FINAL PROJECT REPORT
HYDRAULIC MODEL STUDY
Connors Creek Sanitary Pumping Station

Report UMCEE 97-21

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EXECUTIVE SUMMARY

The City of Detroit is planning a rehabilitation of their existing Connors Creek Sanitary Pumping Station. The pump impellers in this station have suffered damage in the past, apparently due to cavitation. It has also been presumed that there may have been problems with vortices at the pump intakes due to nonuniformities in the approach flow to the pumps. A 1:7.5 scale model of the wet well, including the four pump intakes, and the inlets into the wet wells through the east and west drop shafts was constructed to study the hydraulics of the flow into and within the wet well as well as the flow at the individual pump intakes. An additional issue that was examined in the hydraulic modeling related to the proposed location of a level sensor to control pump operation. The objective was to determine whether the level sensor provides an appropriate measure of the hydraulic grade line within the wet well and to suggest alternate locations if the proposed location was not acceptable.

Flow enters into the wet well from one of two sources, the East Jefferson Relief Sewer or the West Jefferson Relief Sewer, each of which are fourteen feet in diameter. The primary entrance into the wet well from each relief sewer is through separate five foot diameter conduits, each of which discharges into a drop shaft at opposite ends of the wet wells. There is a third five foot diameter connection from the adjacent Storm Pump Station which receives any flow that does not enter the wet well. Current operating procedures do not utilize this third wet well entrance in which case the flow from the two relief sewers is not hydraulically connected during dry weather flow conditions. Therefore the relative contribution of wet well inflow from each relief sewer can vary although it appears that the larger contribution is normally derived from the East Jefferson Relief Sewer. In order to divert dry weather flows into the wet well, small check dams installed within each relief sewer are intended to force all flow

into the wet well. This fixes a maximum hydraulic grade line allowed in the wet well so as not to overtop the check dams during dry weather flows. During wet weather conditions, flow is allowed to overtop the check dams and continue to the Storm Pump Station at which point, a hydraulic connection between the two relief sewers can be established through the Storm Pump Station wet well.

Phase 1 Testing: The initial specifications for testing of dry weather flow conditions provided only generalized guidelines on wet well hydraulic grade lines and pumping conditions. No operational sequence was specified for the pumps and the wet well hydraulic grade lines were constrained only by the need to avoid pump cavitation at low wet well levels and to avoid overtopping the check dams in the relief sewer during dry weather flow conditions. During initial testing of the model, it was discovered that significant head losses were associated with the flow down through the drop shafts and into the wet well. Under these circumstances, it would be hydraulically impossible to operate the pumping station as planned. At intermediate flow rates that may be associated with dry weather flow conditions, it is not possible to maintain hydraulic grade line elevations low enough to prevent overtopping of the check dams in the relief sewers and provide sufficient system storage to allow reasonable pump cycle intervals.

Phase 2 Testing: Further consideration of this problem led to a decision to raise the level of the check dams in the relief sewers and attempt to utilize the storage present within the relief sewers to provide the desired pump cycle intervals. This consideration led to the development of a proposed sequence for pump operation and for on-off levels for each pump in the sequencing. This proposed set of conditions was tested in the physical model and found to be successful in the condition where the wet well inflow is uniformly distributed between the two relief sewers. However, in the case of a 75 percent contribution from the East Jefferson Relief Sewer, which may be more realistic of actual flow conditions, the system is unable to perform hydraulically at the proposed control levels for the pumps. The hydraulic grade line could be met only by raising the elevation of the check dam in the East Jefferson Relief Sewer to such an extent that the ability to pass storm water flows to the Storm Pump Station would be compromised.

Phase 3 Testing: As a result of the above findings, it appears that the only feasible method of operating the wet well is to pass some portion of dry weather flows to the Storm Pump Station and to utilize the third entrance into the Sanitary Pump Station. The physical model was not constructed with this prospect in mind and hydraulic testing for these conditions was not in the original scope of the model study. However, the physical model could be modified to accommodate flows from this third entrance and this additional hydraulic testing could be included in future studies. Although the third inlet could not be modeled, the existing model was used to more accurately define the hydraulics of the other two inlets. These hydraulic results are to be used in calculations to define the final pump operating scheme.

With regards to the major objective of the physical model study, a detailed investigation was performed to examine conditions at the pump intakes and a number of potential problems were discovered. In particular, a significant problem associated with air entrainment in the drop shafts was noted. At low wet well hydraulic grade line elevations, below the invert of the five foot diameter conduits from the relief sewers, the air entrainment occurs due to the water plunging onto the water surface within the drop shaft. However, a hydraulic grade line elevation this low will not generally be acceptable due to the lack of system storage for pump cycling. Water levels within the drop shafts must generally remain above the inverts of the inflow conduits and this type of air entrainment should therefore not be a problem, although it has probably contributed to problems with the pump station performance in the past. Air entrainment was observed even when the five foot conduits were completely submerged at their exit into the drop shafts. This air entrainment was generated by a pair of vortices that formed in each drop shaft due to the velocity in the inflow conduit. The design of the wet well forces this air to pass through the pumps leading to a possibility for a deterioration of pump performance and contributing to bearing wear. The amount of air entrained decreases as the wet well hydraulic grade line increases but never vanishes for the higher flow rates.

Subsurface vortices were observed in the wet well underneath the middle two pumps, Pump 10 and 11. The source of these vortices appears to be the high velocity inflow from each drop shaft in combination with the small wet well volume. These organized vortices are not observed under Pumps 9 and 12, apparently due to the inflows from the drop shafts sweeping out any organized motion in these areas. Due to the small wet well volume and associated high velocities, intermittent vortices were observed throughout much of the wet well, but these are not considered to be significant compared to the air entrainment and organized vortices under Pumps 10 and 11. These organized vortices can probably be largely eliminated by installing cones with vanes on the floor directly under the pump intakes. The use of the third inlet to conduct flow into the wet well will have the effect of reduction the inflow velocities in the other two inlets; this will result in a reduction in both air entrainment in the drop shafts and should reduce the strength of the submerged vortices as well

Testing to measure swirl angles in the pump intakes did not indicate a significant problem. Swirl angles less than 1.6 degrees were measured for all flow conditions tested. This was attributed to the presence of the swirl baffles installed on each pump intake. The swirl baffle was removed from pump 12 and the swirl angles in that pump ranged from 5.7 to 17.2 degrees for the same flow conditions. Visually, vortices in the flow entering the pump intakes were observable by the motion of the air entrained in the flow, but these were confined to one of the four quadrants constrained by the swirl baffle and apparently any organized pre-rotation of the flow was not allowed over the entire flow cross-section. The small swirl angles therefore may not be representative of excellent pump intake conditions, but the swirl baffles do improve the pre-rotation to an acceptable level.

The initial location of the wet well hydraulic grade line level sensor was located in a region where the organized floor vortices observed under Pumps 10 and 11 would have an impact on the sensor readings and in particular, large fluctuations in water levels were recorded in the model. Two alternate locations were suggested to replace this initial location and both seemed to be equally effective and acceptable for purposes of monitoring hydraulic grade line elevations within the wet well.

INTRODUCTION

The Connors Creek raw sewage pumping station has been in operation for a number of years. The existing pumps in this station have suffered damage in the past, apparently due to cavitation. Inspections of the facility have also indicated rough running conditions and loss of pump prime due to air ingestion. These problems have been due in large part to a lack of automatic control on pump operation. The pumps are scheduled to be replaced and alterations are planned for the operation of the pumping station, including the installation of hydraulic grade line sensors from which the operation of the pumps can be controlled. The purpose of the physical model study was to ensure that previous problems with station operation would be avoided. Particular emphasis was placed on the study of inlet conditions for the pumps.

Vortices and inlet swirl can have a detrimental effect on the operation of pumps, lowering efficiency and increasing wear. Severe vortexing can lead to pump vibration, cavitation and impeller pitting. The proposed testing sequence included the following components:

- Examination of surface vortex patterns (within the drop shafts)
- Examination of subsurface vortex patterns in the wet well
- Measurement of swirl in flow into individual pump suction lines
- Measurement of hydraulic grade line differences between the inlet conduits and the wet well.
- Investigation of the placement location for a proposed wet well hydraulic grade line level sensor to be used to automatically control pump operation.

GENERAL SYSTEM DETAIL

The wet well is rectangular in shape with plan dimensions of approximately 21 ft by 61.5 ft. The four pumps lift raw sewage through suction pipes mounted in the ceiling of the 7.5 ft high chamber. These pumps are arranged in a linear fashion along the 61.5 ft length of the wet well. Flow normally enters the wet well from 5 ft diameter inlet pipes at either end of the wet well which in turn conduct flow from the 14 foot diameter Jefferson Avenue relief sewer. Flows through either inlet flow down a drop shaft from the relief sewer before entering the pump station (the conduits connecting the drop shafts and the wet well are also five foot diameter. In order to avoid confusion in this report, the pipes connecting the 14 ft interceptors and the drop shafts will be referred to as *connecting* pipes while those between the drop shafts and the wet well will be called *inlet* pipes). The east drop shaft conducts flow from the East Jefferson Relief Sewer while the west drop shaft carries flow from the West Jefferson Relief Sewer. All dry weather flows in the relief sewers are intended to pass through the pumping station while storm flows from both are permitted to enter the adjacent Storm Pump Station A third inlet connects from the Storm Pump Station to the Sanitary Pump Station. Since this inlet was reported to be closed under normal operating conditions, it was not included in the hydraulic model. Figure 1 provides a plan view of the general layout of the two pumping stations and associated conveyance systems.

The pump capacities for the four pumps were reported to be approximately 49,000 gpm (each of two pumps), 33,500 gpm, and 17,500 gpm. The actual capacity of each pump depends on the hydraulic grade line elevation in the wet well and a range of elevations are possible during normal plant operation.

The physical model included all relevant detail of the wet well and pump suction bells up to the pump impellers, the two inlet pipes, and the connections to the relief sewer including the drop shafts. Details of the tests conducted in the model are described below. Testing was performed controlling the following variables:

- Different combinations of pumps in simultaneous operation
- Different splits of inflow into the wet well from the various inlets
- Different wet well hydraulic grade line elevations

MODEL DESCRIPTION

Modeling Criteria

Although the wet well itself was in a submerged condition, the drop shafts and inlets had free surface flow conditions. Physical models to examine flow patterns in free surface flow are performed using Froude number similarity, which fixes the relations between model and prototype conditions once the physical model scale has been selected. Dynamic similarity requires keeping all Froude numbers, defined by $V/(gL)^{1/2}$, equal in the model and prototype. Here, V refers to any representative fluid velocity, g the acceleration due to gravity, and L is any system length. The relations between prototype and model parameters are related to the scale ratio $\mathbf{L_r}$ which is the geometric ratio between any length in the model and the corresponding one in the prototype ($\mathbf{L_r} = \text{Length}_{\text{model}} / \text{Length}_{\text{prototype}}$). For a Froude scaled model, assuming the same fluid in model and prototype, the following relations must hold for the respective ratio between the model and prototype vaariable:

PARAMETER		**RATIO**
Length	L_r	L_r
Velocity	V_r	$L_r^{1/2}$
Discharge	Q_r	$L_r^{5/2}$
Time	T_r	$L_r^{1/2}$

The critical factors with respect to model testing facilities are the model size and discharge. If the scale ratio is too small, both surface tension and viscous effects may become too great in the model. This consideration generally fixes the minimum model size required to avoid distortion of the model flow due to the effects of viscosity. Padmanabhan and Hecker (1982) suggest from the results of model studies on pump intakes that a minimum Reynolds number of greater than 70,000 be maintained in the physical model to correctly reproduce the air intake and vortex strength. The Reynolds number is to be defined in terms of the flow in the suction pipe as $Re = UD/\nu$, with U the average flow velocity in the suction pipe, D intake diameter, and ν the kinematic viscosity. This constraint becomes instrumental in the selection of the minimum physical model size. With the smallest pump and a modeled discharge of 17,500 gpm and the selected model scale ratio of 1:7.5, the minimum model Reynolds number is about 92,000, thereby meeting this constraint.

Model Construction

The model study was conducted in the Civil Engineering Hydraulics Laboratory located in the G.G. Brown Building at the North Campus of The University of Michigan. The physical model was constructed at a scale ratio of 1:7.5. The physical model was constructed of plywood, Plexiglas and PVC piping. The drop shafts and inlet pipes to the wet wells as well as the cover to the wet well were constructed of Plexiglas in order to visualize the flow. This allowed the model to be visually inspected for the presence of subsurface vortices, air entrainment and other undesirable flow conditions. The pump suction bells were also constructed of Plexiglas for the same purpose as well as to see the rotation of the swirl meters used to determine the pre-rotation in the pump approach flow. The pump suction bells were designed with guide vanes (swirl baffles) to help eliminate any pre-rotation in the flow; these were constructed of 1/8 inch aluminum according to the detail provided in supplied drawings. The remainder of the piping in the system was constructed of PVC pipe. The five foot diameter connecting pipes from the main interceptors were reproduced in the model although the interceptors were not. The extent of the physical model is indicated on Figure 1 and the completed model can be seen in the photographs in Figure 2.

All four pump suction lines were joined into a common manifold (see Figure 2c) connected to a recirculating pump which removed the flow from the wet well and back around to the inlet conduits. The flow was regulated by adjusting butterfly valves on each of the pump suction lines and gate valves on the supply lines to obtain the desired total flow and control the flow distribution among individual lines. The flows were metered in each individual pump suction line by means of calibrated bend meters (Figure 2c). In addition, the flow on the discharge side of the recirculating pump was metered in the pipe connecting to the east inlet by means of an installed orifice meter.

Instrumentation

Flow rates were measured using a combination of calibrated bend meters on each of the four pump suction lines plus an orifice meter installed on the piping connecting to the east inlet. Pressure differences were measured with water-air differential manometers. By comparing the difference between the sum of the flows through the bend meters and the east inlet flow, the discharge to the west inlet could be computed. Preliminary tests were conducted to provide a continuity check. This involved routing all flow through the east inlet which could be metered by the main orifice meter. Flow was established through one, two, or three of the bend meters and independently metered through each of those. The sum of the flow through all the bend meters should be the same as that through the orifice meter. For the six different flow conditions established in this continuity check, continuity was satisfied to within four percent with the exception of one flow condition and half the measurements were within one percent.

The swirl angles were measured with a rotating cruciform (swirl meter), the function of which was to rotate with the component of tangential flow in the pump suction line. The swirl meter was mounted so that it rotates freely on a hub installed along the pipe centerline and consists of four vanes, each with dimensions equal to 0.8 of the relevant intake diameter. One vane was painted to orient the cruciform, especially in a rapidly rotating flow (the vanes can be seen in Figure 2a). Rotation counts were recorded to the closest rotation over 3 minute counting intervals. Counts were recorded every 30 seconds so that variations in the speed of rotation could be observed as well as any potential changes in rotational direction. Clockwise rotation (looking down into the model) was considered to be positive, and counter-clockwise rotation was considered to be negative. The swirl angle is defined by counting the rotations per unit time and computing the angle as

$$\theta = \tan^{-1}\left(\frac{\pi N D}{U}\right)$$

with θ the swirl angle, N the revolutions per unit time of the swirl meter, D the pump intake diameter and U the average axial flow velocity (the line discharge divided by the intake cross sectional area). Swirl angles of less than 5 degrees are generally considered as acceptable for axial flow pumps.

Hydraulic grade line elevations were measured at a number of locations. Within the wet well, these were measured by installation of a stand tube at locations proposed for level sensors. For measurements where the hydraulic grade line needed to be determined with accuracy, the stand tubes were connected to a larger diameter Plexiglas cylinder (stilling well) connected with small diameter tubing to damp local turbulent pressure fluctuations. Within the drop shafts, hydraulic grade lines were determined approximately visually and more precisely with stand tubes connected to pressure taps at the bottom of the drop shafts. Finally, the hydraulic grade line at the upstream end of the connecting pipes (just downstream from the inlets from the interceptors) was measured with a pressure tap/large diameter stilling well/small diameter connecting tubing configuration similar to that employed in the wet well. Point gages were installed in the stilling wells in order to measure hydraulic grade line elevations to within 0.001 ft. The reference levels for the point gages were determined by filling the model to the invert elevations of the connecting pipes (59.9 ft prototype elevation) and using the point gage readings at this condition as a reference for all other readings.

Testing Conditions

This study was conducted in distinct phases. In the first phase of the project, the specific operating rules for the pumping station were not developed and therefore the sequencing of pumps was not specified. The hydraulic grade line elevations were considered to range from a low of 58.0 ft to a high of 70.0. Maximum hydraulic grade lines during dry weather flow conditions were originally intended to prevent overtopping of the check dams in the main interceptors while higher hydraulic grade line elevations would be allowed during wet weather flow conditions. During the preliminary phases of the model testing, a number of operational problems were discovered at the lower hydraulic grade lines; these are discussed further below. At that point, further analyses were performed and a more detailed plan was developed for operation of the pump station at higher wet well hydraulic grade lines. The proposed operational rules are listed below:

Table 1. Proposed Pump Operation Rules for Phase 2 Testing.

# of Pumps Operating	Pumps in Operation	Discharge Capacity(gpm)	Pump On Elevation (ft)	Pump Off Elevation (ft)
1	# 12	17,500	62.2	61.5
2	# 12,10	51,000	63.3	62.2
3	#12,10 & 9 or 11	100,500	64.5	63.3

Note: On/Off Elevations are for operation of last pump in sequence

The second phase of the model testing was conducted for these conditions. In order to completely specify a test condition, the distribution of flows from the two wet well inlets must also be prescribed. Because the two inlets are hydraulically isolated from each other, this distribution is somewhat arbitrary although investigations indicate generally higher flows through the east inlet as compared to the west. Initial conditions for the Phase 2 testing considered an assumed equal split of inflow between the two interceptors, and after completion of those tests, a flow distribution with 75 percent of the inflow though the east inlet and 25 percent through the west inlet was established. It was found to be impossible to set the proposed wet well hydraulic grade lines with this flow split and detailed testing could not be conducted for these conditions. A discussion of this situation is provided below.

A final phase of testing was conducted to establish hydraulic relations between each inlet and the wet wells for a range of flows consistent with those listed in the table above. Investigations on the pre-rotation of the flow entering the pumps were not conducted during this phase of the investigation and measurements were limited to hydraulic grade line elevations.

Test Results

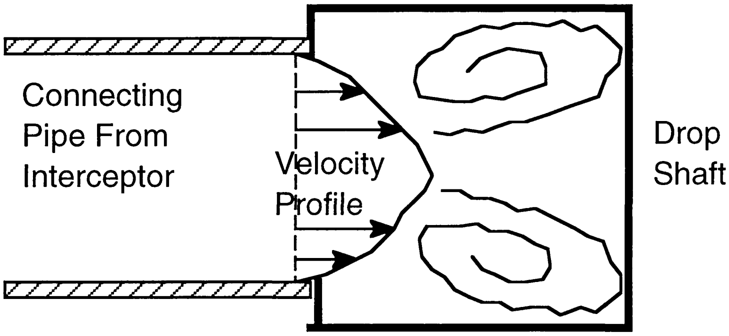
In this section, results are discussed according to the different phases of the testing as described above.

Phase 1 Results

General Flow Conditions

During the preliminary phases of the testing, a number of flow conditions were observed that would generally be regarded as undesirable with regards to pump intake conditions. These included air entrainment into the flow, the presence of submerged vortices, and considerable turbulence within the wet well. All of these factors can contribute to rough running conditions for the pump impellers and unbalanced loads on the pump shafts.

Since the pump intakes are installed in the wet well ceiling, all air entrained into the flow will exit the wet well through the pumps. The source of the air entrainment is the flow through the drop shafts. There were two mechanisms that could contribute to observed air entrainment. If the water level in the drop shaft was low enough, the plunging flow from the inlet pipes entrains air; this situation is visualized in the photograph in Figure 3. With the pipe invert elevations at 59.9 ft, this would be an approximate cutoff for this type of behavior, with lower drop shaft water levels resulting in significant air entrainment due to the plunging of the flow. However, air entrainment was still observed at drop shaft levels well above the 70 ft elevation level which is substantially above specified dry weather operating levels. This air entrainment was due to the presence of air entraining vortices in the drop shafts. These vortices were created by the inflow from the inlet conduits which created higher velocities near the center of the drop shafts as indicated in the conceptual sketch below which is of a cross section through the drop shaft near the inflow.



The swirl induced as the inflow struck the opposite wall of the drop shaft and returned along the sides was sufficient to induce considerable air entrainment, especially at higher flow rates. The vortices and air entrainment under these conditions can be seen in the photographs included as Figure 4. The volume of air entrained was a function of both flow rate and drop shaft water level; this issue was studied further in the Phase 3 investigation and is discussed in more detail below.

Submerged vortices were produced within the wet well under all flow conditions observed although the strength and persistence of these vortices appeared to depend on the particular combinations of pumps in operation. In general, the most persistent vortices were observed under Pumps 10 and 11, the two inner pumps. The videotape indicates these vortices which were visualized by the introduction of fine black sand into the wet well. The vortices were attached to the wet well bottom. When pumps 10 and/or 11 were operating in conjunction with 9 or 12, the inflow from the drop shafts washed out these large and persistent vortices at the outer pumps, presumably due to the high velocities through the inlet conduits connecting the drop shafts and the wet well. However if only Pump 12, for example, was in operation, there were more persistent submerged vortices under it. These submerged vortices could probably be significantly reduced by the placement of cones beneath each pump intake.

Some preliminary measurements of swirl angles were made during the Phase 1 investigation. These indicated very small swirl angles, generally less than one degree for the few cases studied. However, there was still a significant amount of vortex motion apparent in the pump suction lines. Since all the testing conditions involved air entrainment into the flow as discussed above, one could observe these vortices by the organization of the air bubbles. Figure 5 is a photograph of flow through one of the pump intakes. Due to the low light conditions, which necessitated longer film exposure speeds, and the high velocities through the intakes, the air bubbles tend to show up as streaks; The videotape is a better source for flow visualization. Nevertheless, organized bubble motion is clearly visible in Figure 5. The observations of significant vortex motion but measured small swirl angles can be explained by the operation of the swirl baffles. These baffles served to divide the inflow into four separate quadrants, and no organized vortex larger than roughly one-quarter the inflow area was permitted. This resulted in the formation of independent vortices in each of the four quadrants. These vortices, however, were insufficient to produce a large organized rotation that created swirl meter rotation. As discussed below in the Phase 2 results, the removal of the swirl baffle from Pump 12 increased the swirl angle in that intake by about an order of magnitude for the flow conditions studied. Thus, it is apparent that the swirl baffles are an essential component of the pump intakes in order to keep the overall swirl at acceptable levels.

The high turbulence level within the wet well was readily apparent through the flow visualization afforded by the air entrained into the flows. The major source of this turbulence was due to the expansion of the inflows into the wet well directly under the pump intakes. This turbulence along with the submerged vortices caused significant water level fluctuations in the stand tube at the location of the proposed level sensor within the wet well (this was to the side of the wet well but between Pumps 10 and 11). At the highest flow rates, the variation in water level within the stand tube was in excess of 5 ft prototype. The stand tube was of smaller diameter than the correctly scaled diameter, so it is possible that actual prototype fluctuations would be somewhat less than this. However, this would not be generally acceptable for purposes of controlling pump operation, so alternate locations were investigated in the Phase 2 study.

Observations of the flow also indicated significant head losses in the flow through the drop shafts as well as in the conduits connecting between the drop shafts and the wet well. An attempt was made to estimate the distribution of losses between the drop shaft and the connecting conduit. This was accomplished by simultaneously measuring hydraulic grade lines at the top and bottom of the drop shafts as well as within the wet well at several different flow rates. This was done for both east and west inlets. There were a number of difficulties in performing these measurements. As indicated in Figure 4a, for example, the water surface within the drop shaft is not level, even if the inlet conduit is essentially submerged. An average water surface elevation had to be estimated. In addition the other locations were subject to significant turbulent fluctuations and damping of these was necessary in order to be able to make measurements. Head losses through the east drop shaft/inlet pipe were somewhat greater than through the west connection at a given flow rate.

The drop shafts are designed with a basket strainer and other internal appurtenances to screen large solids from entering the wet well. Preliminary testing was performed with the basket as well as other internal geometry reproduced in detail. No differences in the change in head between the drop shafts and the wet well could be discerned compared to testing in which these details were omitted from the model. Consequently, all further testing was conducted without the basket strainer and other internal dropshaft elements for convenience in visualizing the flow.

The Plexiglas conduits that served as the inlet pipes connecting the drop shafts and the wet well were found to have a slightly smaller than specified internal diameter and therefore this dimension was not reproduced at the exact geometric scale in the model. This would result in larger velocities in the connecting pipe than required to produce dynamically similar flow conditions and would also result in larger head losses. Since the relation between total head loss and flow rate was nearly quadratic (head loss proportional to the discharge squared) it was assumed that the losses could be expressed as a function of the velocity squared. Therefore, the head losses between the drop shaft and the wet well were adjusted downward by the square of the ratio of the actual conduit area to the geometrically scaled area; these results are referred to as adjusted head losses. There was no need to make such a correction for the losses in the drop shafts since they were constructed on the basis of exact geometric similarity.

The results of the head loss measurements are presented in Figures 6 and 7 for the east and west inlets, respectively. The head loss presented in each figure is the elevation difference between the water level in the drop shaft and that in the stilling well connected to the wet well. As expected, both figures indicate an approximately quadratic relation between the head loss and the flow rate: $h_L \propto Q^{2}$. Head losses are fairly substantial; at a station capacity of approximately 150,000 gpm, the head losses through each inlet are on the order of two feet if the flow is evenly distributed and would be early six feet in the east inlet if 75 percent of the inflow entered through it.

- During the Phase 1 investigation, it became apparent that there were hydraulic limitations to the possible control of the pump sequencing during dry weather flow conditions. This is introduced by the requirement to avoid diverting flow to the storm wet well during dry weather operating conditions. Check dams in the interceptors were originally set an elevation of 62.5 ft and water levels at those points could not be exceeded without the undesirable flow diversion. The minimum wet well hydraulic grade line to avoid cavitation was initially specified at 58.0 ft so there is only a range of 4.5 ft of hydraulic grade line elevation difference between the two points in the system which can be exceeded at some flow rates according to Figures 6 and 7 which do not account for the total head change between the interceptors and the wet well. This situation is particularly exacerbated in the east entrance if a significant fraction of the inflow enters through it. Another more difficult problem is introduced when the inflow into the drop shafts is in an unsubmerged state as would typically be the case in this range of hydraulic grade lines. Under this flow state, the flow through the conduit connecting the interceptor and the drop shaft would be controlled by the interceptor water level and the occurrence of critical flow in the free surface flow at the exit from the connecting pipe at the drop shaft. Lowering the water level in the drop shaft would not increase the flow through the connecting pipe. In a condition where the flow through that pipe was nominally above the capacity of the particular combination of pumps in operation, the water level in the drop shafts (and thus the wet well) will increase until the next pump turns on. At this point, the pumping capacity is now far in excess of the inflow rate and the only storage available is in the drop shafts which have a cross-sectional area of only 49 square feet. Regardless of the pump combination, this would result in an evacuation of all water in the drop shafts, ingestion of air into the wet well and subsequent loss of pump prime in a matter of seconds. It is also likely that pump cavitation would occur during a portion of the cycle. This sort of cycle must be associated with the current operation of the pump station. It is clearly infeasible to cycle pumps on this short a time scale. Consequently, alterations in the proposed pump station operation were developed which utilized the available storage in the interceptors. This requires higher wet well hydraulic grade lines so that the flow within the drop shafts is maintained in a submerged condition.

This set of flow conditions was investigated during the Phase 2 testing as described in the next section.

Phase 2 Results

A proposed plan for sequencing the pump operations was developed with the provision of operating at higher wet well hydraulic grade lines to provide submerged inflow conditions in the dropshafts and to utilize the storage available in the interceptors to lengthen the pump cycle times. The proposed operating conditions were summarized in Table 1. The model was initially tested at these flow conditions under the assumption that the inflow into the wet well was equally contributed by the east and west inlets. The hydraulic grade line elevations listed in Table 1 were to be associated with conditions in the main interceptors. Since there are differences in head losses between the two inlets (as can be seen in Figures 6 and 7) at this flow distribution, the hydraulic grade lines in both interceptors cannot be set at a common level. The greater head loss associated with the flow in the east inlet was considered to control the pump operation and the hydraulic grade line measured in the east connecting pipe was used to set the prescribed hydraulic grade lines. Swirl angles were computed for both the on and off water levels at each combination of pump operation. The results of these measurements are included in Table 2. As can be seen, the swirl angles are well below five degrees under all operating conditions. This is in spite of the observations of submerged vortices within the wet well and is apparently related to the presence of the swirl baffles. Removal of the swirl baffles from Pump 12 resulted in significant increases in swirl angle by more than an order of magnitude in most cases as listed in Table 2.

Two new piezometer locations were suggested; these locations are indicated in Figure 8. Piezometers were installed at these two locations at the appropriately scaled diameter for the bubbler pipe proposed for the prototype. Visual observations were made of the water level fluctuations in the two piezometers. The range of fluctuations is indicated in Figure 9 and was roughly the same for both piezometer locations. The fluctuations are also seen to increase with total flow rate as expected. This range of fluctuations is substantially less than at the original location and is presumed to be suitable for the intended water level sensing application.

Following these experiments, an inflow distribution was selected in which 75 percent of the inflow entered through the east drop shaft to reflect a situation where the majority of the inflow enters through the East Jeffereson Relief Interceptor. It was not possible under this inflow distribution to set the desired hydraulic grade line elevations at the upstream end of the east connecting pipe. The inflow into the drop shafts became unsubmerged and the occurrence of critical flow at the inflow prevented lowering the hydraulic grade line to the desired level. It was therefore concluded that the pump operating conditions listed in Table 1 would only be achievable when the inflow into the wet well was approximately equally distributed between the two inlets. Although this is apparently a possible flow condition, it may not be a common one and further modifications in the pump station operation are required in order to provide feasible operating conditions over the entire range of potential inflow conditions.

Phase 3 Results

As a result of the Phase 2 findings, it was concluded that the only feasible method of operating the wet well is to pass some portion of dry weather flows to the Storm Pump Station and to utilize the third entrance into the Sanitary Pump Station. The physical model was not constructed with this prospect in mind and hydraulic testing for these conditions was not in the original scope of the model study. However, the existing model could be used to define the hydraulics of the two modeled inlets. These results can then be incorporated into an calculations of the system hydraulics with the third inlet open. This will allow the definition of feasible pump operating levels.

The third phase of model testing was intended to more carefully define the hydraulics of the east and west inlets to the wet well. Tests were performed on these individually with flow passing through only one of the inlets at a time. The purpose of this testing was to define the hydraulic grade line elevations necessary to provide submerged inlet conditions in the drop shafts and to define necessary hydraulic grade lines to minimize air entrainment insofar as possible. These experiments involved the measurement of hydraulic grade lines in both the wet well and at the upstream end of the inlet pipe into the drop shaft. This upstream hydraulic grade line elevation will basically reflect the hydraulic grade line in the interceptor except for the entrance loss in the flow from the interceptor. Examination of different pipe junction geometries listed in Idelchik (1994) indicates that this entrance loss should be on the order of about 0.4 to 0.5 of the downstream velocity head (velocity head in the connecting pipe). In addition, visual observations were made on the amount of air entrainment within the drop shafts. In this regard, it was noted that that as the wet well hydraulic grade line was gradually increased, the air entrainment decreased until a further increase in hydraulic grade line elevation resulted in little additional reduction in air entrainment.

The basic procedure involved setting an arbitrary flow rate at a relatively low wet well hydraulic grade line at which the inflow into the drop shaft was clearly at an unsubmerged condition. The hydraulic grade line elevations were measured in both the wet well and at the upstream end of the inlet pipe. Water was added to the model increasing the hydraulic grade line elevations, air entrainment was observed and hydraulic grade line elevations were again measured. This process was repeated for increasing hydraulic grade line elevations until the inlet into the drop shaft was clearly in a submerged condition. The entire process was repeated for several different flow rates. These measurements were performed for both the east and west inlets.

Measurement results for a typical flow condition are presented in Figure 10; corresponding graphs for the other flow conditions tested are presented in the Appendix as well as the basic data. At low wet well hydraulic grade lines, the flow into the drop shaft is in an unsubmerged flow state and the occurrence of critical flow at the downstream end of the connecting (entrance to the drop shaft) pipe controls the hydraulic grade line elevations further upstream. Consequently, a change in wet well hydraulic grade line does not alter the hydraulic grade line elevation in the inlet; this effect is clearly seen in Figure 10. This flow state is unacceptable with regards to pump station operation since there is no feasible way to stage the pump sequencing to match the inflows into the wet well with the limited available system storage. At higher hydraulic grade line elevations, the flow into the drop shaft is in a submerged state and there is basically a one-to-one correspondence between the change in hydraulic grade lines measured at the two locations. The transition between these two flow states is not abrupt although it does occur over a limited range of hydraulic grade lines. Two methods were selected for defining the transition state. The first (called the "average" transition point) involved extending the straight line portions of the unsubmerged and submerged stages of the curves and noting the intersection; this is indicated in Figure 10. The second approach yielded a more conservative description and was defined by the highest hydraulic grade line elevation that deviated from the straight line defined by the submerged flow state. This definition (called the "high" transition point) is also depicted in Figure 10. A final adjustment to these levels was made to account for the larger than expected head losses in the model due to the slightly undersized connecting pipe between the drop shaft and the wet well as discussed previously. The results for both definitions of the transition hydraulic grade lines for the east and west inlets, respectively, are presented in Figures 11 and 12. The Appendix also includes tables with all of these results summarized. Figures 13 and 14 present the total change in hydraulic grade line well under submerged conditions in the drop shaft between the upstream end of the connecting pipe and the wet. Figures 15 and 16 present hydraulic grade line elevations associated with changes in air entrainment as described above. Although these observations are fairly qualitative, they are also reasonable consistent and can probably be used with a fair amount of confidence. The hydraulic grade line estimates above which no significant reduction in air entrainment was observed are generally well below those in Figures 11 and 12 to maintain submerged conditions at the drop shaft inlets. Therefore, it appears that the maintenance of submerged inlet conditions will also ensure the minimum achievable air entrainment with this pump station design.

The addition of a portion of the inflow into the wet well through the third inlet will have an influence on the pressure fluctuations at the proposed level sensor locations. In general, the reduction in magnitude of inflow velocities by distributing the flow among three inlets instead of two will reduce the magnitude of the pressure fluctuations within the wet well. Neitherither of the proposed sensor locations indicated in Figure 8 appear to be in a location where they will be adversely impacted by the inflow from the third inlet. It appears that the level sensor located closest to pump 10 would be the best in this flow configuration, but both are probably still acceptable.

CONCLUSIONS AND RECOMMENDATIONS

Preliminary testing of the physical model for the proposed operation of the pump station indicated that it will not generally be possible to operate in a satisfactory fashion over the anticipated ranges of discharges. The major problems were related to the control of pump sequencing by sensing of hydraulic grade lines within the wet well. At high flow rates, the head changes in the flow through the connecting pipes, drop shafts and inlet pipes may create upstream heads greater than the elevations of the proposed crests of the check dams in the Jefferson Avenue Relief Interceptor. Hydraulic grade lines within the wet well cannot be reduced to compensate for this because of the possibility for pump cavitation and the fact that at low wet well hydraulic grade lines, the inflow into the drop shafts is not controlled by the wet well HGL but rather by the occurrence of critical flow at the inlet to the drop shafts. Raising the elevation of the check dams is not a viable option since the capability of passing storm water flows over them during wet weather conditions must be maintained. The only solution to this hydraulic problem appears to be to allow excess dry weather flows to pass into the Storm Pump Station and to allow the connection between it and the Sanitary Pump Station to provide the necessary flow capacity. A detailed hydraulic analysis will need to be performed to ensure that satisfactory hydraulic performance will occur under this flow configuration.

Investigations of the conditions at the pump intakes indicated that swirl angles were well below generally accepted limits. These small swirl angles were apparently due to the presence of the swirl baffles since the removal of the baffle under pump 12 raised the swirl angle above the recommended five degree limit for all conditions tested. Therefore, the swirl baffles are an essential part of the pump station design.

In spite of the small swirl angles, a number of poor inlet conditions were observed, including excessive turbulence, persistent submerged vortices under pumps 10 and 11 (in particular), and entrained air passing through the pump intakes. The excessive turbulence is a function of the wet well design and there is probably no feasible way to eliminate it. Air entrainment occurs in the drop shafts and also cannot be avoided with the current design but can be minimized by maintaining the water levels in the drop shafts at sufficiently high elevations. Maintaining the drop shafts to produce a submerged inlet condition (necessary for other station operation considerations) will also produce a minimum air entrainment situation. The submerged vortices can probably be drastically reduced by the installation of floor mounted cones under each pump intake. A variety of configurations have been used in other installations for these cones, but the sketch in Figure 17 indicates a potential configuration. A typical dimension of the horizontal dimension of the cone is the outside diameter of the suction bell. The height of the cone in many installations is the entire distance between the floor and the bottom of the suction bell. In this installation, the presence of the swirl baffles probably does not make this necessary, but a height on the order of the width of the cone would probably be appropriate.

The proposed water level sensor locations indicated in Figure 8 appear to be fairly adequate for purposes of sensing wet well hydraulic grade line.

Finally, it will generally be necessary to operate the pump station at a sufficiently high hydraulic grade line elevation to maintain a submerged inflow condition in at least one of the dropshafts. Figures 11 and 12 indicate the elevations estimated from the model tests for the east and west drop shafts, respectively. Two different measures of the necessary hydraulic grade line elevation are provided with the "high" one providing a more conservative estimate. These hydraulic grade line elevations were measured at the upstream end of the connecting pipes and an entrance loss will need to be added to these levels to determine elevations in the interceptors.

REFERENCES

Idelchik, I.E. (1994) "Handbook of Hydraulic Resistance," CRC Press, Boca Raton, Fla.

Padmanabhan, M. and G.E. Hecker, (1982) "Assessment of Scale Effects of Vortexing, Swirl, and Inlet Losses in Large Scale Sump Models," Alden Research Lab, Worcester Polytechnic Institute, Report to Nuclear Regulatory Commission, NUREG/CR-2760

Table 2. Swirl Angles Measured For Proposed Permutations of Pump Operation.

		SWIRL ANGLES				
		Pump				12
Pumps in Operation	East Inlet HGL (ft)	9	10	11	12	No swirl Baffle
12	**61.5**				1.397	5.700
12	**62.2**				0.761	
10, 12	**62.2**		0.026		0.451	9.000
10, 12	**63.3**		0.771		0.873	
9, 10, 12	**63.3**	-0.119	0.514		0.394	14.300
9, 10, 12	**64.5**	-0.243	0.797		0.169	
10, 11, 12	**63.3**		0.185	-0.863	0.789	17.200
10, 11, 12	**64.5**		0.257	-0.200	0.225	
9, 10, 11, 12	**64.5**	1.564	-0.015	1.214	0.828	13.100
9, 10, 11, 12	**65.5**	-0.189	0.668	-0.415	0.338	

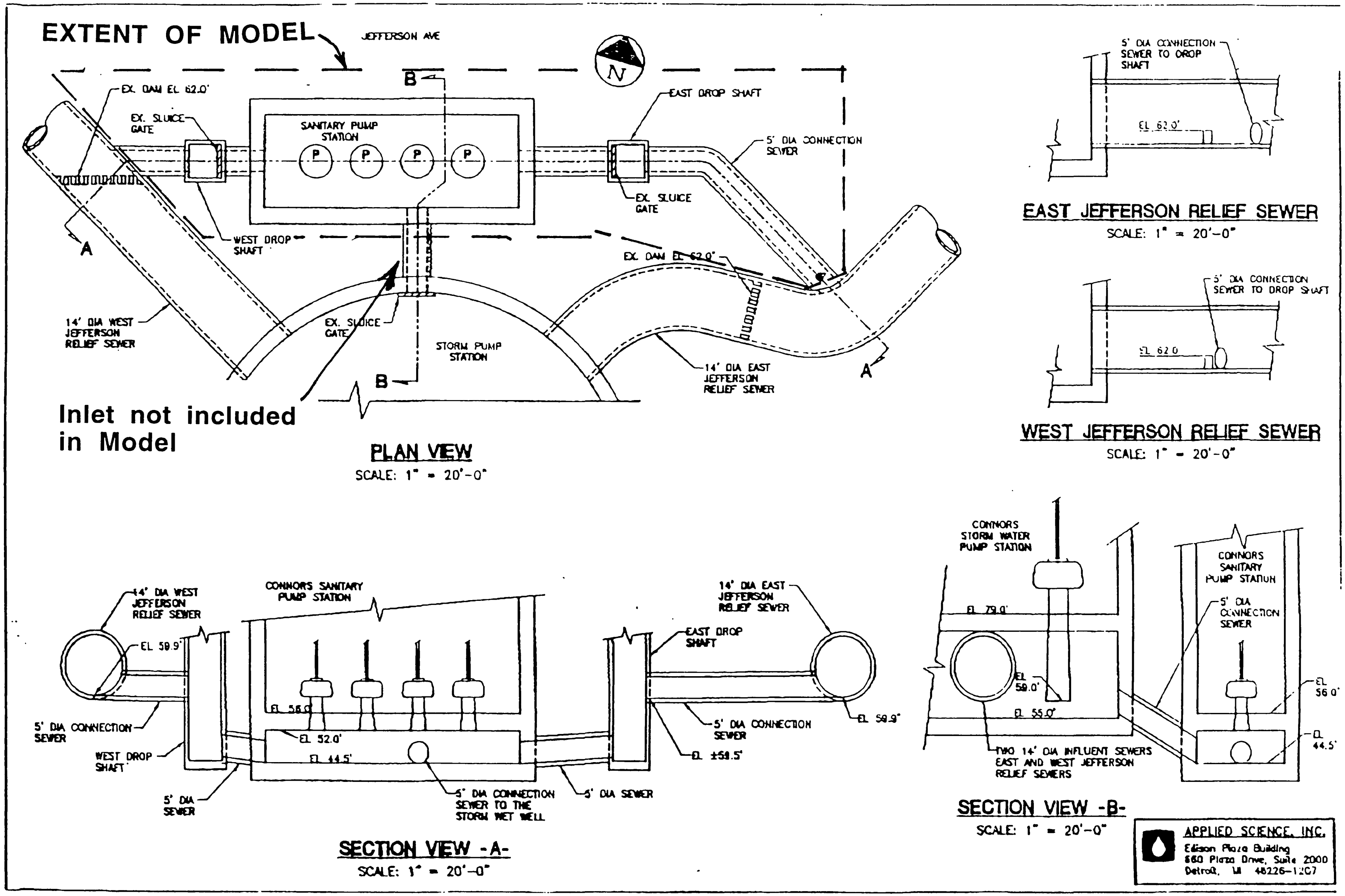


Figure 1. Layout of Conner Creek Sanitary and Storm Pump Stations.

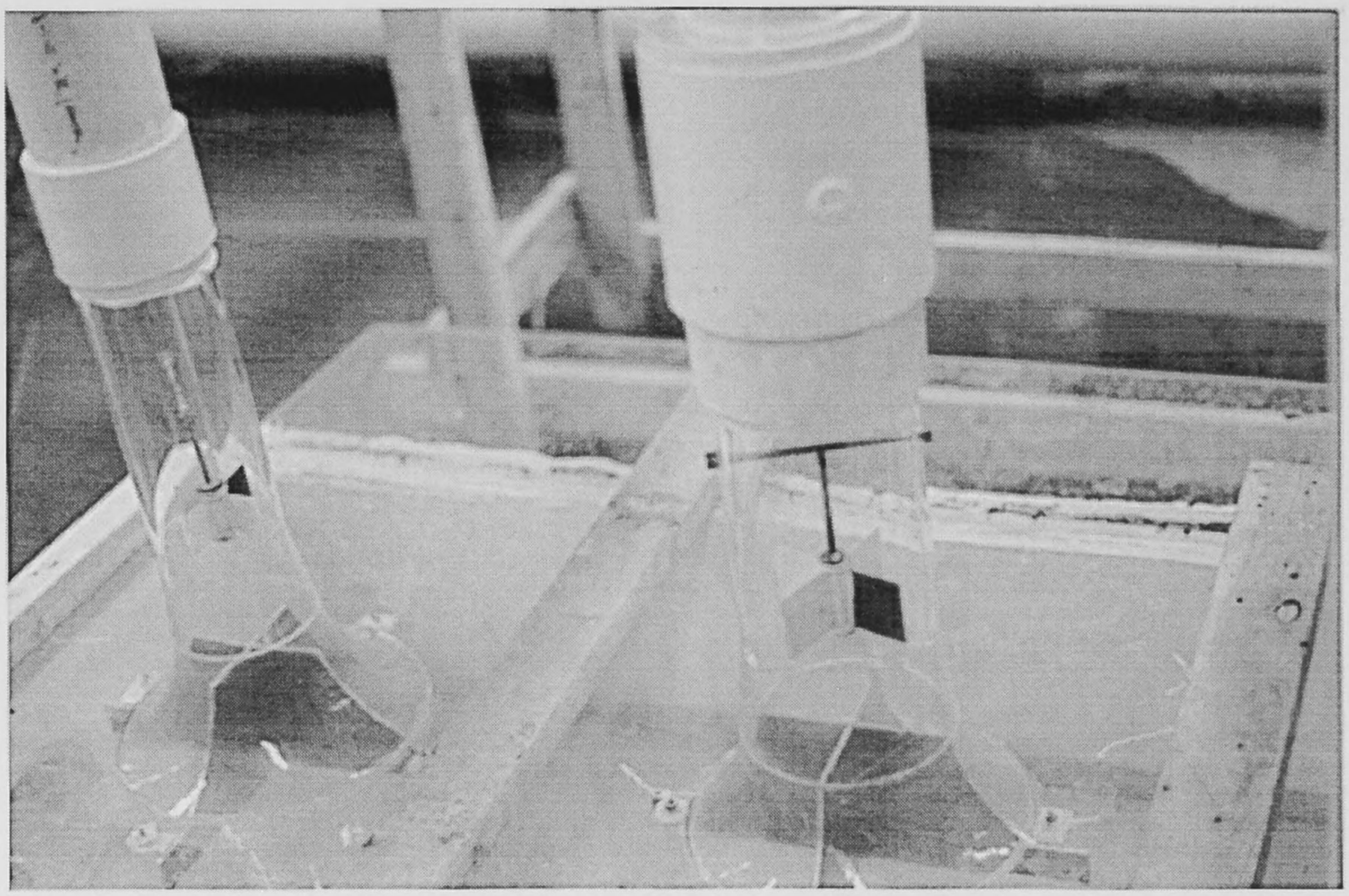


Figure 2a. Model Pump Intakes with Swirl Meters Installed.

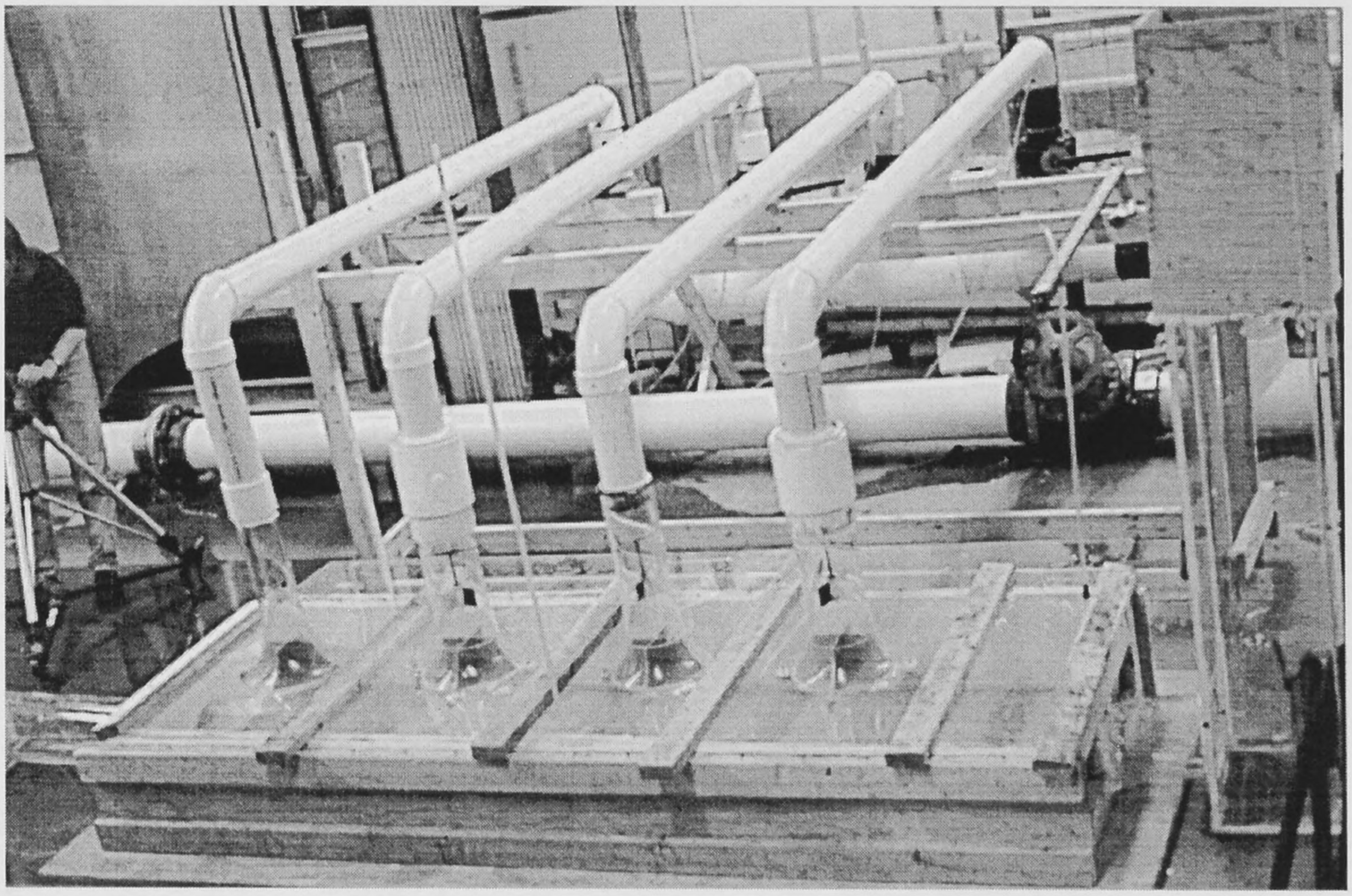


Figure 2b. Model of Wet Well and Pump Intakes. West Drop Shaft on Right.

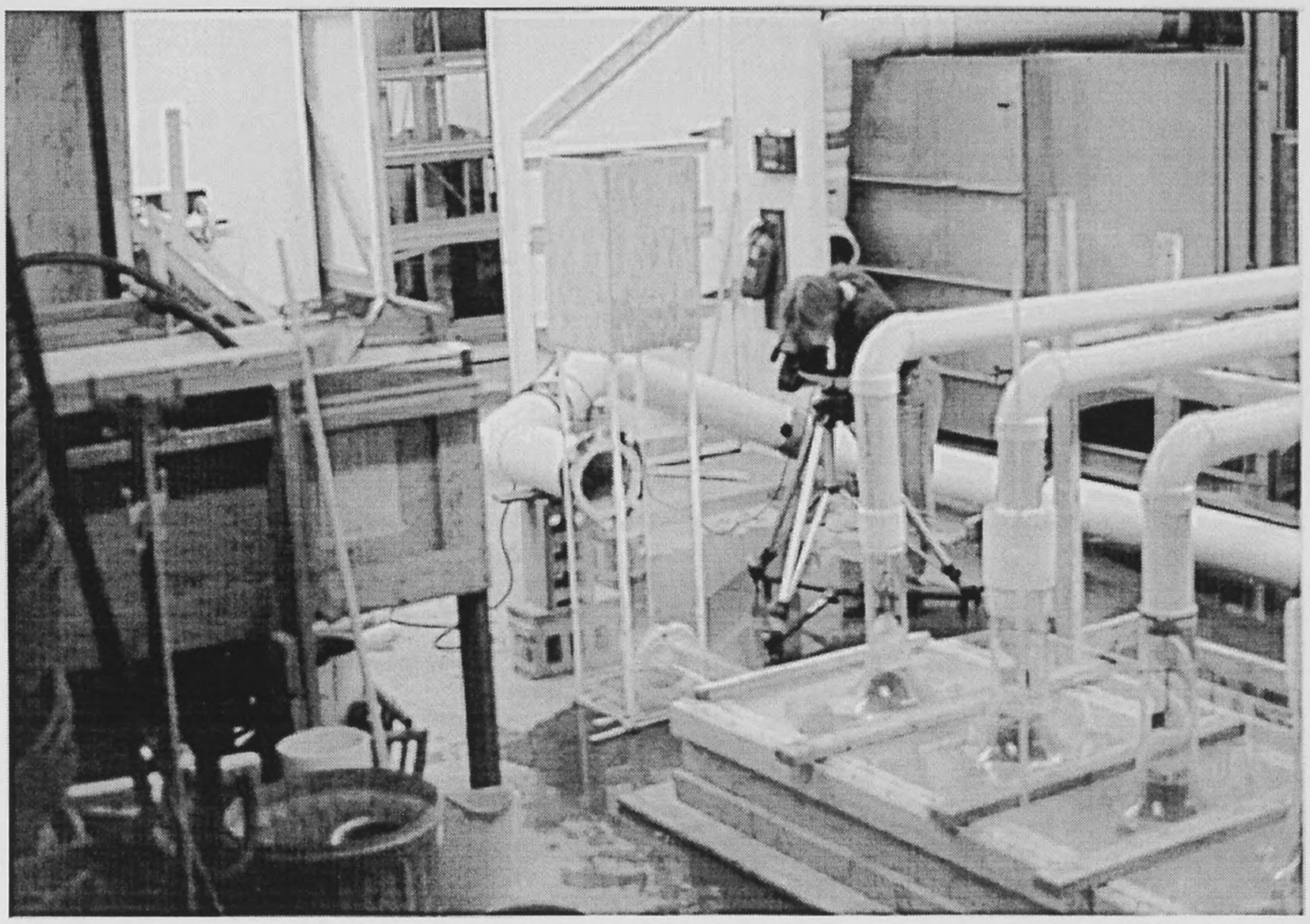


Figure 2c. East Drop Shaft with PVC Connecting Pipe and Plexiglas Inlet Pipe to Wet Well.

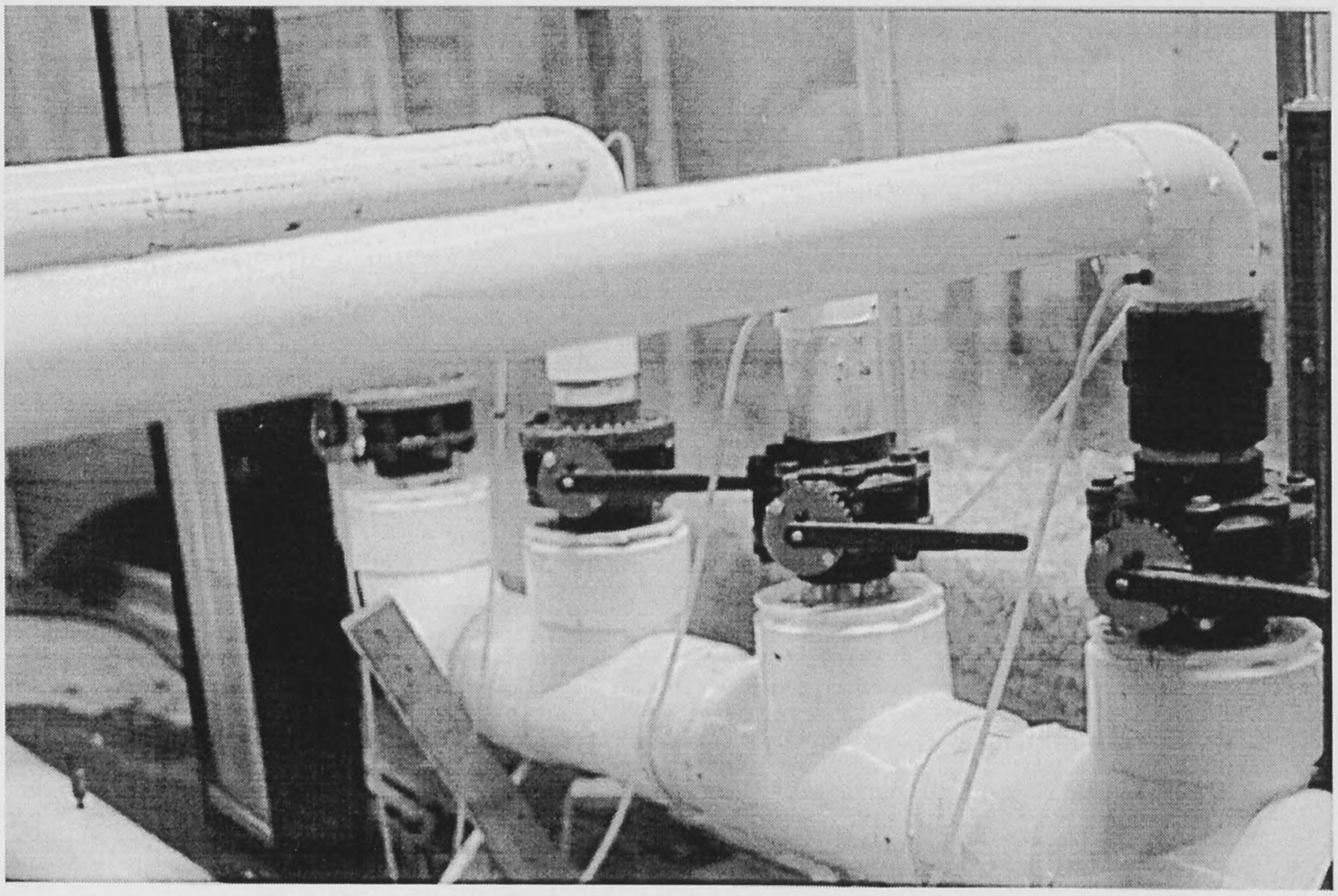


Figure 2d. Bend Elbow Meters and Manifold to Recirculating Pump.

Figure 3. Air Entrainment Due to Pumging Flow at Low Water Level in West Drop Shaft.

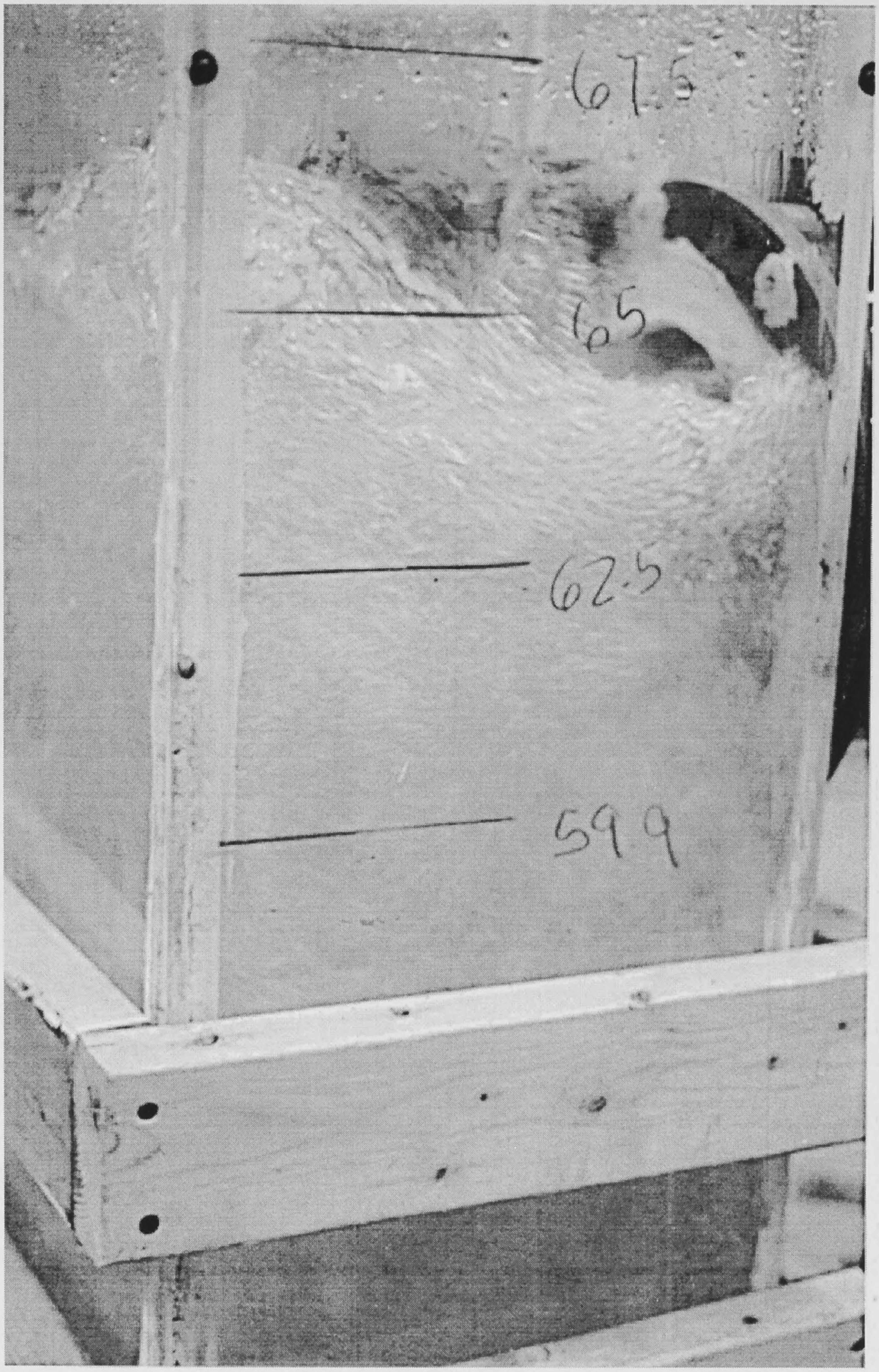


Figure 4a. Air Entrainment at Intermediate Water Level in East Drop Shaft.

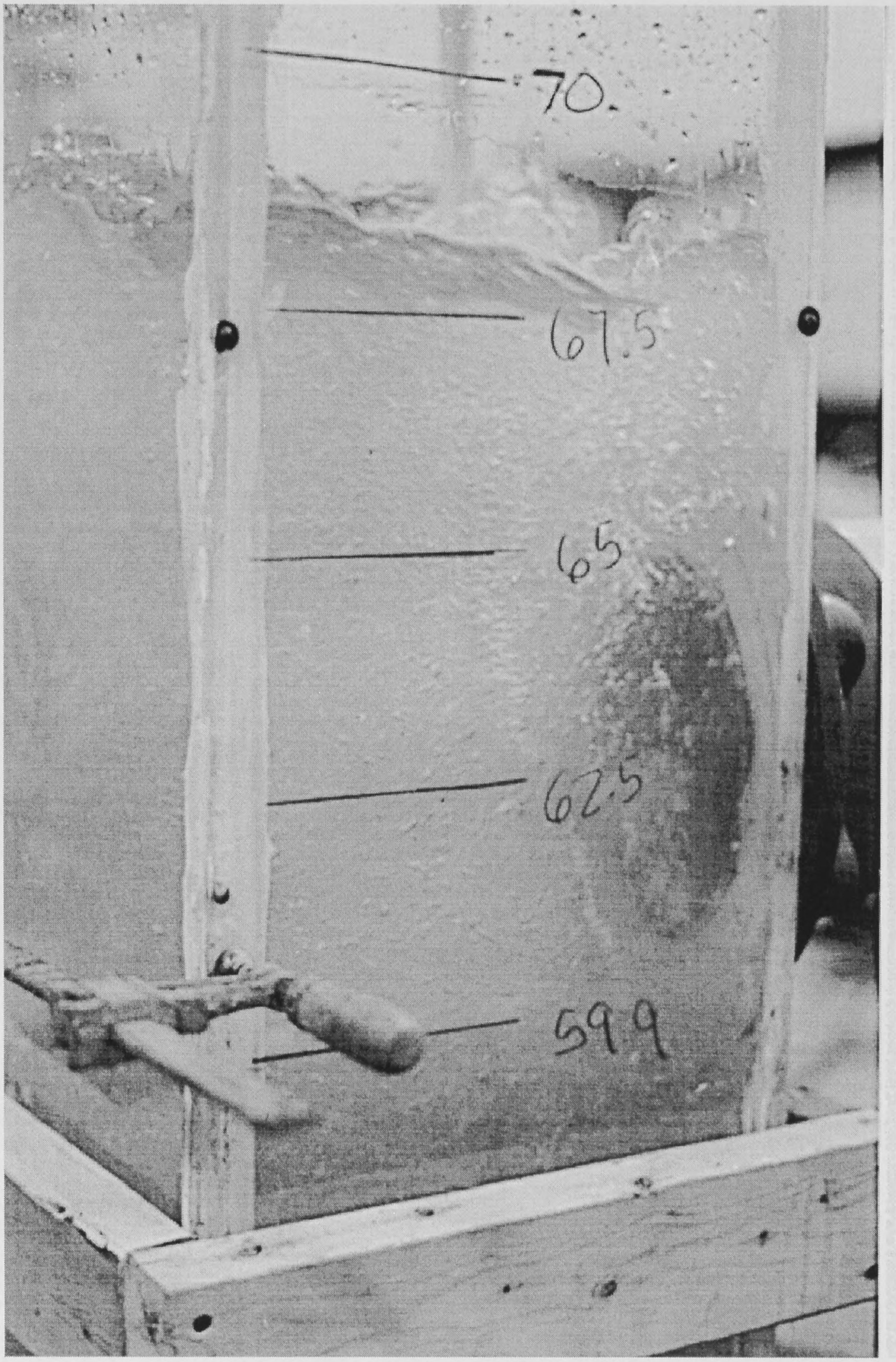


Figure 4b. Air Entrainment at High Water Level in East Drop Shaft.

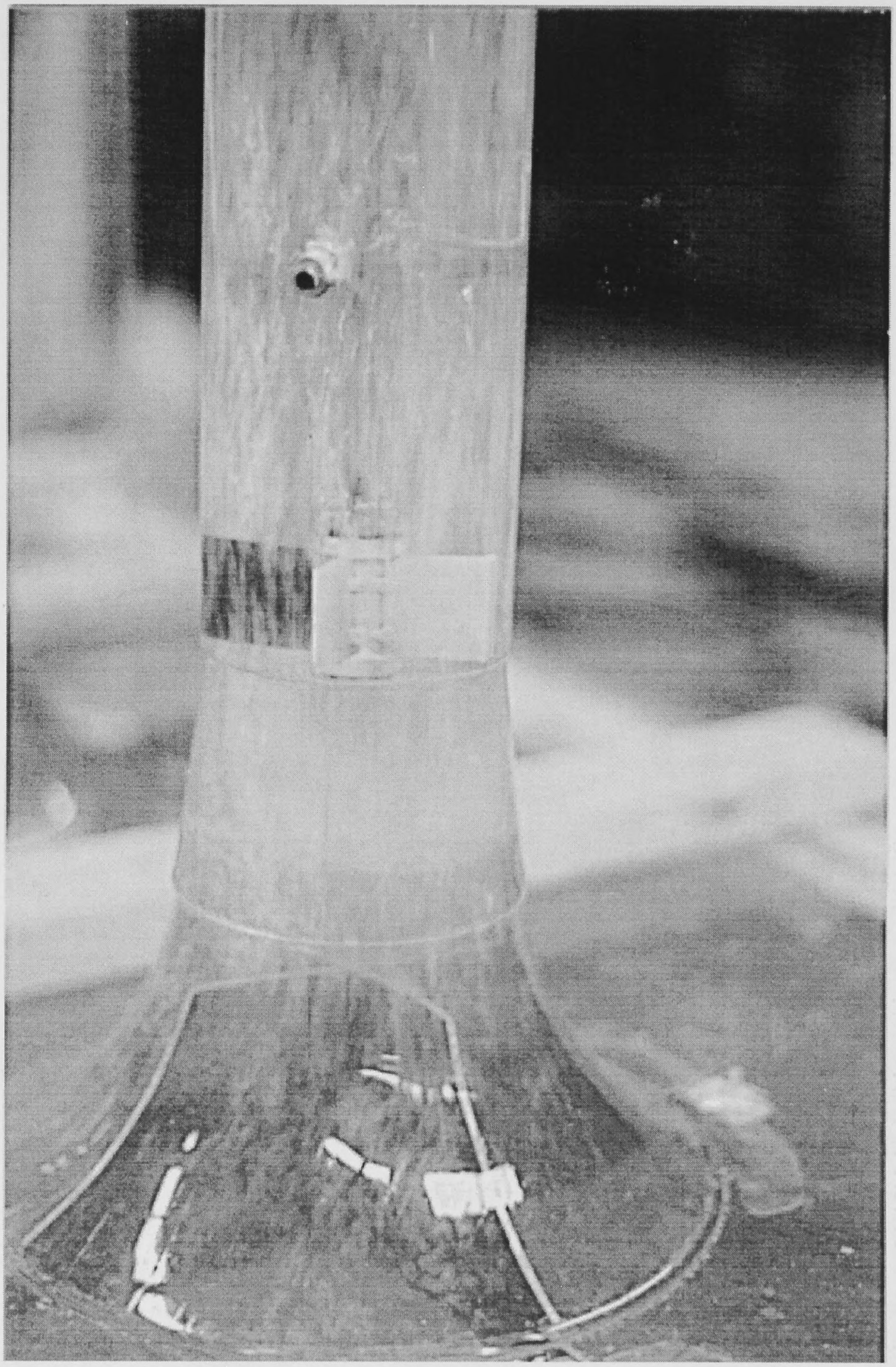


Figure 5. Small Scale Vortices in Pump Intake Visualized by Trails of Entrained Air Bubbles.

Figure 6. Adjusted Head Loss, East Drop Shaft

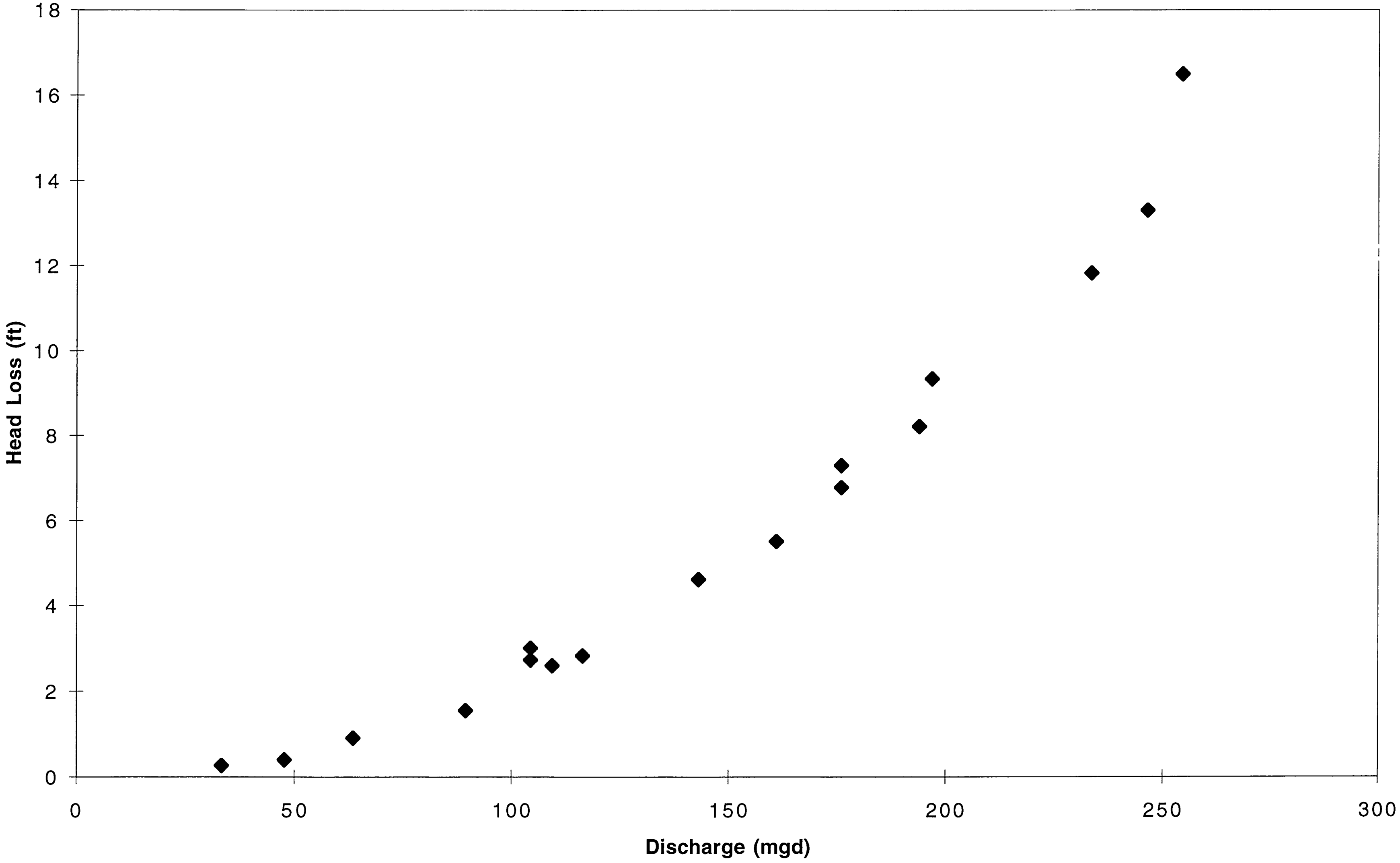
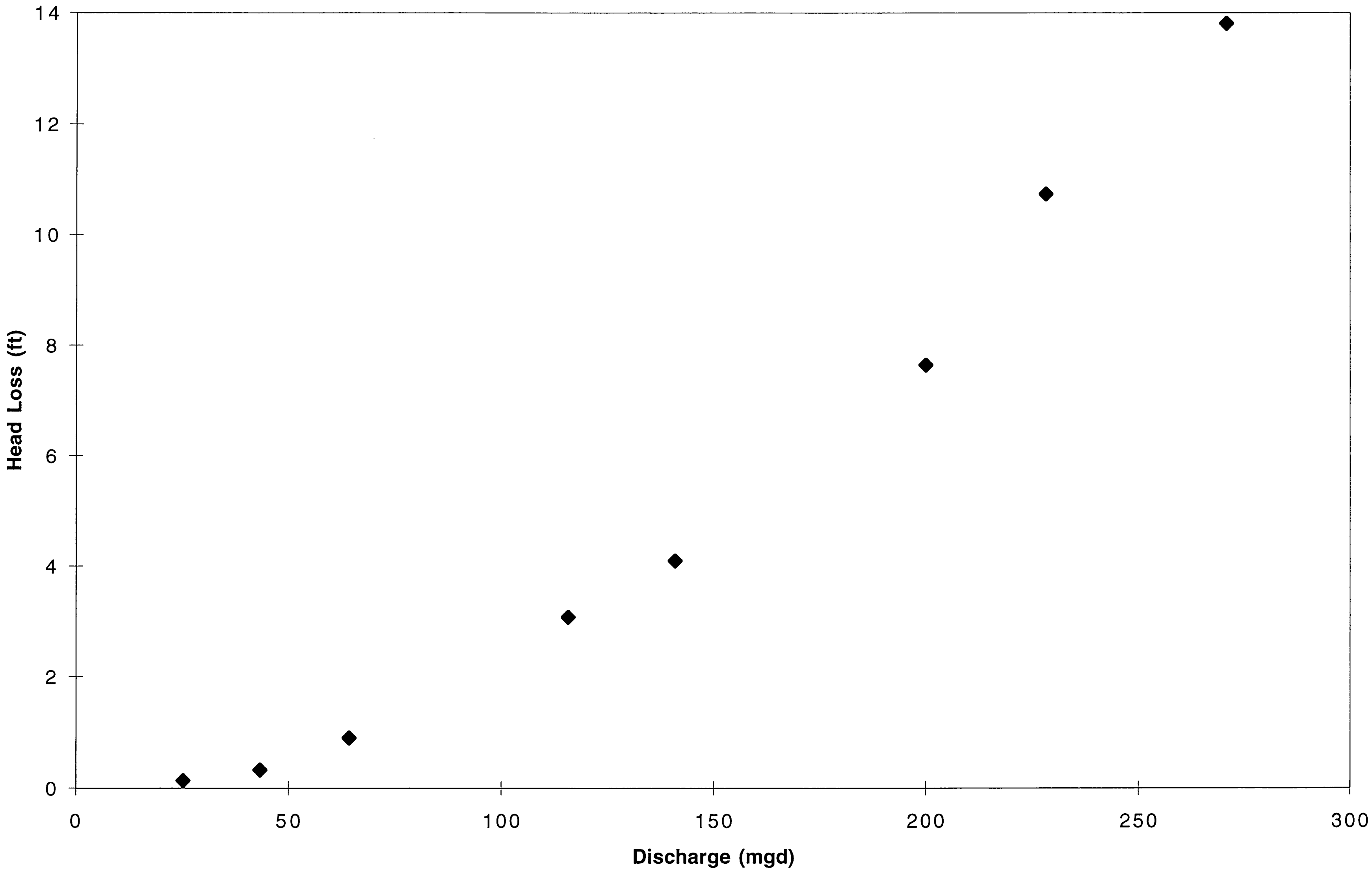


Figure 7. Adjusted Head Loss, West Drop Shaft



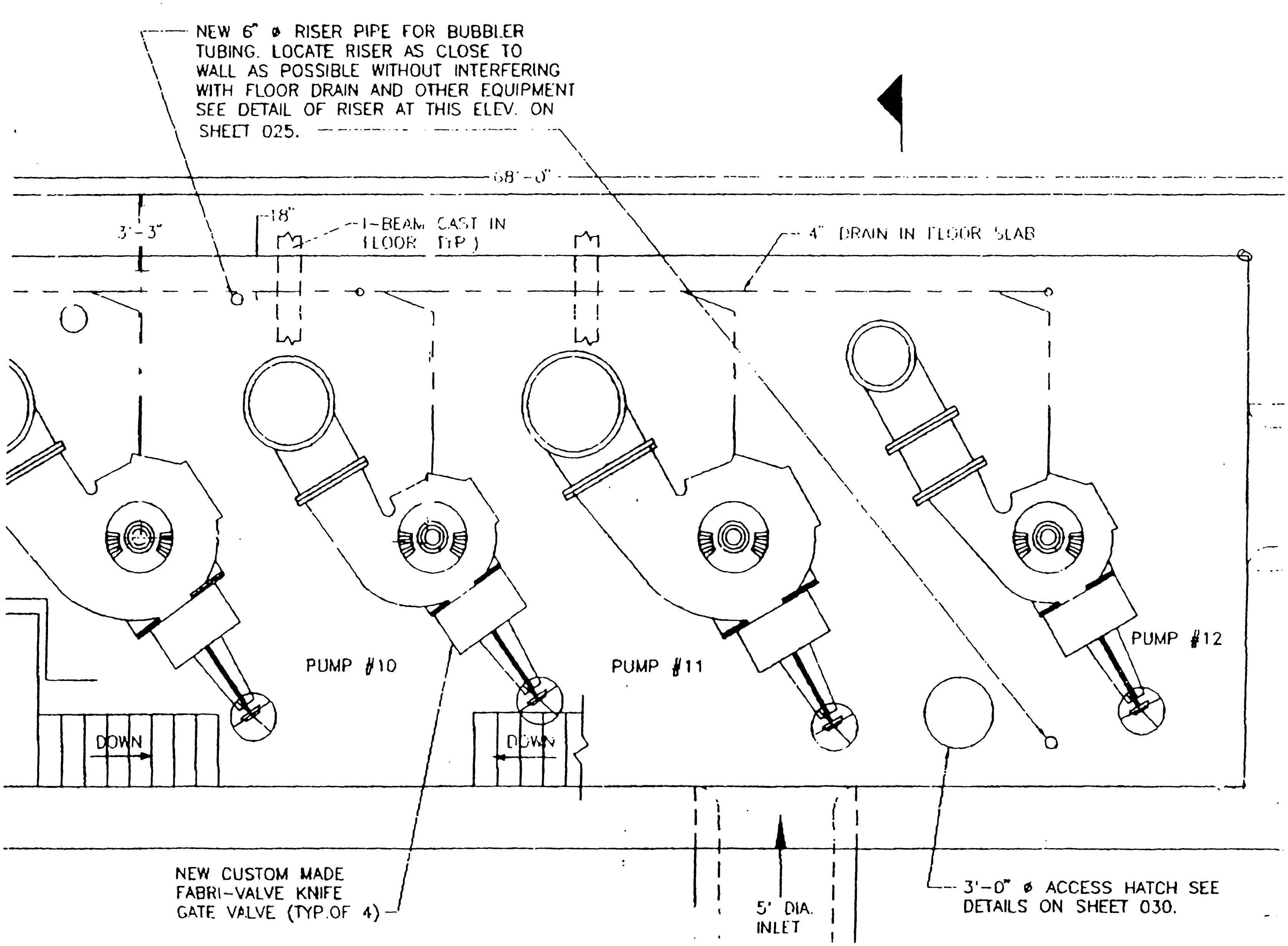


Figure 8. Proposed Locations of New Level Sensors

Figure 9. Approximate range of piezometer fluctuations (either location)

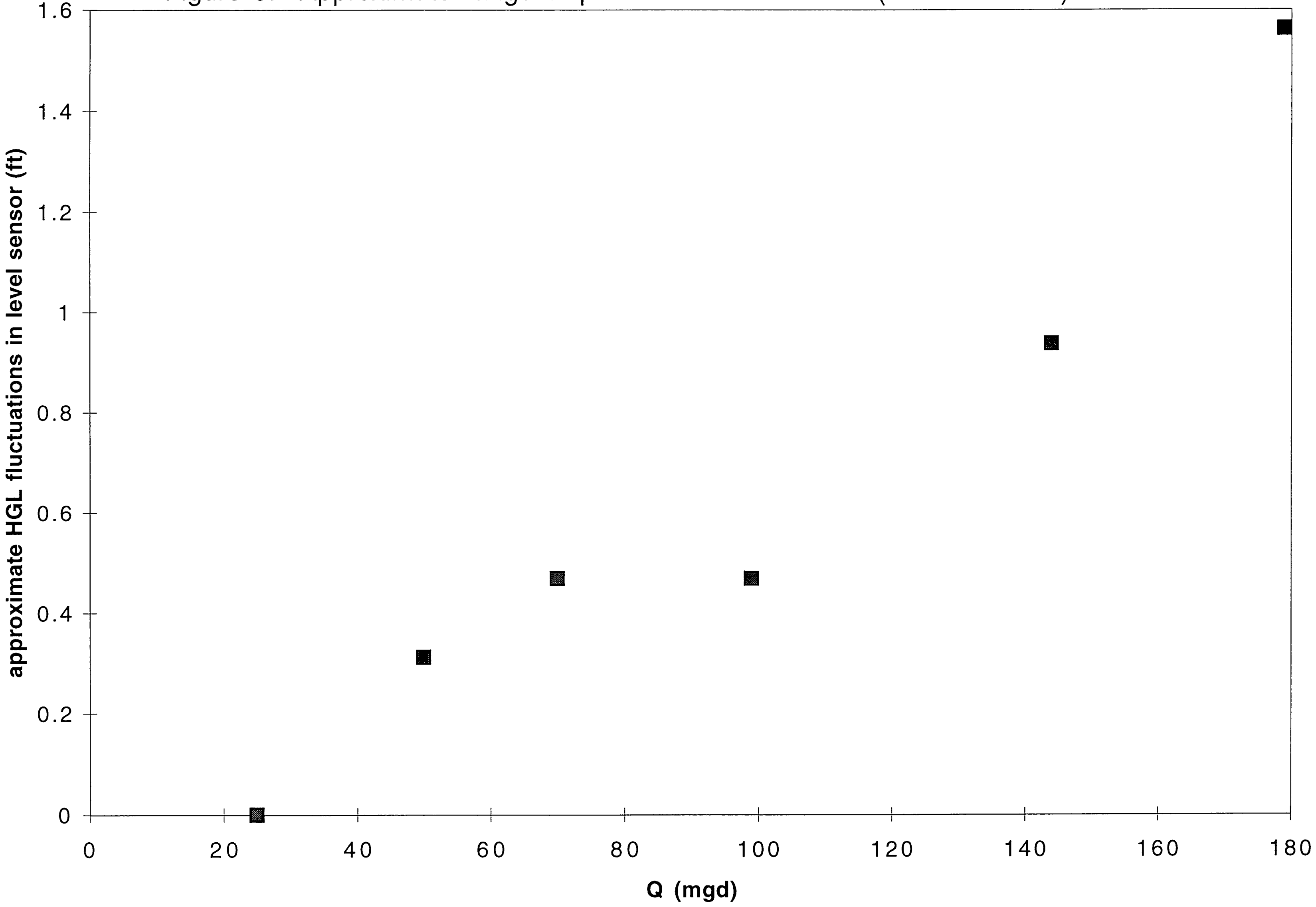


Figure 10. Definition of Transition Hydraulic Grade Lines, Q = 70 mgd

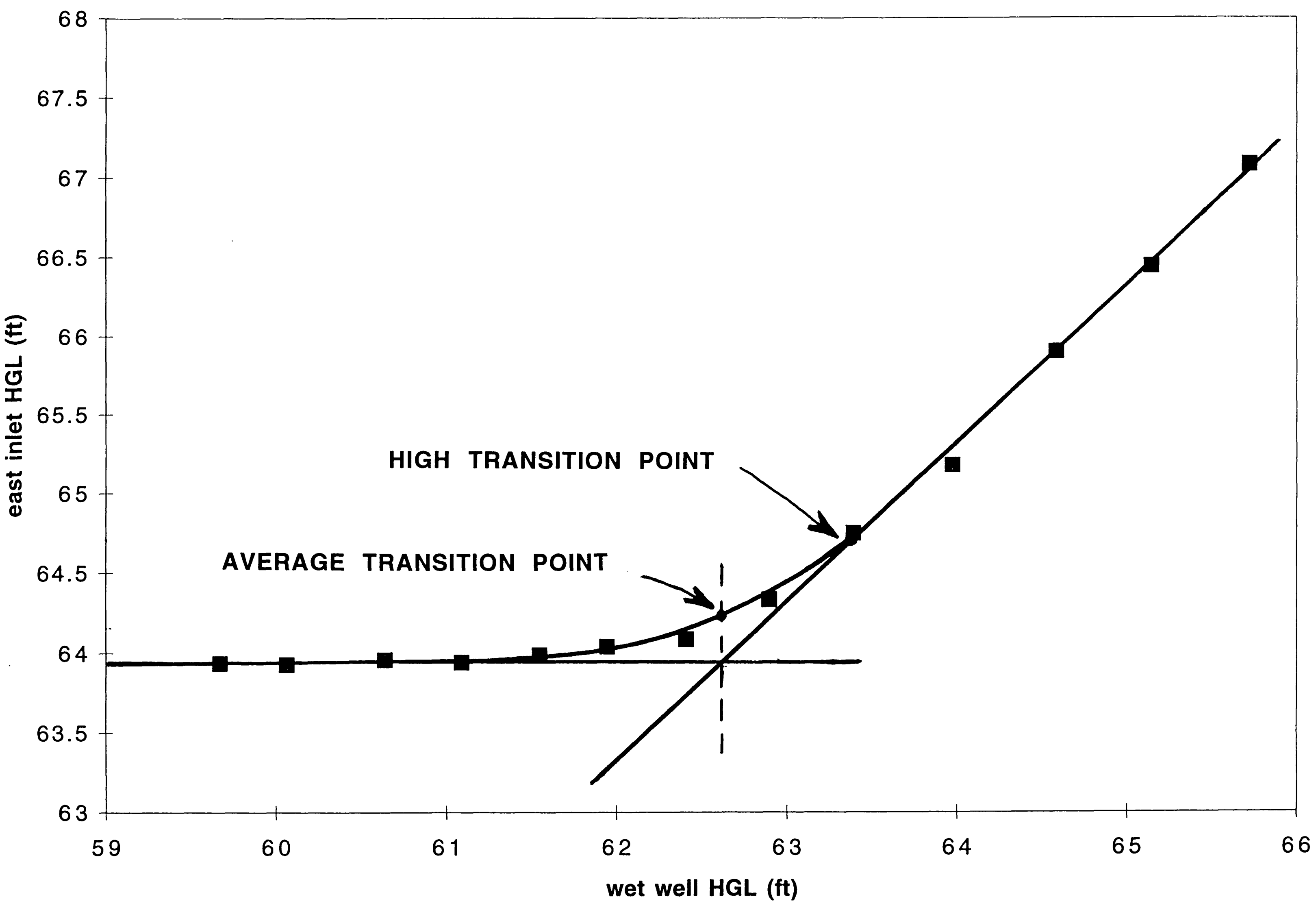


Figure 11. HGL at which wet well produces no backwater effect in east inlet

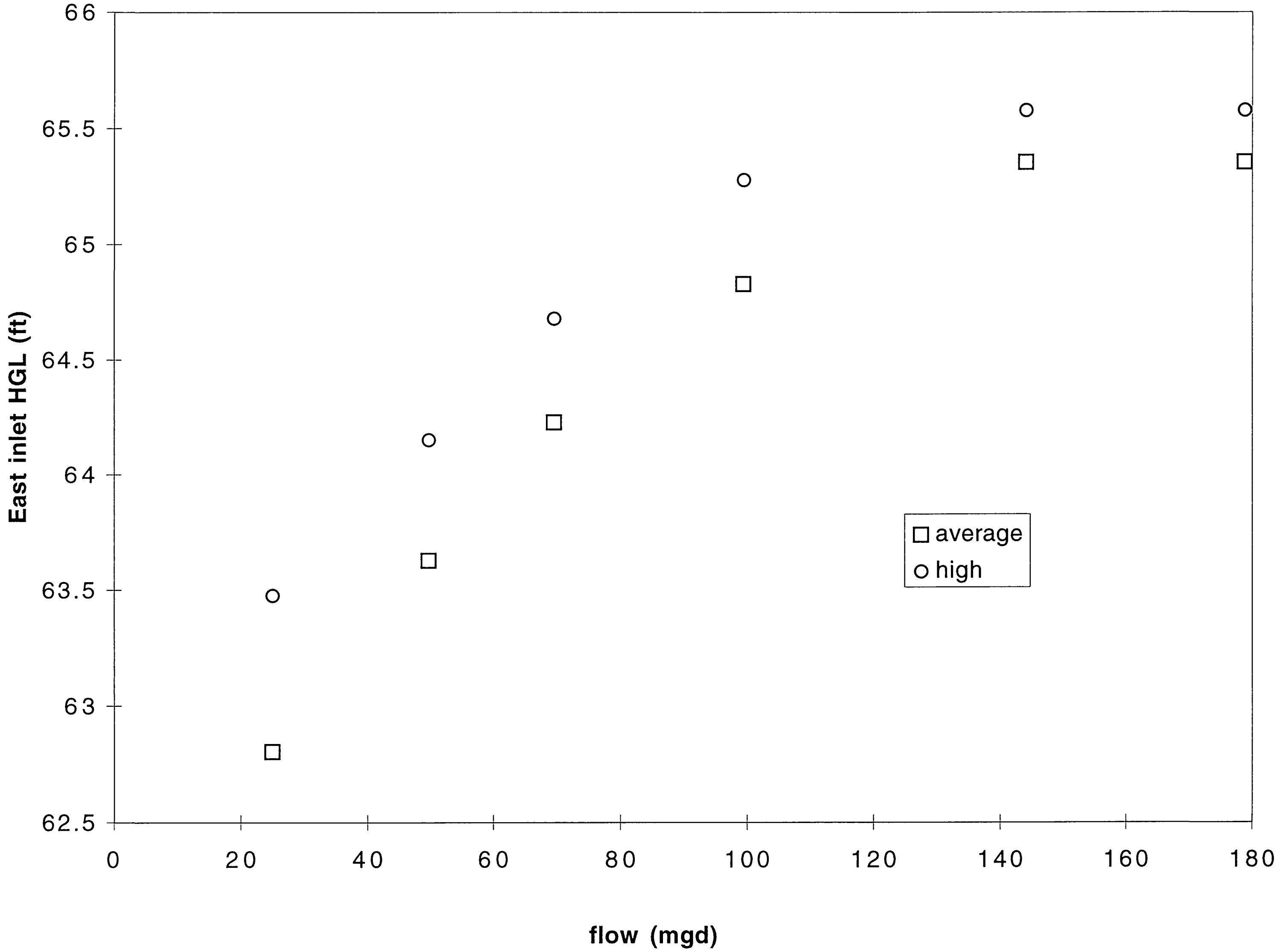


Figure 12. HGL at which wet well produces no backwater effect in west inlet

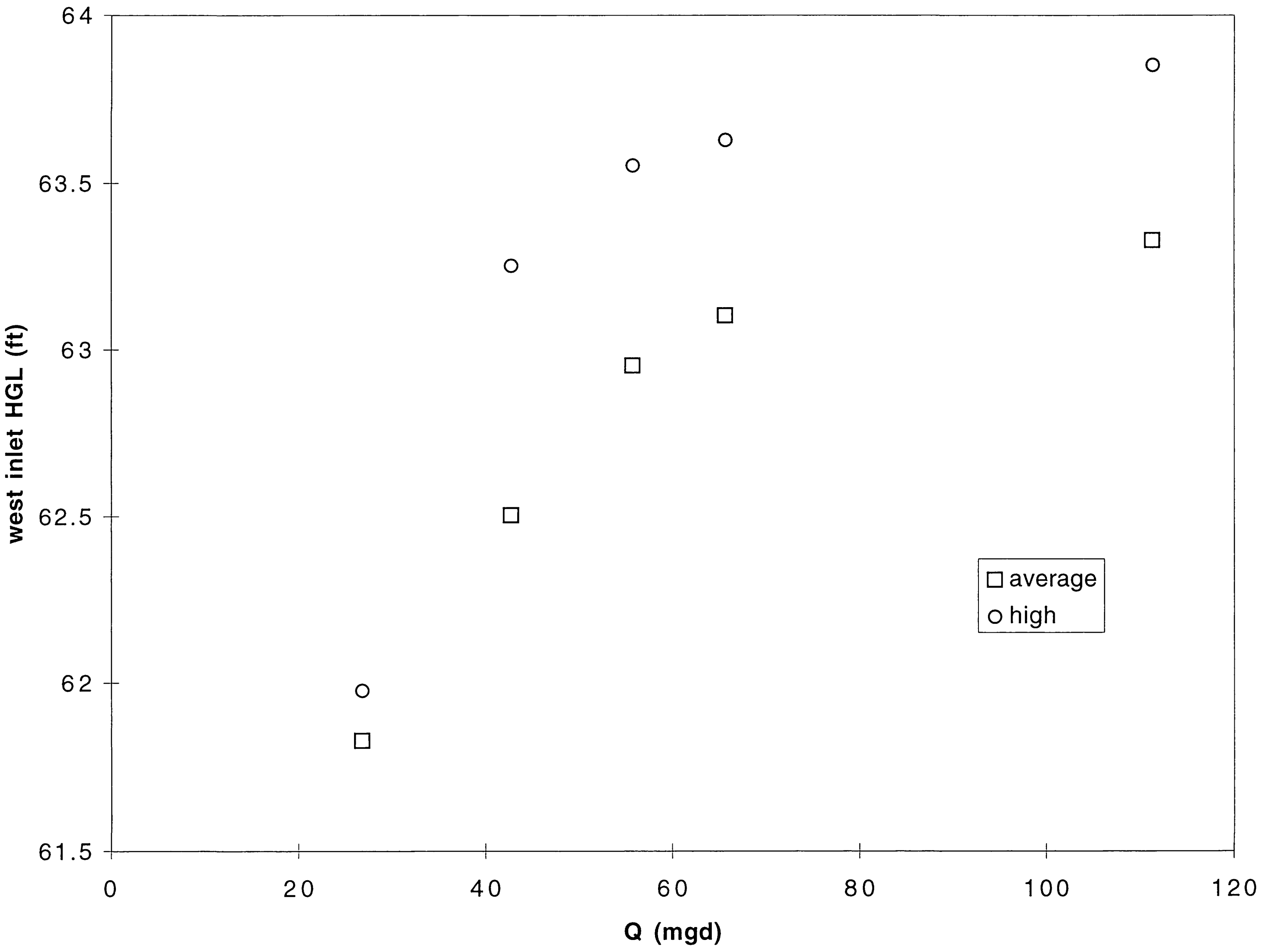


Figure 13. HGL difference between east inlet and wet well as a function of flow rate (submerged conditions within drop shaft).

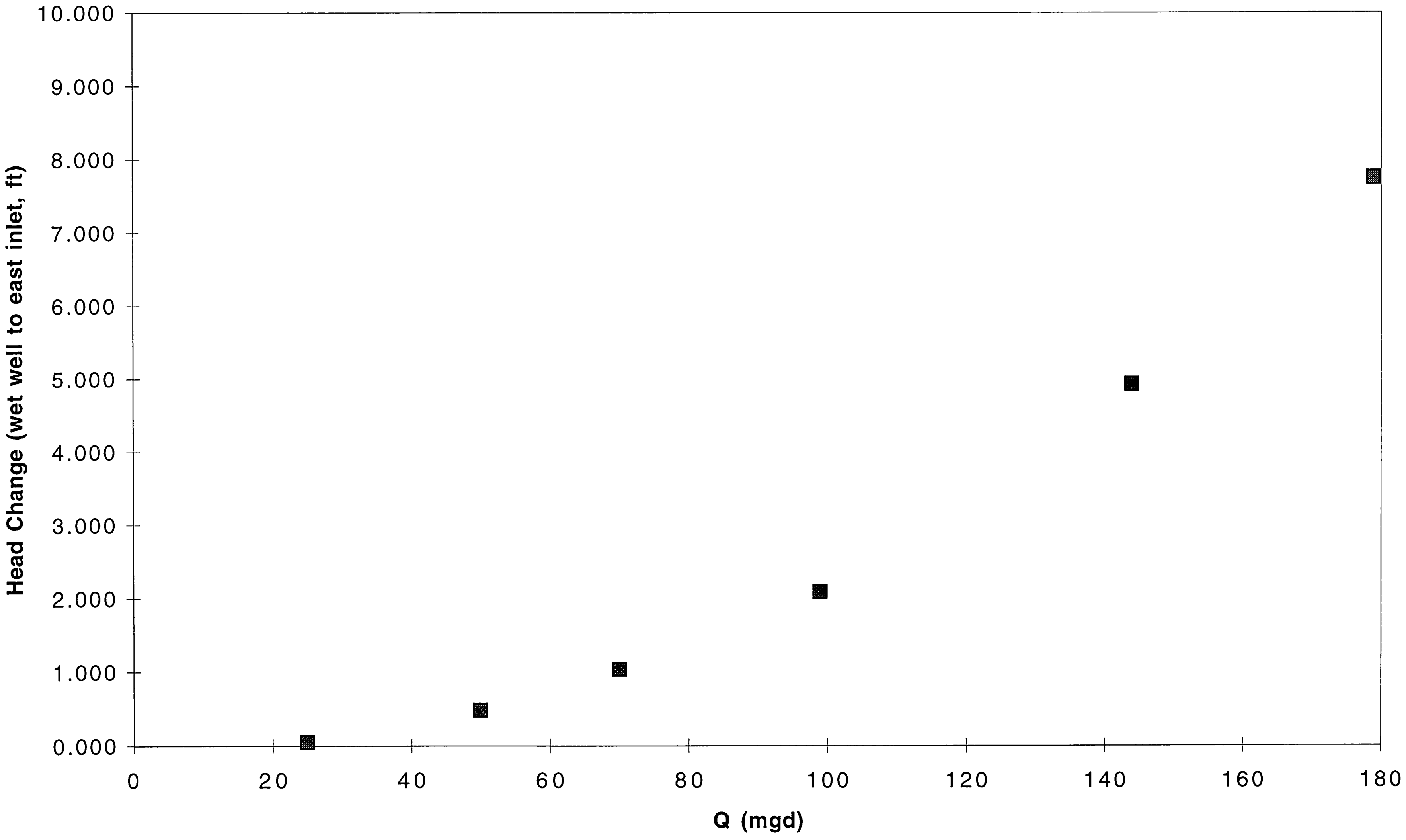


Figure 14. HGL difference between west inlet and wet well as a function of flow rate (submerged conditions within dropshaft).

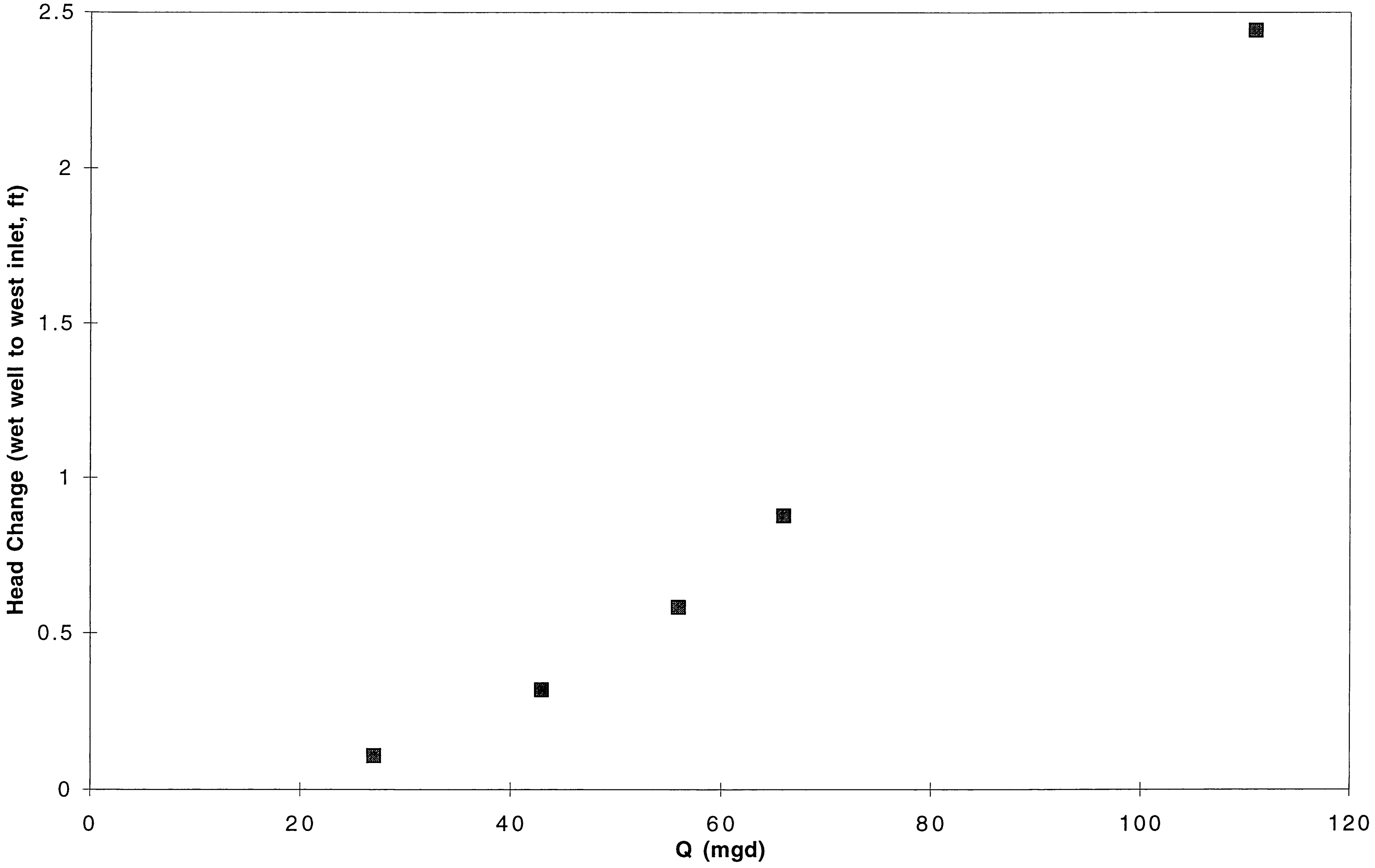


Figure 15. Wet well HGL elevations associated with air entrainment in east inlet drop shaft

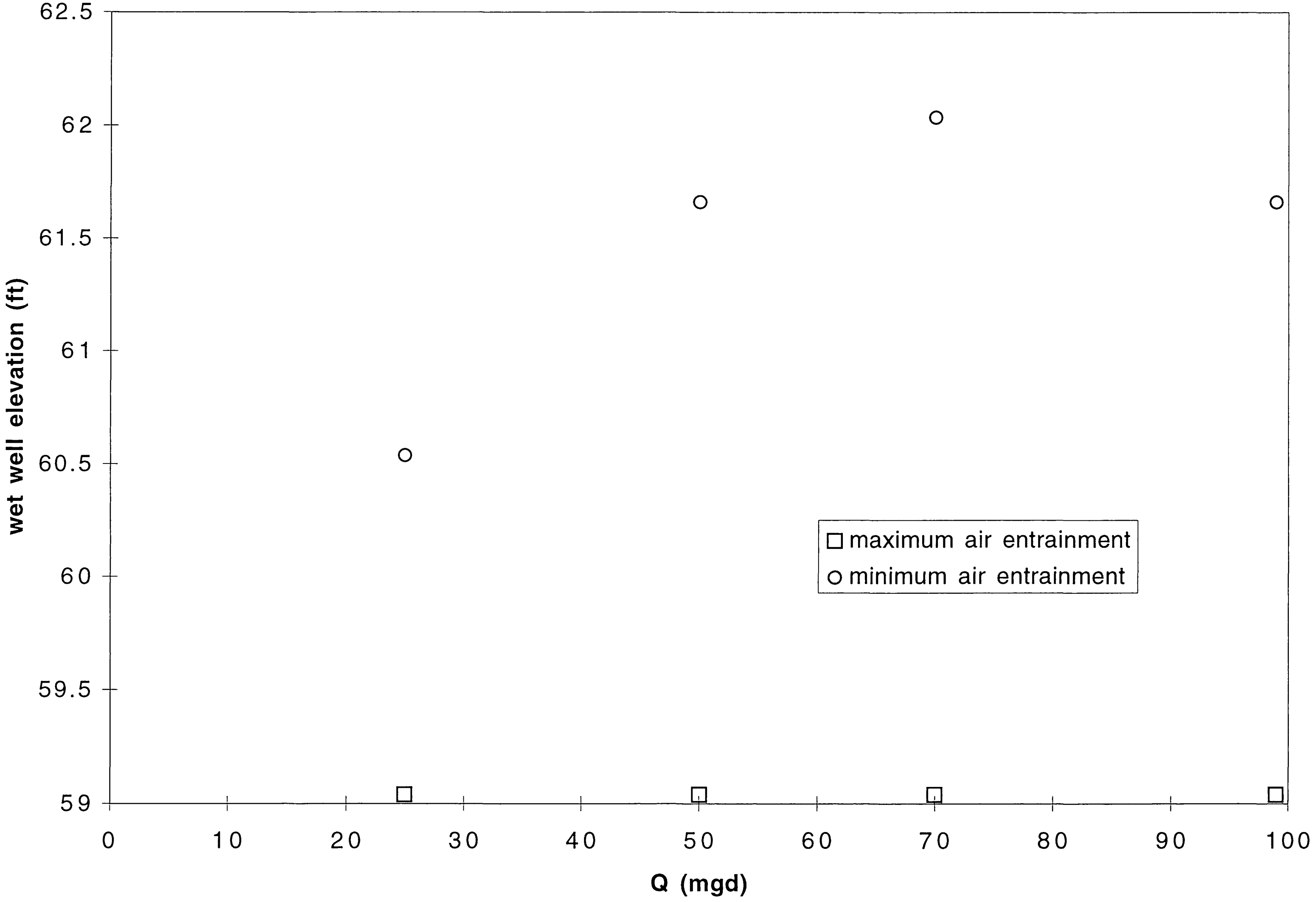
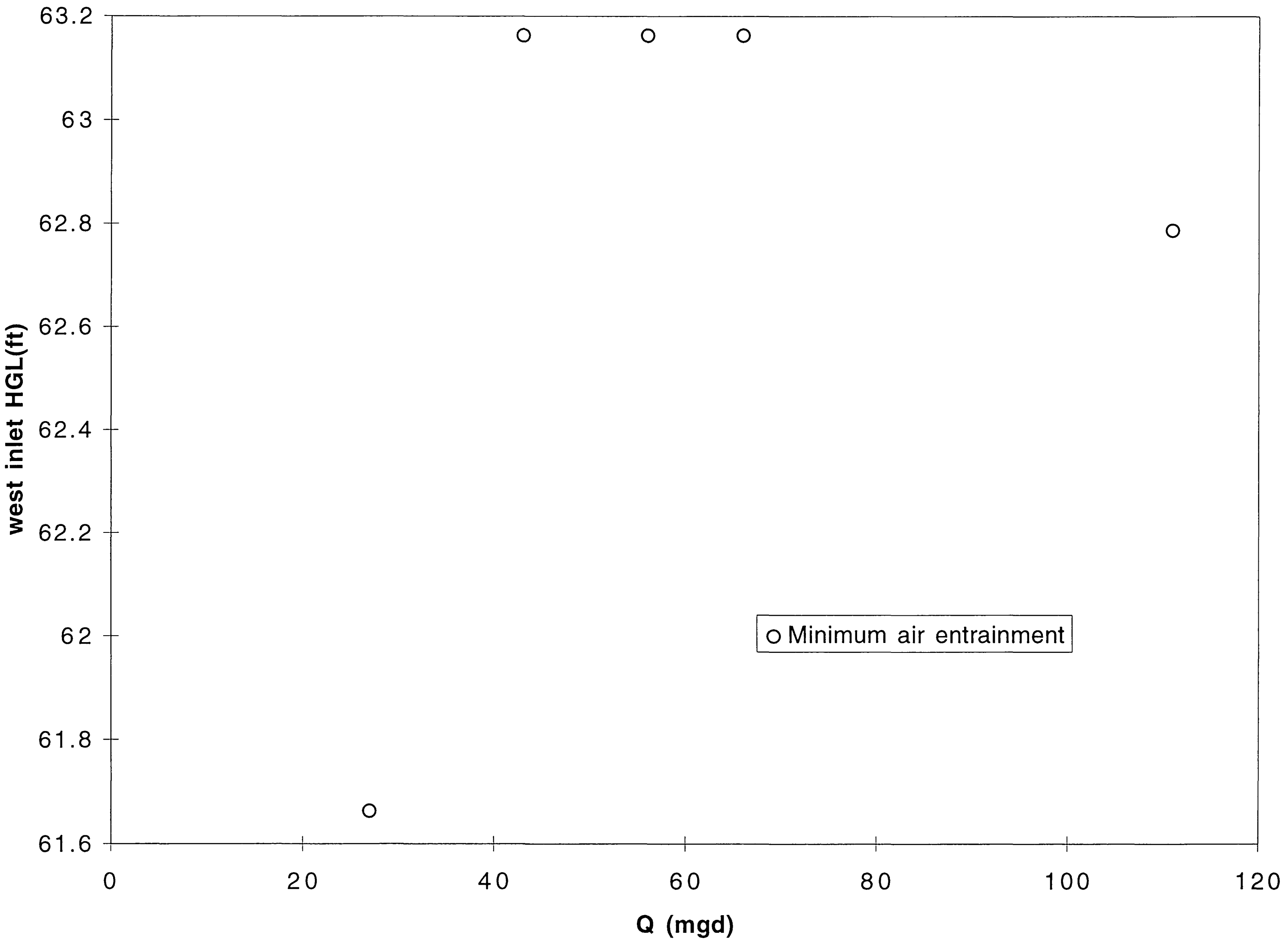


Figure 16. Wet well HGL elevations associated with air entrainment in west inlet drop shaft



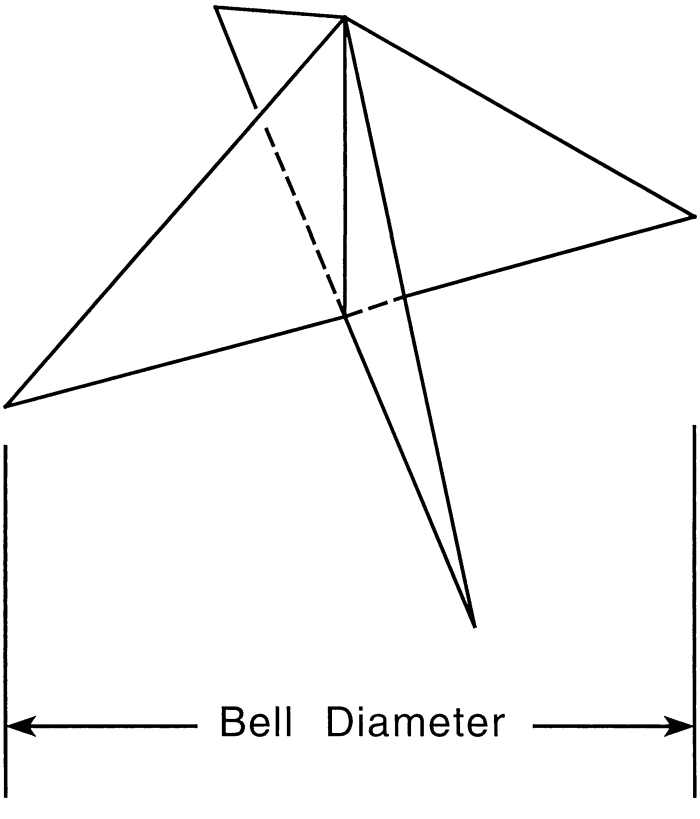


Figure 17. Typical Configuration for Cone Placed Under Pump Bell.

APPENDIX

Basic Data

Table A-1. Head Losses in East Drop Shaft and Inlet pipe.

Q (gpm)	Measured loss	Adjusted loss(ft)	
176909	20.2	16.5	
162397	14.5	11.8	
136828	11.4	9.3	
122316	8.3	6.8	
122316	8.9	7.3	
99511	5.6	4.6	
80853	3.4	2.8	
62195	1.9	1.5	
44227	1.1	0.9	
33170	0.5	0.4	
23150	0.3	0.3	
76016	3.2	2.6	
72560	3.3	2.7	
72560	3.7	3.0	
111950	6.7	5.5	
134755	10.0	8.2	
171380	16.3	13.3	

Table A-2. Head Losses in West Drop Shaft and Inlet pipe.

Q (gpm)	Measured loss	Adjusted loss(ft)	
17490	0.2	0.1	
30130	0.4	0.3	
44704	1.1	0.9	
80438	3.7	3.1	
97991	5.0	4.1	
138970	9.3	7.6	
158527	13.1	10.7	
188173	16.9	13.8	

Table A-3. Variation of East Inlet Hydraulic Gradeline
with Wet Well Hydraulic Gradeline.

Q = 25 mgd			Q = 50 mgd			Q = 70 mgd	
Wet Well HGL	Inlet HGL (ft)		Wet Well HGL	Inlet HGL (ft)		Wet Well HGL	Inlet HGL (ft)
59.41	62.47		59.50	63.41		59.68	63.94
59.83	62.45		60.59	63.41		60.07	63.93
60.43	62.45		60.88	63.40		60.64	63.96
60.79	62.46		61.25	63.40		61.09	63.94
61.07	62.46		61.63	63.40		61.55	63.99
61.44	62.46		62.07	63.40		61.95	64.04
61.81	62.46		62.43	63.46		62.41	64.09
62.21	62.62		62.83	63.64		62.90	64.33
62.62	62.92		63.19	63.91		63.40	64.75
63.07	63.27		63.61	64.24		63.98	65.18
63.51	63.66		64.06	64.63		64.59	65.90
63.95	64.08		64.57	65.14		65.15	66.44
64.42	64.48		65.35	65.89		65.73	67.08
64.96	65.01						
65.47	65.63						
66.06	66.11						
Q = 99 mgd			Q = 144 mgd			Q = 179 mgd	
Wet Well HGL	Inlet HGL (ft)		Wet Well HGL	Inlet HGL (ft)		Wet Well HGL	Inlet HGL (ft)
59.53	64.63		56.79	64.90		56.69	65.81
60.06	64.63		57.85	64.91		57.12	66.34
60.61	64.63		58.32	64.96		57.58	67.26
60.91	64.67		59.27	65.24		54.60	65.14
61.27	64.72		59.75	65.65		55.31	65.14
61.75	64.80		60.34	66.46		55.64	65.22
62.44	65.09		60.57	66.52		55.92	65.33
63.03	65.62		60.94	66.93		56.24	65.45
63.44	66.07		61.45	67.39		56.49	65.50
63.99	66.49					56.99	66.09
64.59	67.03						

Table A-4. Variation of West Inlet Hydraulic Gradeline with Wet Well Hydraulic Gradeline.

Q = 27 mgd			Q = 43 mgd			Q = 56 mgd	
Wet Well HGL	Inlet HGL (ft)		Wet Well HGL	Inlet HGL (ft)		Wet Well HGL	Inlet HGL (ft)
59.36	61.73		59.96	62.20		59.71	62.63
59.81	61.73		60.70	62.20		60.07	62.63
60.13	61.73		61.12	62.33		60.59	62.65
60.43	61.73		61.52	62.50		61.02	62.65
60.84	61.73		61.88	62.69		61.48	62.69
61.18	61.73		62.32	62.95		61.99	63.00
61.76	61.94		62.61	63.19		62.32	63.24
61.98	62.14		62.99	63.46		62.66	63.47
62.24	62.39		63.51	63.88		63.13	63.88
62.54	62.69		64.12	64.38		63.54	64.26
						64.05	64.63
Q =66 mgd			Q = 111 mgd				
Wet Well HGL	Inlet HGL (ft)		Wet Well HGL	Inlet HGL (ft)			
59.40	62.92		59.71	63.19			
59.87	62.92		60.26	63.55			
60.60	62.95		60.74	63.84			
61.21	62.98		61.19	64.15			
61.58	63.05		61.36	64.42			
61.99	63.26		61.81	64.75			
62.38	63.52		62.27	65.16			
62.80	63.88		62.77	65.69			
63.22	64.17		59.16	63.06			
			59.62	63.10			
			58.76	63.06			

Table A-5. Hydraulic Grade Line and Other Data

East Inlet

	Transition HGL (ft)			Head Change, wet well to inle	
Q (mgd)	Average	High		Measured	Adjusted
25	62.8	63.5		0.101	0.051
50	63.6	64.2		0.579	0.479
70	64.2	64.7		1.288	1.038
99	63.6	64.2		2.541	2.091
144	65.4	65.6		5.981	4.931
179	65.4	65.6		9.263	7.753

West Inlet

	Transition HGL (ft)			Head Change, wet well to inle	
Q (mgd)	Average	High		Measured	Adjusted
27	61.8	62.0		0.15	0.11
43	62.5	63.3		0.41	0.32
56	63.0	63.6		0.70	0.58
66	63.1	63.6		1.10	0.88
111	63.3	63.9		2.94	2.44

Fig. A-1 - east inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=25 mgd

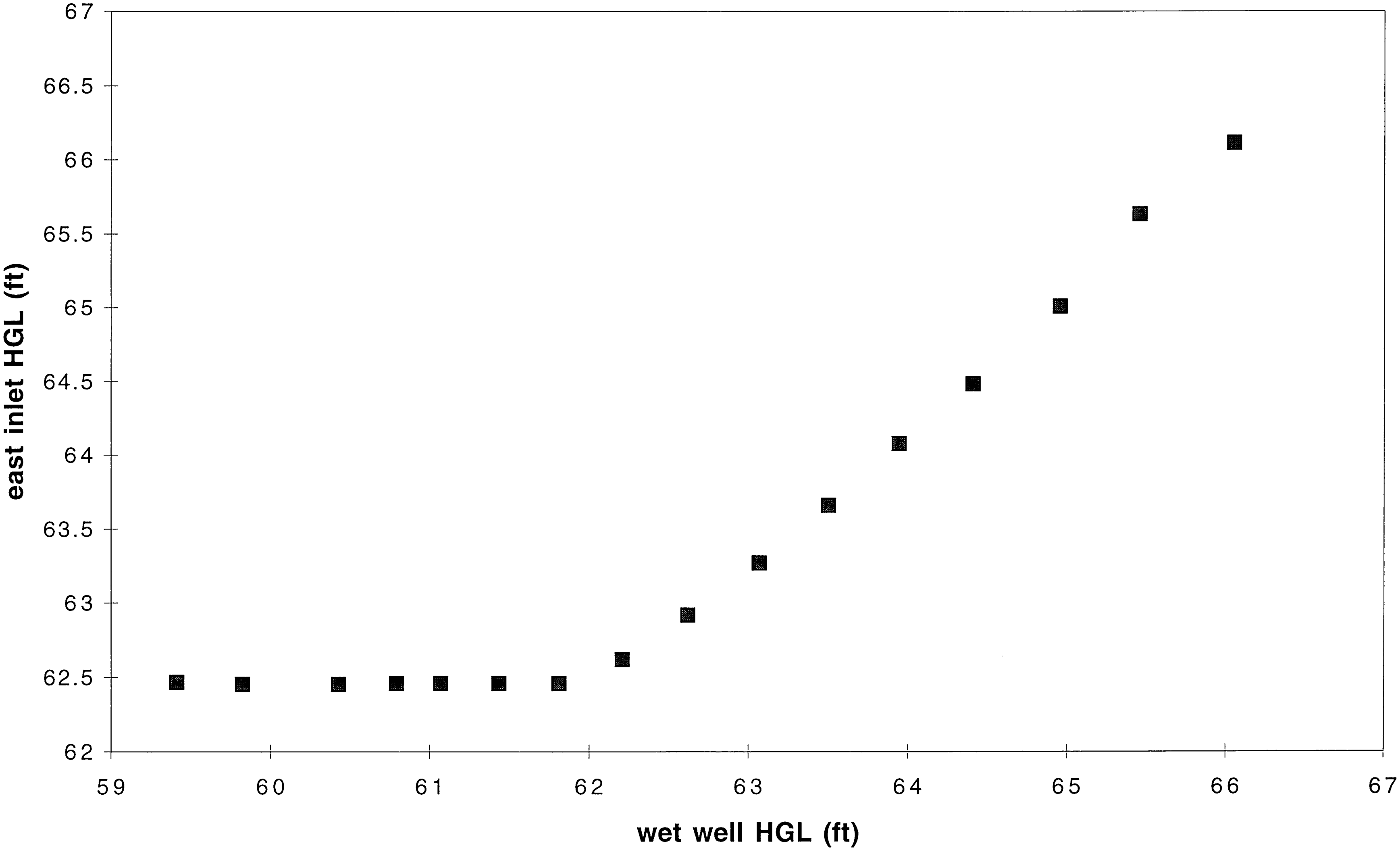


Fig. A-2 - east inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=50 mgd

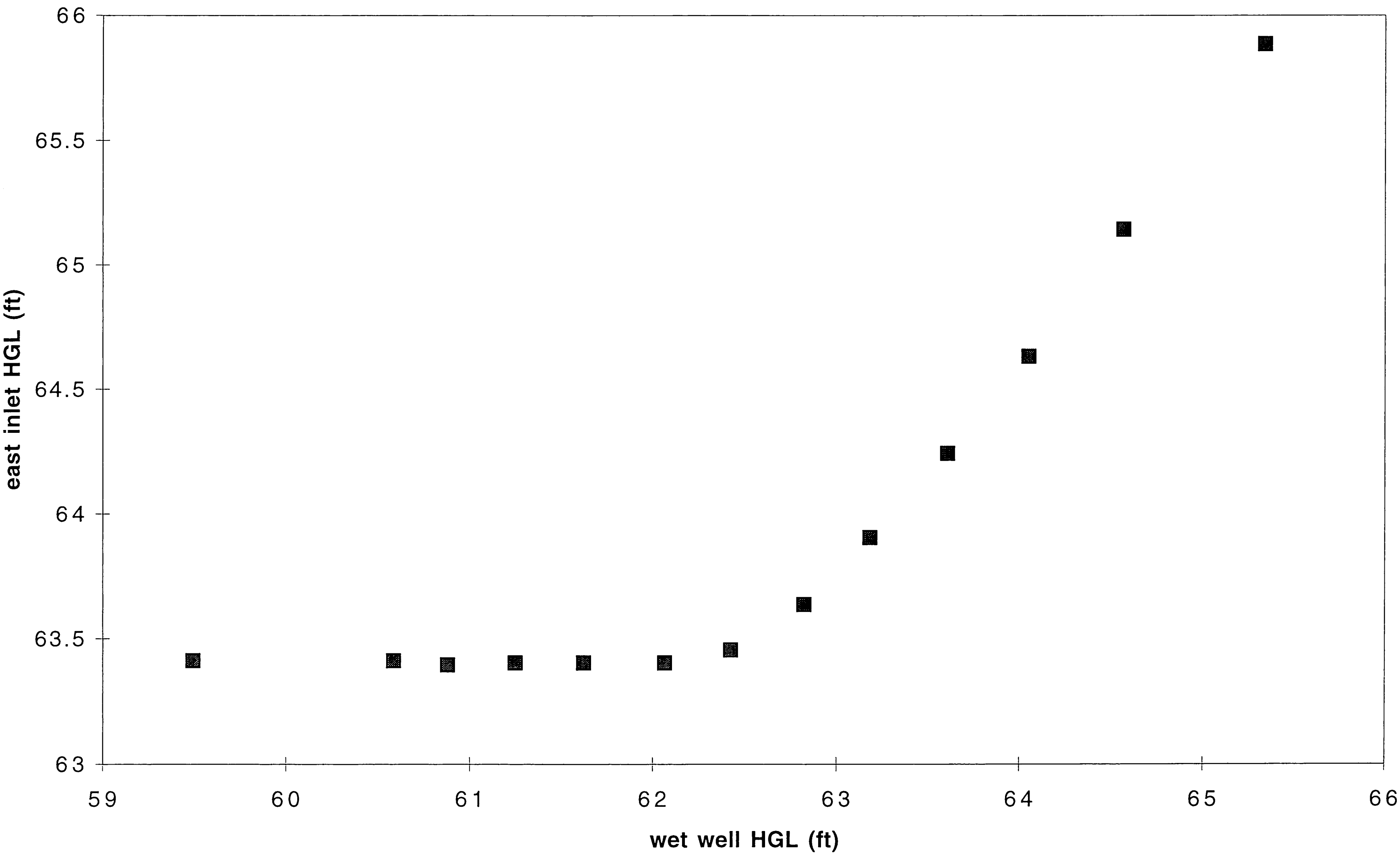


Fig. A-3 - east inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=70 mgd

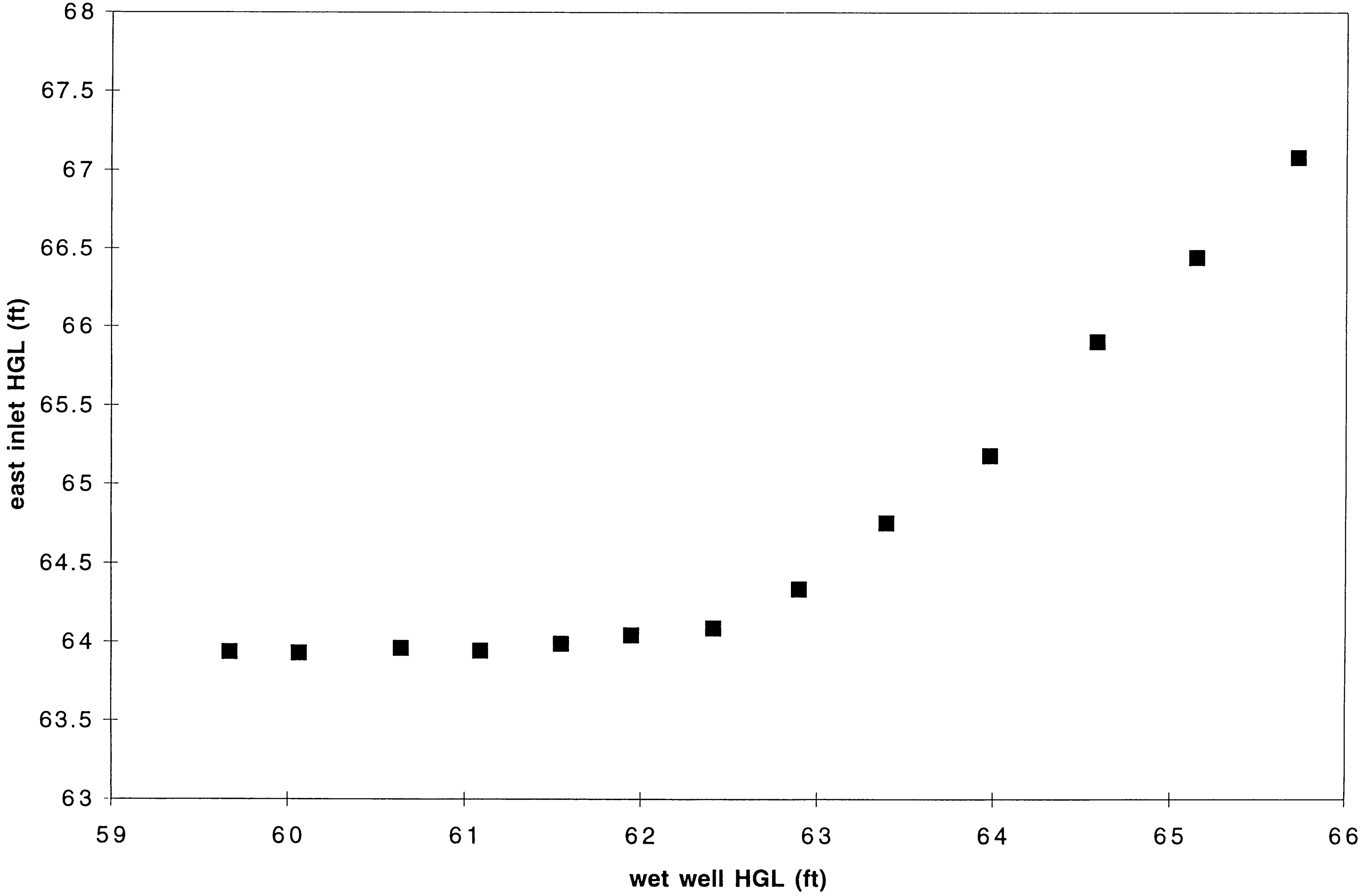


Fig. A-4 - east inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=99 mgd

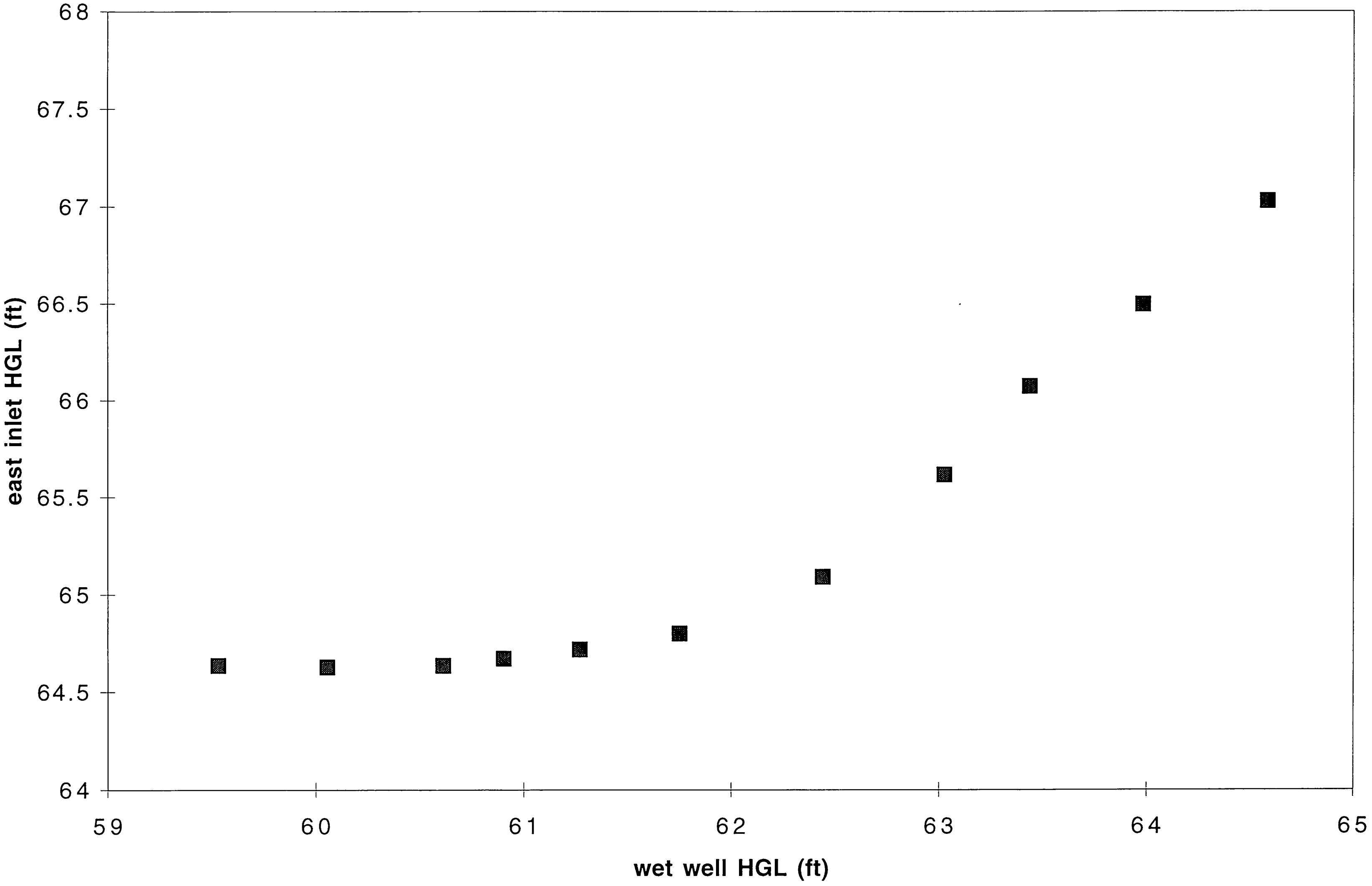


Fig. A-5 - east inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=144 mgd

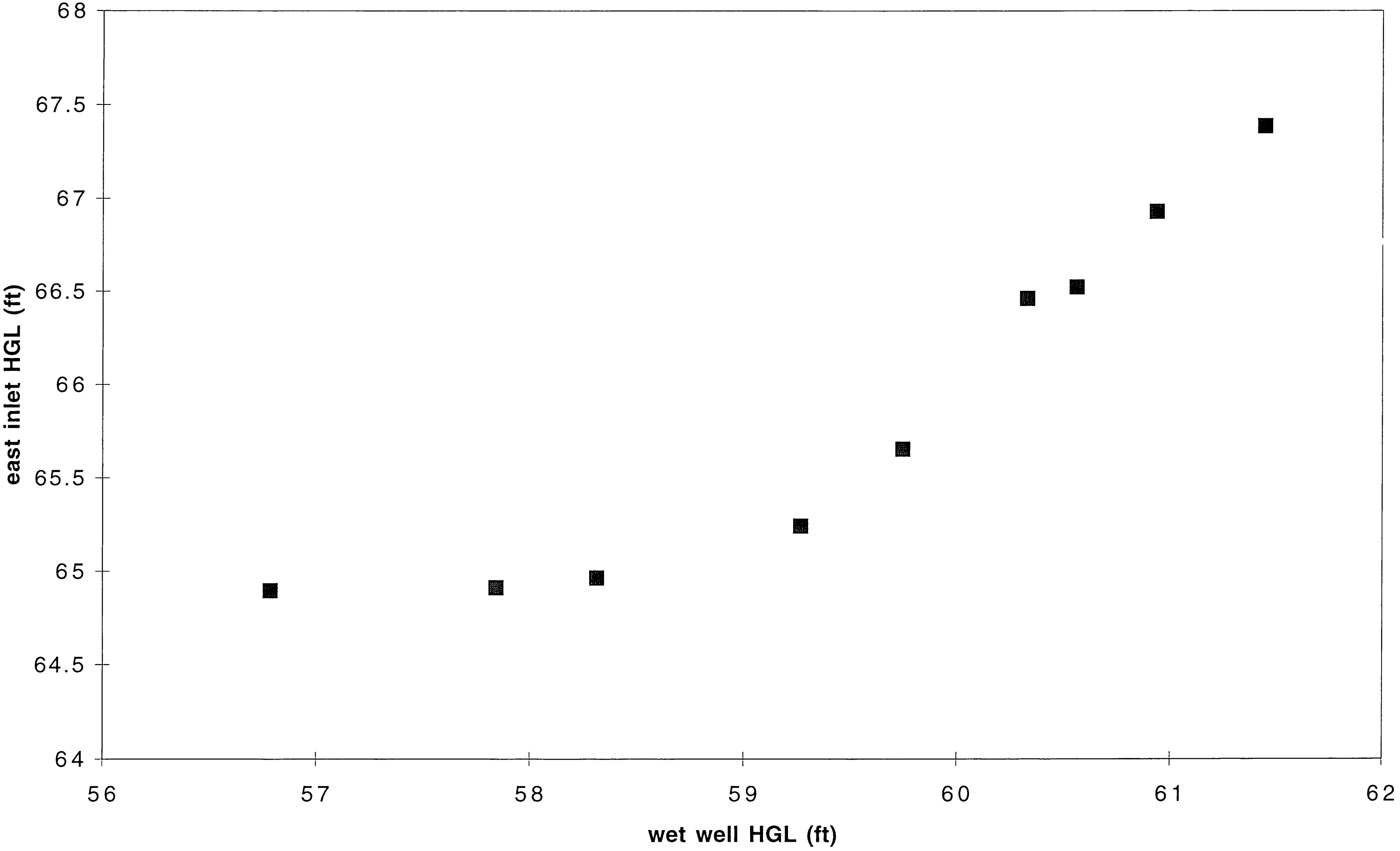


Fig. A-6 - east inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=179 mgd

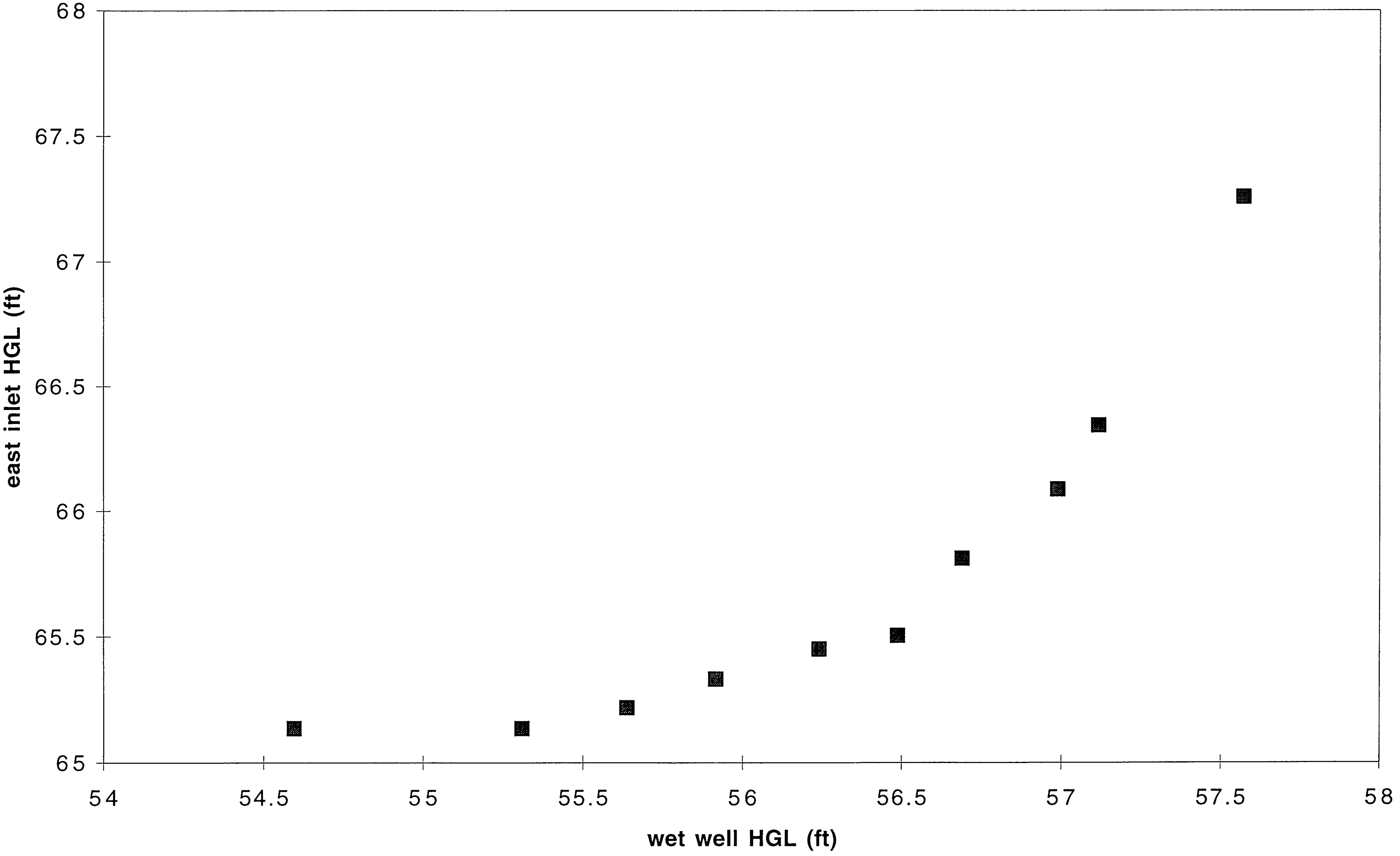


Fig. A-7 - West inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=27 mgd

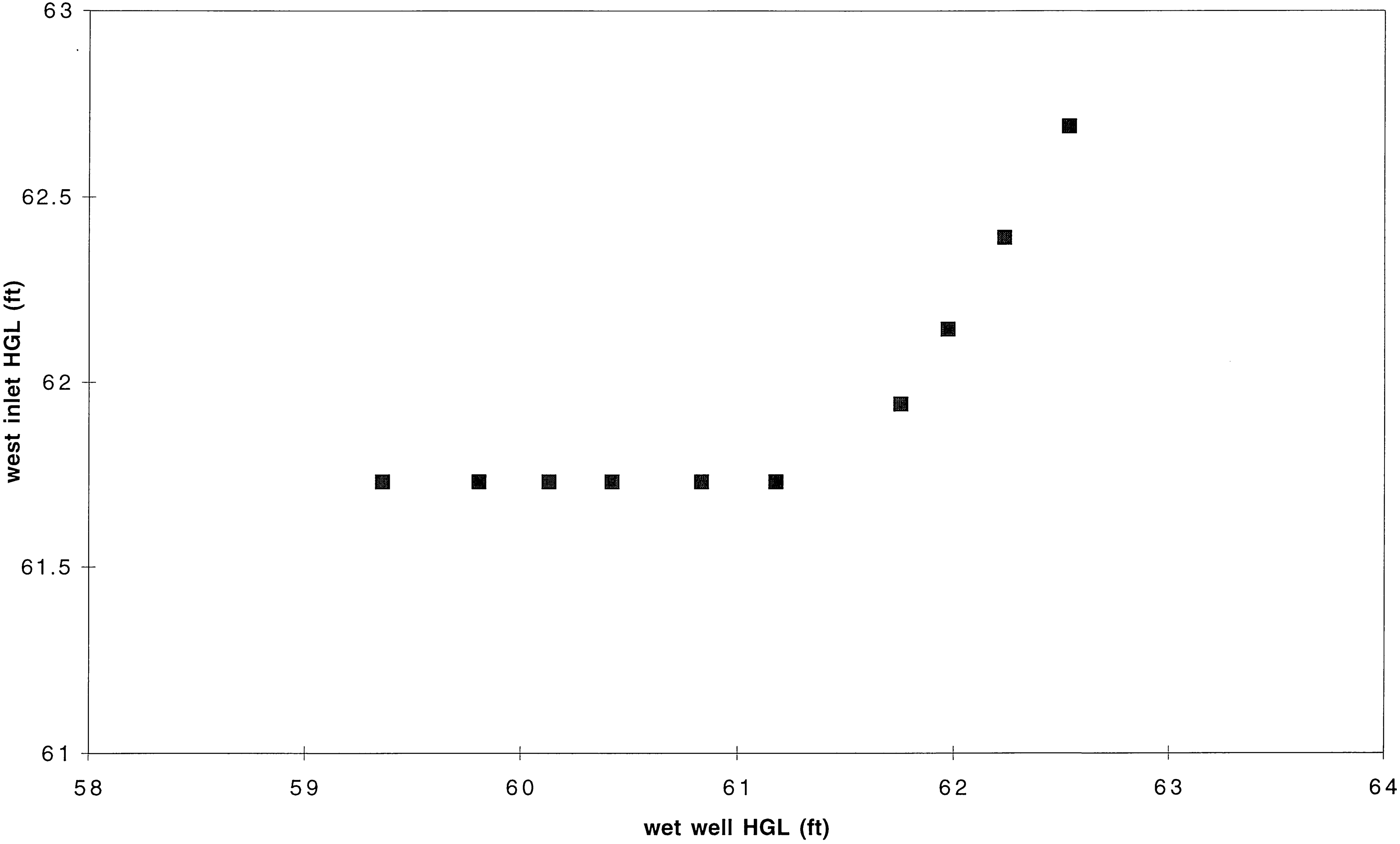


Fig. A-8 - West inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=43 mgd

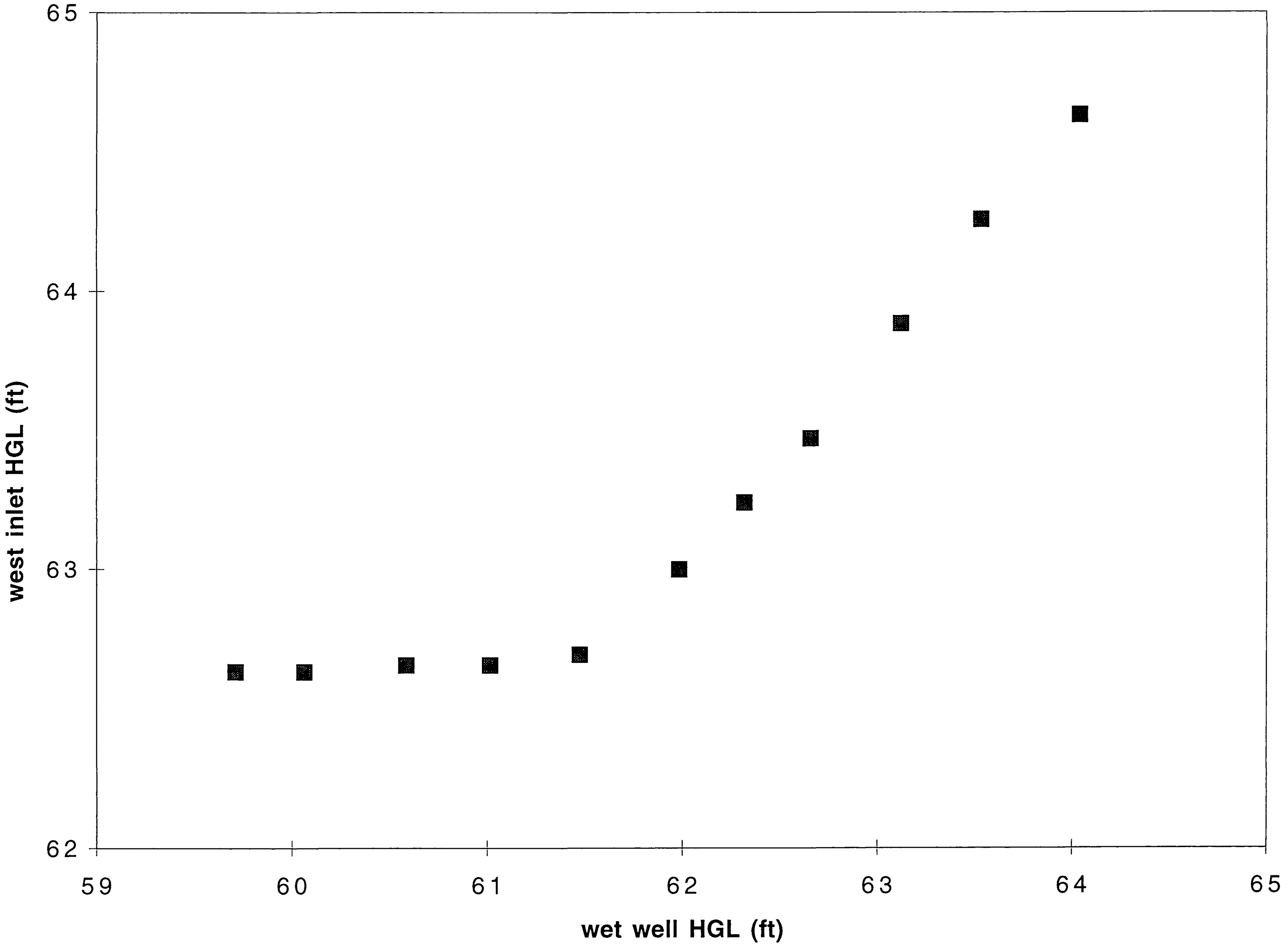


Fig. A-9 - West inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=56 mgd

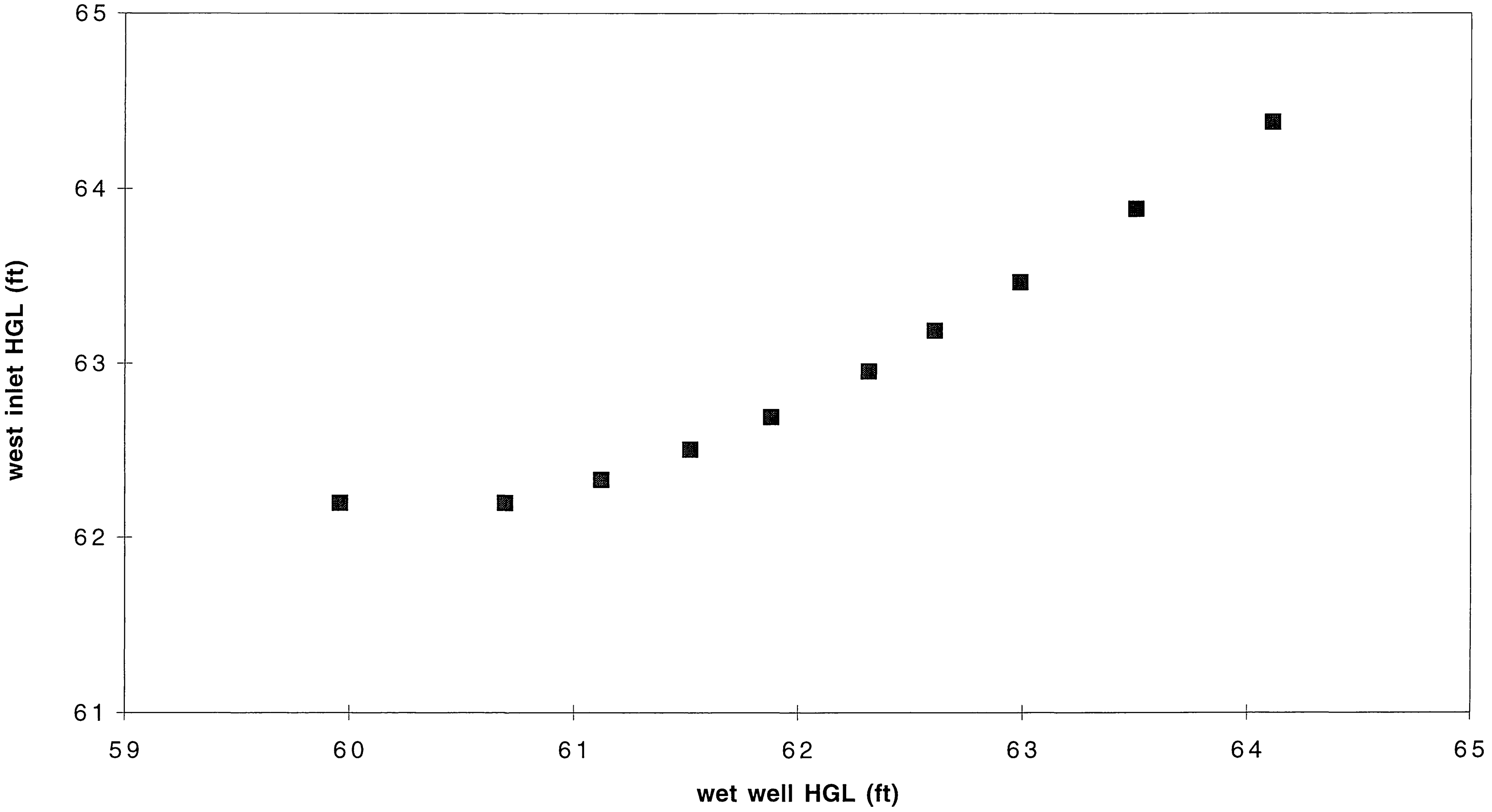


Fig. A-10 - West inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=66 mgd

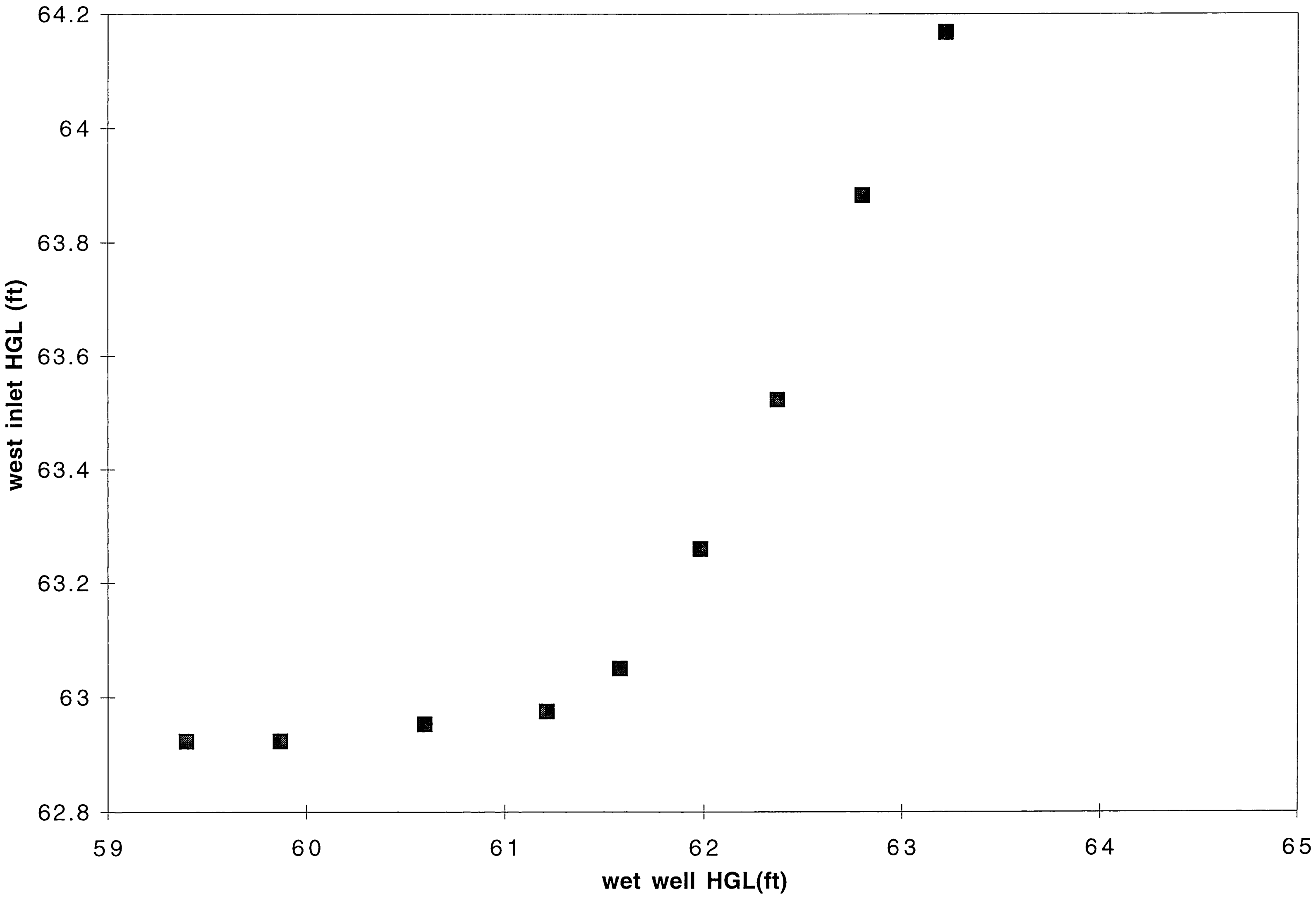
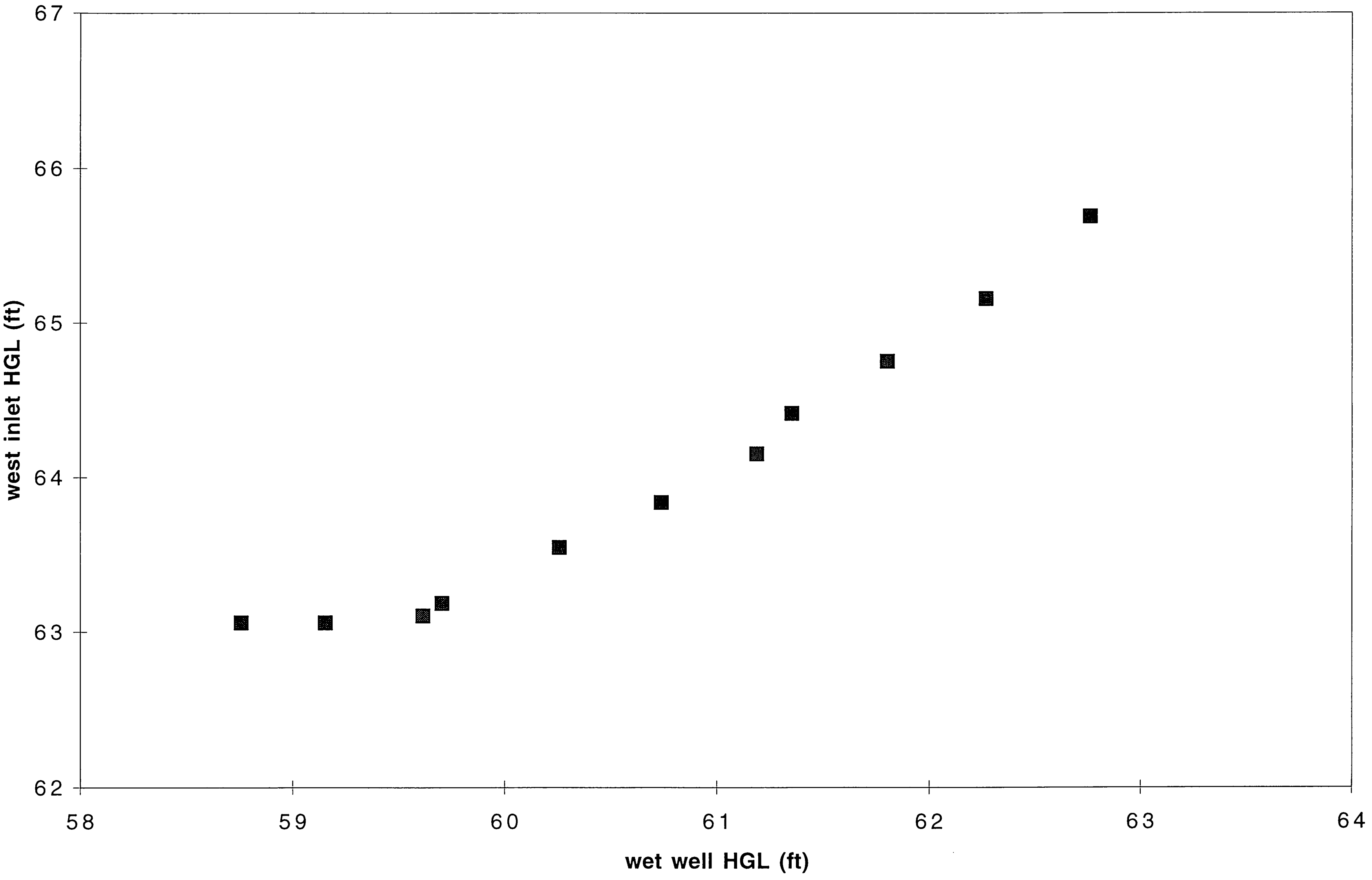


Fig. A-11 - West inlet hydraulic grade line (HGL) as a function of wet well HGL, Q=111 mgd



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AIIM SCANNER TEST CHART # 2

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Greek and Math Symbols

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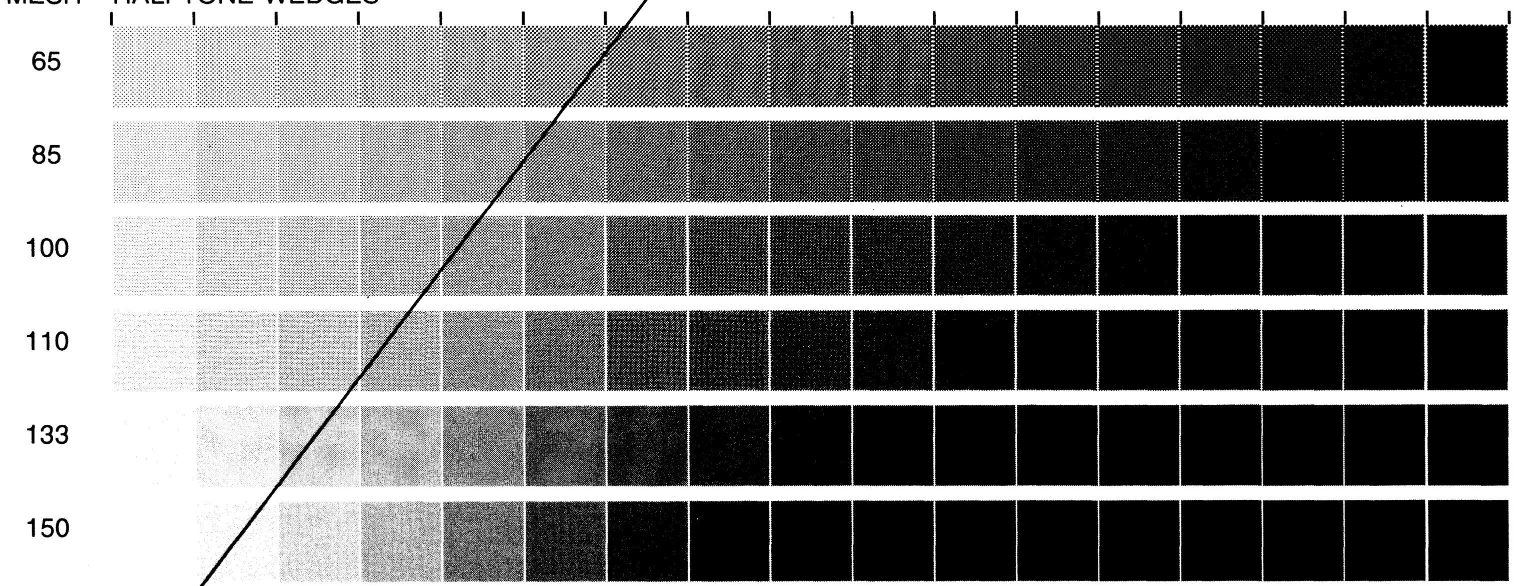

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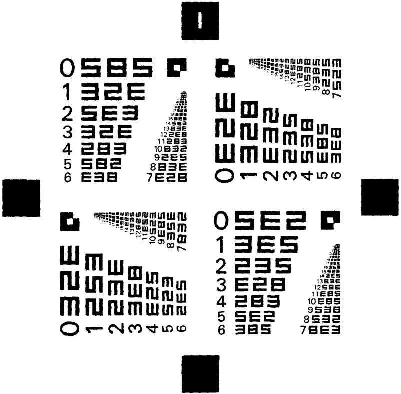
RIT ALPHANUMERIC RESOLUTION TEST OBJECT, RT-1-71



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