the natural topography in order to allow the water to flow by gravity wherever possible when crossing the Mississippi River basin. As such, this route is the hydrologic divide between the Mississippi River basin and drainage basins to the north (Hudson Bay) and west (Missouri River). Following comparison of all three routes, the Ridge Route was selected as the most feasible and it serves as the basis of design for estimating cost and energy requirements.

Determination of size and number of pumping plants

Following route selection, the requirement for pumping plants and conveyance structures was dictated by the topography of the route corridor. The cost and design manual provided the guidelines for conduit and open-channel selection as previously described. Using this information, a reasonable estimate of the number of pumping plants required was determined from the U.S.G.S. topographic maps. From an economic point of view, it is important to minimize the pressurized-conduit flow and rely upon open-channel flow wherever possible. An initial set of pumping plants is required to lift the water from lake level up to the ridge line. From this point on, additional pumping plants are required wherever the ground slope became less than the slope dictated by the chosen canal cross-section, or where the distance from the ridge line down to the canal became excessive. Pumping stations would then be required to lift the water to the ridge line through force main conduits where flow by gravity in the open channel would follow. Although this was a somewhat arbitrary procedure in this preliminary estimate, elevation changes constitute most of the pumping head requirements and little reduction in total energy required could be attained by optimization of the pumping station locations. On the other hand, since the system construction cost will later be shown to be strongly dependent on the length of closed conduits, the system costs could be reduced by a more careful design analysis.

The total head required at each pumping plant site was determined by adding the static lift to the head losses at the pump stations (estimates obtained from the cost and design manual) and the friction in the pressurized conduits. Table II details an example of this calculation for the pump stations required for the initial lift of water from lake level to the ridge

TABLE II

Determination of pumping plants heads (example)

Initial lift from Silver Bay, Minnesota (Lake Superior, elev. = 198 m) to Whyte, Minnesota (elev. = 579 m)

Total length = 25.7 km
Total static lift = 381 m

Friction loss of 1 m per 1000 m of discharge conduit (four lines); plant loss of 4.6 m

Use six pumping plants:

For each plant		
static head	=	63.5 m
friction head	=	4.3 m (25,700 m (1 m per 1000 m) per six plants)
plant head	=	4.6 m
total head		72.4 m
Six plants → capacity	=	283 m^3 s^{-1}
head	=	72.4 m

line. A maximum lift of 76 m per station was imposed on these calculations to remain within the range of conditions for which system costs were provided in the cost and design manual. The analysis for pumping plant locations was performed along the entire Ridge Route, resulting in an estimated requirement of eighteen pumping plants with an average lift per plant of ~ 60 m. [These numbers vary from those presented by Bulkley et al. (1982) due to revisions in the final calculations.]

Gross annual energy and power plant requirements

The next step is to estimate the energy required to pump the design flow along the proposed route. The pumping head was summed for each of the required stations to give a total head requirement of ~ 1130 m. This was used along with the design flow of 283 m^3 s^{-1} and an assumed plant efficiency of 82% to give an energy requirement of $3.83 \cdot 10^6$ kW. Finally, this was converted to $3.35 \cdot 10^{10}$ kW-hr. $yr.^{-1}$ to readily facilitate the computation of the number of required power plants.

Once the gross annual energy requirements have been estimated, the number of power plants to supply this power can be determined. For this study, it is assumed that a 1000-MW power plant is representative of the size of power plant that would be built. Furthermore, it is assumed that each power plant would operate 60% of the time to allow for operational maintenance and other downtime activities. Table III shows the calculation which resulted in an estimate of seven 1000-MW power plants being required to divert 283 m^3 s^{-1} from Lake Superior to the Missouri Basin.

TABLE III

Number of 1000-MW power plants required

Number of 1000-MW plants required assuming a load factor of 60% (downtime adjustment)
Power per plant → 1000 MW = 1 GW (24 hr. a day) (365 days a year)
(0.6) (24) (365) = 5256 GW-hr. $yr.^{-1}$
To produce 33,500 GW-hr. $yr.^{-1}$ need 33,500/5256 = 6.37
Need → 6.37 or seven power plants
Cost = $1 billion per plant
First cost = $ 7 billion

TABLE IV

Cost estimate

Route — Ridge line route:

Length = 984 km
Total static lift = 1130 m
Number of pumping plants = 18
Number of power plants at 1000 MW per plant = 7

Cost:

Pumping plants	= $ 3,030,000,000	
Land	= $ 134,070,000	(at $1900/acre)
Relocations	= $ 90,250,000	
Conduits	= $13,555,872,000	
Aqueduct	= $ 2,706,000,000	(W/50% rock)
Siphons	= $ 85,000,000	(assuming length = 750 m)
Automation and communication	= $ 32,500,000	
First cost	= $ 19.6 billion*1	
Cost of power plants	= $ 7 billion*2	

Annual costs:

Operation and maintenance of pump plants (not including energy costs)	= $4,585,000 $yr.^{-1}$	
Pumping plant replacement	= $2,740,000 $yr.^{-1}$	
Operation and maintenance of canals	= $5,688,750 $yr.^{-1}$	(normal maintenance)
	or	
	$7,195,500 $yr.^{-1}$	(high maintenance)
Automation and communication	$ 129,150 $yr.^{-1}$	
Annual cost	$15,600,000*1	

1 acre = 4046.9 m^2.
*1 January 1979 prices.
*2 1982 prices.

Cost estimates

Cost estimates were obtained from two sources. The cost and design manual provided first cost estimates (January 1979 prices) for pumping plants, land, relocations, conduits, aqueducts, siphons, automation and communication equipment, Personal contact with planning officials at Detroit Edison Company and Consumer's Power Co. provided estimated costs for new conventional power plants. These estimates ranged from U.S.$ 1000 to U.S.$ 1500 per kW of installed capacity. The figure of $ 1000 per kW of installed capacity was chosen, although it may be on the low side. Table IV summarizes the cost estimate for this project. The estimated first cost is $ 19.6 billion for the conveyance system including pumping plants, land, canals, etc., as described. Since a significant fraction of this cost is associated with closed conduits, the total could probably be reduced somewhat in a more careful design. The estimated first cost of the seven power plants is $ 7 billion. The annual cost (exclusive of energy costs for pumping) of operating the diversion system is estimated at $ 15.6 million as shown in Table IV. It is important to note that certain costs have not been considered, including:

(1) Annual cost of operation and maintenance of seven 1000-MW power plants.

(2) Preparation of Environmental Impact Statement.

(3) Fish and wildlife mitigation.

(4) Relocation of utilities: pipeline; power lines; roads; water lines; telephone lines.

COAL SLURRY RETURN LINE

To provide a comparison for a potential alternative water diversion project, a preliminary calculation was made of the water and energy requirements for a return water line from Lake Superior to Gillette, Wyoming. Full economic evaluations were not made for this diversion. However, using several assumed conditions — namely, a distance of 1600 km; a pipe diameter of 1.22 m (48 in.) and a flow rate of 1.42 $m^3\ s^{-1}$ (50 cfs); the calculations outlined in Table V imply that the total energy requirements for the return water line only would be $\sim$ 500 GW-hr. $yr.^{-1}$. This is $\sim$ 9% of the reliable annual production of one 1000-MW power plant. The total water requirement to fill both the return water line, the coal slurry pipeline and provide one year's supply to operate the water at each end of the pipeline is $\sim 1.19 \cdot 10^8\ m^3$. If it is assumed that this water can be recycled with 10% losses, the annual make-up water would be $1.2 \cdot 10^7\ m^3$. From this very rough estimate of the energy and water requirements for a single coal slurry pipeline, it appears that the energy and water requirements are negligible in comparison with the major diversion that is the main focus of this paper.

TABLE V

Coal slurry pipeline return line

Flow rate 1.42 m^3 s^{-1}	
Length 1600 km	
Estimated friction loss	2012 m
Elevation change from Lake Superior to Gillette, Wyoming	1340 m
Total lift	3352 m
Energy requirement (based upon pumping plant efficiency = 82%) 500 GW-hr. $yr.^{-1}$	

SUMMARY

Calculations have been performed for the estimated requirements to divert 283 m^3 s^{-1} of Lake Superior water to the Missouri River basin. They show a diversion whose total pumping lift is 1130 m. Its length is 984 km and would require approximately eighteen pumping plants to deliver the required flow. The estimated first cost of the project is \$19.6 billion plus \$7 billion for the power plants to provide the required energy. Annual operating and maintenance costs for the diversion system alone (excluding power plants) is estimated at over \$15 million. Obviously, energy costs to drive the pumping stations would increase this amount significantly.

Preliminary discussions of several water diversion projects of this type have been discussed in various circumstances, and it is difficult to visualize in the very early phases of project conceptualization whether or not a particular project is economically feasible. Estimates of the type described in this paper are required in the very early stages of planning for management of water resource systems. A quantitative estimate is then available from which decisions can be made on whether more detailed studies are justified. For example, it can be easily demonstrated that the costs of delivering Lake Superior water to the Missouri River are around an order of magnitude higher than are presently paid for most irrigation water for agricultural purposes. On this basis, further decisions regarding the potential diversion and uses of the diverted water can be made.

ACKNOWLEDGEMENTS

The support and assistance of the Southwest District, Corps of Engineers, U.S. Army, is providing the Cost and Design Manual for the Ogallala High Plains Study is gratefully acknowledged.

The assistance and encouragement of the Great Lakes Commission in undertaking this preliminary study is also gratefully acknowledged.

REFERENCES

Bulkley, J.W., Wright, S.J. and Wright, D., 1982. Preliminary of the diversion of 10,000 cfs from Lake Superior to the Missouri River Basin. Pap. presented at Great Lakes Water Conference, Mackinac Island, Mich.

Dewey, H.G., 1966. California's State Water Project-On Schedule. Civ. Eng., 36(1): 48—53.

D.W.R. (Department of Water Resources), 1968. The California State Water Project in 1968. State Calif., Dep. Water Resour., Sacramento Calif., Bull No. 132-68.

D.W.R. (Department of Water Resources), 1974. California State Water Project: Vol. 5, Control Facilities. State Calif., Dep. Water Resour., Sacramento, Calif., Bull. No. 200.

Fredericksen, H.D., 1969. Design of the California aqueduct. J. Irrig. Drain. Div., Proc. Am. Soc. Civ. Eng., 95 (IR2): 307—328.

Golze, A.R., 1965. Power plans and demands of the California Water Project. Civ. Eng., 35(2): 35—39.

H.P.A. (High Plains Associates), 1982. Six-State High Plains Ogallala Aquifer Regional Resources Study. Stud. for High Plains Associates — Camp Dresser & McKee, Inc., Black & Veatch — by Arthur D. Little, Inc., Cambridge, Mass., 231 pp. and appendices.

I.J.C. (International Joint Commission), 1981. Diversions—international great lakes diversions and consumptive uses study. Int. Joint Comm., Great Lakes Reg. Off., Windsor, Ont., No. 5.

Jansen, R.B. 1972. Edmonston pumping plant: Nations Mightiest. Civ. Eng., 42(10): 67—71.

N.W.C. (National Water Commission), 1973. Water policies for the future. Fin. Rep. to the President and to the Congress of the United States, Natl. Water Comm., U.S. Government Printing Office, Washington, D.C., 579 pp.

Pearson, W.R., 1981. High Plains—Ogallala aquifer study: Water transfer element. Pap. presented at 43rd Midwest Fish and Wildlife Conference, Witchita, Kans.

Revelle, R., 1982. Carbon dioxide and world climate. Sci. Am., No. 2, pp. 35—43.

U.S.A.C.E. (U.S. Army Corps of Engineers), 1980. Cost and Design Manual. Prepared for the water transfer element of the High Plains, Ogallala Aquifer Study. U.S. Army Corps Eng., Southw. Div., App. E, Aug. 1980 (*note*: the Cost and Design Manual is also included in the H.P.A., 1982, reference).