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**DEVELOPMENT OF DESIGN CRITERIA
FOR SIDESTREAM ELEVATED POOL AERATION STATIONS**

by
Thomas A. Butts

Prepared for and in cooperation with
The Metropolitan Sanitary District of Greater Chicago

September 1988



Illinois Department of Energy and Natural Resources

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INTRODUCTION

The Chicago metropolitan area is located along the headwaters of the Illinois Waterway as shown on figure 1. The Illinois Waterway is special among the many streams and rivers within Illinois: it drains 43 percent of the state and small portions of Wisconsin and Indiana. During dry weather, its headwaters consist principally of treated Chicago area wastewaters diluted with flow diverted from Lake Michigan at the three locations shown on figure 2. The waterway is no longer a free-flowing stream; it consists of eight navigational pools extending over 327 miles between the Mississippi River and Lake Michigan (figure 1).

Chicago-area treated wastewater flows are derived from approximately 5.1 million people and a large, mixed industrial base. The Metropolitan Sanitary District of Greater Chicago (MSD) operates treatment facilities that discharge an average of 1400 million gallons per day of secondary and tertiary treated sewage into 70.5 miles of constructed channels and "improved" natural water courses, as shown in figure 2.

Historical Perspective

Prior to 1900 most Chicago-area wastes were discharged to Lake Michigan via either the Chicago River or the Calumet River systems, which are shown on figure 2. In 1871, a deep cut was made between the Chicago River and the Illinois and Michigan (I & M) Canal as a means of flushing a significant portion of the wastes down the canal and eventually to the Illinois River at LaSalle-Peru, where the canal intersects the river. In most respects, this attempt to relieve the Chicago area of unsanitary water conditions was unsuccessful. Consequently, plans were soon formulated to dig what was to become known as the Chicago Sanitary and Ship Canal. This canal was to be bigger, deeper, and more hydraulically efficient than the old I & M canal. It was eventually completed, and on January 17, 1900, the first Lake Michigan water was released into the high-capacity Sanitary and Ship Canal.

The Sanitary and Ship Canal is designed to handle a maximum flow of 10,000 cfs. However, in 1913, the United States filed the first of a long succession of suits designed to limit total diversion well below this. This suit requested a diversion limitation of 4167 cfs, and a U.S. Supreme Court decision was rendered in 1925 upholding this request. This constraint prompted the MSD to eventually construct three major treatment facilities to prevent downstream water quality deterioration. The locations of these plants are shown on figure 2.

Since 1925, through legal suits and subsequent court decisions, several changes have occurred in the amount of diversion allowed and the way it is to be administered and controlled. In 1930, the annual average diversion was set at 1500 cfs exclusive of municipal water supply needs. Between

January 31, 1957, and June 12, 1967, flows up to 8500 cfs were allowed. However, after June 12, 1967, total diversion was limited to 3200 cfs on an average annual basis, with a 5-year accounting period used. Present policy dictates that:

- 1) The regulation of discretionary diversion (direct wastewater dilution needs) and stormwater runoff flow is the responsibility of the Illinois Department of Transportation, Division of Water Resources (DWR). Prior to 1967, the MSD was responsible for regulating these activities.
- 2) A 40-year accounting period is to be used for computing the 3200 cfs average annual diversion, as opposed to the previously set 5-year period.
- 3) Discretionary diversion is set at a maximum of 320 cfs on an average annual basis.
- 4) The accounting year runs from October through September. Previously it ran from March through February. The new period coincides with the U.S. Geological Survey standard "water year."

DWR encourages municipalities and subdivisions to fully utilize the flexibility of the 40-year averaging period. Diversion for navigation-related operations is limited to 255 cfs, including 130 cfs (40-year period) for lockages, 30 cfs (40-year period) for lock leakages, and 95 cfs (5-year period) for navigational makeup. The 320 cfs direct discretionary diversion allotment that is presently being used for water quality enhancement during summer months is scheduled to be reduced to 101 cfs on October 1, 2000. By this date, Phase I of the MSD Tunnel and Reservoir Project (TARP) and instream aeration projects are projected to be completed and will provide improvements in water quality.

Future Considerations

The MSD treatment plants are well operated and produce good effluents. Butts et al. (1983) conducted a computer model study of the effects of effluents from the three major plants (figure 2) on downstream dissolved oxygen (DO) and ammonia concentrations. The results showed that upgrading of only the Calumet treatment plant is warranted, and that if this were to be done, only modest improvements in downstream DOs would be realized during dry, warm-weather conditions.

The minimum DO standard set for the Chicago-area watercourses shown in figure 2 is 4.0 mg/l (Illinois Pollution Control Board, 1986). This is probably an unrealistically high standard for present application in that waterway physical characteristics limit the assimilation of even low levels of oxygen-consuming wastes. During low flows, long residence times occur, allowing much dissolved oxygen to be used or depleted through the stabilization of dissolved biochemical oxygen demand (BOD) and sediment oxygen demand (SOD). The deep, slow-moving water facilitates sediment deposition and the creation of very high SODs. Discretionary diversion from Lake Michigan during critical low-flow periods helps reduce the severity of the DO depletion somewhat since high-DO water is introduced into the system and detention times are reduced. However, several reaches, particularly

along the Calumet Sag Canal and the Sanitary and Ship Canal, periodically exhibit DO concentrations below 2.0 mg/l.

To help alleviate these severe DO depletions, the MSD presented testimony to the Illinois Pollution Control Board (IPCB) in the early 1970s regarding the use of instream aeration in conjunction with wastewater treatment. The IPCB accepted the MSD's proposal, and two instream aeration stations were constructed in 1979 and 1980. These two stations are located at Devon and Webster Avenues on the North Shore Channel (figure 2) and use compressed air, distributed via bottom diffusers, to transfer oxygen to the water column during critical periods.

Construction costs along with routine operation and maintenance costs associated with the establishment and running of these stations have been higher than anticipated. However, the results achieved from the two operating systems indicate that significant localized improvements in DO can be realized by using some form of instream aeration. Consequently, the instream aeration concept need not and should not be abandoned. The use of sidestream elevated pool aeration stations has been included in recently proposed regulatory changes now before the IPCB. These changes involve revising the effluent standards relative to the MSD's three major treatment facilities, upgrading two sections of waterway to a "General Use" designation, and revising the waterway DO standard in the Cal-Sag Channel from 4.0 mg/l to 3.0 mg/l.

On the basis of the criteria established by these proposed regulatory changes, a system of sidestream elevated pool aeration (SEPA) stations has been proposed as an alternative to the previously constructed compressed air systems. This system will allow low-DO water to be withdrawn from the waterway by means of spiral pumps. The water will be routed through an elevated pool and passed over a weir or series of weirs to be aerated before being routed back to the waterway downstream of the intake point. The concept, as originally envisioned, is presented in figures 3 and 4. The DO concentration of the sidestream will be raised sufficiently to provide an overall DO concentration of 3.0 mg/l or higher in the receiving stream. The SEPA stations will operate only during critical periods when the DO concentrations in the waterway fall below 3.0 mg/l.

Computer model studies conducted by the MSD, which have simulated DO conditions throughout the waterway system, indicate that SEPA stations are needed at five critical locations along the Cal-Sag Channel (figure 5). Each station will have the capability of withdrawing approximately 50% of the total flow from the waterway.

Study Objectives and Scope

The artificial reaeration of large streams through use of the SEPA concept has never been attempted before. Even design criteria for the reaeration of wastewater effluents and small streams based on weir aeration concepts are limited. Additionally, some of the limited published information is misleading and/or incorrect, and if not properly screened and/or utilized, it could provide unexpectedly poor results in the final analysis of any major large-scale SEPA-like project.

The Water Quality Section (WQS) of the Illinois State Water Survey (ISWS) has performed numerous weir and spillway aeration studies during the last decade. These studies have involved both controlled and uncontrolled field studies and controlled laboratory studies. Much practical information has been gleaned from this work. A good understanding of basic weir-aeration theory has been achieved, and concepts have evolved that can be helpful in designing efficient weir-aeration systems.

The primary purpose of this endeavor was to perform a full-scale, on-site weir aeration pilot study to verify selected design criteria previously established by the ISWS and others. The verified data were to be used to develop practical engineering design procedures and equations for use in designing economical and efficient SEPA stations.

Specific input by the WQS of ISWS consisted of:

1. Designing the weir system to be studied. Schematic diagrams of the basic designs to be evaluated were provided.
2. Providing information on desirable sampling methods and sampling frequencies, based on data generated during previous WQS weir-aeration studies.
3. Providing computer services for data storage, data reduction, and data analyses. The WQS has developed efficient computer programs designed specifically for handling the type and magnitude of data generated during this study.
4. Disseminating data and information to the MSP on a timely basis so they could proceed with preliminary and final SEPA station design. This report constitutes a formalization of previously disseminated data and information.

The MSD was responsible for developing detailed construction plans of the full-scale weir and for constructing it on-site. MSD personnel conducted the daily experiments and periodically sent the results to the WQS laboratory in Peoria for review and comments. ISWS personnel inspected the weir setup before the initial startup and once during an actual experimental run.

Acknowledgments

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Special recognition is given to Bernard Sawyer and Gilbert Elenbogen of MSD's Research and Development Laboratory, who made the study possible through their careful supervision of the daily experimental runs. Their dedication to the project was exemplary.

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WEIR AERATION THEORY AND CONCEPTS

The fact that aeration occurs at weirs, dams, spillways, and waterfalls is readily apparent as evidenced by the white-water turbulence that normally appears below such structures. However, the mechanism by which this aeration occurs has never been clearly or fully defined, especially in terms of practical engineering design concepts and parameters.

Basic Concepts

Gameson (1957), in some original weir and dam aeration work, proposed the use of an equation involving both theoretical and rational concepts that relate water fall height, water temperature, structural geometry, and water quality to a factor defined as the deficit ratio, r . The definition of r is:

$$r = (C_S - C_A) / (C_S - C_B) \quad (1)$$

where C_g is the DO saturation concentration at a given temperature and C_A and C_B are, respectively, the DO concentrations above and below the dam or flow-release structure.

Although equation 1 is simple, it serves to illustrate two principles important to dam aeration concepts. First, it demonstrates that the upstream DO concentration dictates the rate of oxygen exchange at any weir or dam. Second, for a given set of water and temperature conditions, higher ratios reflect higher aeration efficiencies. Relative to the first concept, Gameson (1957) and Gameson et al. (1958) found in laboratory experiments that the ratio is independent of above-dam DO concentrations of $C_g + 10$ mg/l. However, data collected by Barrett et al. (1960) indicate that this independence may be reduced to $C_g \pm 4$ mg/l for full-sized field structures.

The original dam aeration formula (Gameson, 1957; Gameson et al., 1958) relating temperature, water quality, dam cross-sectional design, and differential water levels to the deficit ratio has been modified and refined and appears in the following form (Water Research Centre, 1973):

$$r = 1 + 0.38 abh (1 - 0.11h)(1 + 0.046T) \quad (2)$$

where a is the water quality factor; b is the weir, spillway, or gate coefficient; h is the static head loss at the dam (i.e., upstream and

downstream water surface elevation difference) in meters; and T is the water temperature in °C.

This equation can be used to model the relative and absolute efficiencies of a weir spillway or flow-release structure by determining specific values of 'b.' Every spillway or gate has a specific coefficient, but generalized categories can be developed in reference to a standard. The standard weir (b = 1.0) is by definition a sharp-crested weir with the flow free-falling into a receiving pool having a depth equal to or greater than $0.1h + 6$ cm. An idealized step weir (a series of sharp-crested weirs) has a b-value of 1.9 (Water Research Centre, 1973); however, actual field-measured values are usually lower.

The formula was developed by British researchers from data collected at many relatively low-head channel dams and weirs transecting small streams. Good reproducibility can be achieved when h does not exceed 3 to 4 meters, the maximum height of the dams at which data collections were made during development of the formula. In addition, close examination of the equation reveals that the factor $(h)(1 - 0.11h)$ mathematically restrains the use of the equation to heights of 4.55 meters or less.

The water quality factor (a) has to be evaluated experimentally in the field or estimated from published criteria. Refinements of Gameson's (1957) early categorization of a-values are: grossly polluted water, a = 0.65; moderately polluted, a = 1.0; slightly polluted, a = 1.6; and clean water, a = 1.8. These values are based on a minimal amount of field and laboratory data. Their direct applications are subjective, and since considerable numerical latitude exists between values, significant errors can result.

Flow Considerations

Conspicuously missing from equation 2 is a flow-related variable. Considerable divergence of opinion currently exists concerning the effect flow rate changes have on weir or dam aeration. Some researchers have concluded that weir aeration is affected very little over a wide range of flows, while others have presented data directly contradicting this.

Barrett et al. (1960) conclude, as a result of numerous field studies of channel dams and weir installations, that the omission of a flow-rate factor in equation 2 does not appear to greatly affect its validity. British researchers (Water Research Centre, 1973) indicate that a 3.5-fold change in flow produced no significant change in "r" for a step-weir in a river. Butts and Evans (1980) concluded that a two-fold range in flow did not affect aeration in small-scale laboratory experiments using a V-notch weir and water falls up to one meter.

In contrast, Apted and Novak (1973) state that, "Contrary to previous thought, the oxygen uptake is seen to be dependent upon the discharge. This is a result of an increase in jet penetration with an increase in discharge (as shown by Hausler [1961])." By plotting flow rates versus deficit ratios, Apted and Novak show that an inverse relationship exists between flow and oxygen uptake. Tebbutt (1972) indicated that the reaeration efficiency of a cascade decreases slightly with increased flow in laboratory-scale experiments.

Several other researchers, according to Nakasone (1987), have shown that aeration efficiency increases with discharge up to a certain point and then decreases with additional increases in discharge. This contention is supported somewhat by field observations reported by Butts and Evans (1978); they concluded that the aeration capacities of channel dams and river spillways are very sensitive to flow. Full-scale installations appear to be most efficient toward the high end of the low-flow spectrum, with efficiencies subsequently dropping off slowly but gradually at flows below and above the optimum. Mastropietro (1968) presents dam reaeration formulas and computational methodologies that incorporate flow as the most important independent variable. Tebbutt et al. (1977) conducted laboratory, step-weir aeration studies and concluded that the main factors controlling reaeration performance are flow per unit width and total fall, with secondary influences being related to individual step height and the overall slope of the step-weir system. Butts and Adkins (1987) expanded upon Butts and Evans' (1980) work using a V-notch free-falling weir. They found that increasing the flow range 10-fold from the previous 2-fold experimental range produced small but statistically significant differences in the reaeration rate as measured by "r." However, for actual field conditions, for which unit flow rates were much higher, Butts and Adkins (1987) found that flow rate ranks only sixth out of a total of 13 independent variables statistically equated to the deficit ratios determined for the flow-release gates at the Starved Rock dam on the Illinois River. Additional experimental work is needed to better define the role flow rate plays in full-scale dam and/or weir aeration efficiencies.

Weir Geometry

Structural configuration (geometric design) of a weir or spillway is a second factor affecting aeration efficiencies that has evoked some contradictory conclusions in the literature. The dam or weir coefficient "b" in equation 2 is an all-inclusive factor taking geometric factors into account. Certain basic weir designs have been clearly established as superior aerators.

Basic Structures

British researchers (Water Research Centre, 1973) have defined a standard weir as a sharp-crested, free-falling weir having a b-value of unity as referenced to equation 2. Spillways and weirs that are not free-falling, such as Ogee spillways and sloping-face structures, usually produce b-values less than 1.0, whereas stepped weirs (as opposed to cascades) produce b-values greater than 1.0.

A cascade is defined as a spillway consisting of a large number of small steps with no significant receiving depth below each step. For a weir to be considered a step weir, each step must be followed by a receiving pool; the flow cannot merely splash onto a flat surface as it passes to successively lower levels. The theoretical b-value for a 4-step weir having a total fall of 2 m and an r-value of 1.304 can be shown to be 2.89 (Water Research Centre, 1973). Cascades usually produce smaller b-values than those for sharp-crested, free-falling weirs with deep receiving pools. Jarvis (Water Research Centre, 1973) studied 13 cascades and reported that

the b-values for these structures ranged from 0.2 to 0.7. Tebbutt et al. (1977) conducted three laboratory experiments using 45-degree steps in conjunction with three riser heights of 7.3 cm, 12.7 cm, and 25.4 cm. The respective weir-aeration coefficients were calculated as 0.98, 1.17, and 0.84. Butts and Evans (1983) reported b-values of 0.65 and 0.75 for two large Fox River cascade structures.

Tailwater Pool Design

The tailwater pool design of a spillway or weir greatly influences the reaeration efficiency of a head loss structure. Hydraulic jumps at the foot of sloped spillways and deep pools below free-fall weirs appear to improve DO uptake significantly. The casual conclusion that free-falling water splashing onto an apron produces excellent aeration because of the breakup of the flow due to the momentum of the falling water is not necessarily true. A number of investigators, including the Water Research Centre (1973), Apted and Novak (1973), Avery and Novak (1974), and Nakasone (1987), conclude that water discharging into a deep pool or stilling basin produces significantly higher rates of oxygen transfer than when it falls on a shallow surface.

Laboratory weir aeration studies conducted by the State Water Survey (Butts and Evans, 1980; Butts and Adkins, 1987) showed by means of statistical methods that flows discharging into pools are apt to be aerated to a much higher degree than when they are allowed to splash directly onto a plate, irrespective of changes in inlet DO, flow, and total water fall heights. Photographs of V-notch weir overflows splashing onto the clear-plastic receiving box used during the 1987 State Water Survey study showed that maximum aeration was achieved when the bubble jet was not allowed to penetrate to the bottom. This concurs with British researchers' findings that the deficit ratio increases with increases in receiving depth until roughly a steady state condition is reached. They state, "In general it would appear that, to obtain the maximum benefit from a given fall, the depth of the receiving water should be at least 6 cm greater than one-tenth of the weir height" (Water Research Centre, 1973). Nakasone (1987) presents a criterion that sets the optimal tailwater depth at three-tenths of the waterfall height. He further states that aeration efficiencies decrease when the tailwater depth exceeds this factor.

Weir-Face Design

Another geometric factor that needs consideration is the weir-face configuration. Nakasone (1987) reviews Van der Kroon and Schram's (1969) work on weir design and expands upon it somewhat. These researchers have shown, using small-scale laboratory models, that increased aeration can be achieved by partitioning a continuous, sharp-crested weir into a number of individual nappes. However, these studies indicate that the effectiveness of partitioning is reduced after a certain degree of division is reached. For very small installations, Nakasone indicates that the optimum ratio of the width of an individual partitioned nappe to the total width of the weir is 0.25. For large installations, Nakasone recommends using individual nappes less than 1 meter wide.

Various geometric configurations can also be used to regulate discharge rates or to maintain a constant unit discharge across the face of the weir

during flow rate increases. Sloping or stepped crests can be used to accomplish these goals. Such designs should be considered if reaeration efficiencies are found to directly relate to flow rate changes.

Receiving Pool Length

Weir aeration is effectuated most efficiently via oxygen transfer from air bubbles entrained in pools or stilling basins below weirs or spillways (see "Tailwater Pool Design" subsection). The establishment of this fact naturally leads to the conclusion that optimal tailwater depths have to be maintained downstream at distances that will allow optimal oxygen transfer to occur. Using data from small-scale laboratory weir experiments, Nakasone (1987) developed the following empirical equation for estimating the optimal distance (L_0) in meters.

$$L_0 = 0.0629 (D + 1.5 H_c)^{0.134} q^{0.666} \quad (3)$$

where D is the difference in elevation between the crest of the weir and the downstream water surface in meters, H_c equals approximately 2/3 of the head on the weir in meters, and q is the unit hydraulic loading in m^3/hr per meter of weir. Nakasone states that for practical design purposes distances equal to $0.8L_0$ can be used because his experimental data indicate that only about 0.5% of the entrained air remains at this point. However, he recommends, as a minimum, design distances of $0.7L_0$.

Water Quality Considerations

Water quality has to be considered when evaluating on-site pilot plant weirs, evaluating in-stream structures, and predicting aeration rates for specific conditions. Water quality affects aeration efficiencies in two ways: first, it affects the oxygen uptake rates, and second, it affects saturation levels. These effects may be either negative or positive. The a -value in equation 2 is an "all-inclusive" parameter that is an attempt to relate general water quality conditions to weir aeration rates.

Kothandaraman (1971) reported that most contaminants retard oxygen uptake, although a few appear to enhance it. He found that aeration rates could be reduced up to 60% by adding large portions of domestic sewage to tap water. However, suspended sediments, depending upon the type, were found to either moderately increase or decrease aeration rates. Experiments conducted by McHenry et al. (1973) to determine the influence of suspended sediments on surface aeration rates, using 0.115-mm Florida quartz sand, showed that reaeration rates decrease as the average sediment concentration increases. This decrease was found to be monotonic and was attributed to the dynamic influence of suspended particles on the turbulent flow field.

Preul and Holler (1969), in conducting year-round, in situ dam aeration studies and laboratory scale-model studies of Tainter gate reaeration efficiencies, recognized the fact that water contaminants could affect their results. Nevertheless, they made no attempt to ascertain these effects. Alpha (α), the oxygen transfer ratio of polluted or chemically contaminated water to unpolluted or uncontaminated water, was assumed to be equal to unity although sodium sulfite and cobalt chloride were added to the water used in their laboratory experiments for deoxygenation purposes. Susag et

al. (1967) used r -values ranging from 0.9 to 1.0 to evaluate the reaeration potential of flow-release structures at several Mississippi River navigation dams below Minneapolis-St. Paul.

British researchers (Water Research Centre, 1973) conducted experiments by adding synthetic anionic detergents to tap water used in laboratory weir-aeration experiments. Detergent concentrations of 0.01, 1.0, and 10.0 mg/l reduced deficit ratio values by 0, 5, 8, and 16%, respectively.

Butts and Adkins (1987) correlated 13 parameters to r -values derived during their aeration studies of Starved Rock dam Tainter gate flow releases on the Illinois River. Stepwise regression techniques indicated that the second, third, and fourth most significant parameters were related to water quality. Most significant was the gate opening height, followed by surfactants (MBAS), suspended solids, and algae counts. However, they found that the least influential independent variable (ranked 13th) was the water quality factor (α), which supposedly is a "catch-all" factor representing generalized water quality conditions in equation 2. Illinois River α -values at Starved Rock averaged 1.24, which, according to published criteria (Water Research Centre, 1973), classifies Illinois River water in the Starved Rock area (60 miles below Lockport) as slightly to moderately polluted.

Dissolved oxygen saturation concentrations are the driving force behind reaeration rates. DO deficit changes occur via a first-order kinetic reaction. Simply stated, this means that high-deficit (or low-DO) water is aerated much more rapidly than water nearly saturated with oxygen. Consequently, accurate determinations of weir aeration rates are dependent upon precise knowledge of saturation concentrations. Published values have all been derived by using clean, unpolluted water. A general equation developed by the American Society of Civil Engineers (1960) for estimating saturated DO concentrations in fresh water over a wide range of water temperatures is:

$$C_s = 14.652 - 0.41022T + 0.00791T^2 - 0.00007774T^3 \quad (4)$$

where C_s = DO saturation in mg/l at sea level and T = water temperature in degrees Celsius.

The use of book-value saturation concentrations for evaluating weir aeration efficiencies of field installations can result in erroneous and/or misleading results. The theoretical consequences of using book-value saturations in place of field-derived values are discussed by Butts and Evans (1984). Butts and Adkins (1987) present actual comparisons between r -values derived by using book and field-derived saturation concentrations for Illinois River water at the Starved Rock dam. The ratio of field-measured DO saturation values to book values, often referred to as the beta-factor (β), ranged between 1.00 and 1.14 for 19 sampling dates at Starved Rock; the average β -value was 1.06. Water above the dam is often supersaturated with DO during warm weather as a result of algal activity. Continuous deaeration during supersaturated periods failed, on most occasions, to "push" the DO down to the book-value saturation levels, and during subsaturation periods, long periods of aeration almost always succeeded in producing DO saturation concentrations greater than the book values.

In contrast, DO saturation experiments conducted by Butts et al. (1987a, b) at the Dresden Island and Brandon Road dams showed that field-measured DO saturation concentrations could be either greater or less than book saturation in these areas of the Illinois Waterway. The β -values ranged from a low of 0.94 to a high of 1.04 for 17 sampling dates at Dresden Island, while β -values for 18 sampling dates at Brandon Road ranged from 0.91 to 1.13. The respective average β -values were 1.006 and 0.985. On four occasions ambient DOs above the Dresden Island dam were near or above book saturation, but on no date did ambient DOs above the Brandon Road dam approach saturation.

This information is relevant to this study in that the efficiency of a weir aeration system may be greater or less than that which would apparently result from using book-value saturations. Ambient saturation concentrations less than "book" will result in efficiencies greater than the apparent efficiencies calculated by using book values. Conversely, waters with ambient β -values greater than 1.0 have the potential of absorbing oxygen to a greater degree than expected, resulting in inflated efficiencies when referenced to book-value saturations.

METHODS AND PROCEDURES

This study is unique in that it employed an on-site, full-scale weir system to evaluate the effectiveness of reaerating waters naturally low in dissolved oxygen. Full control over most variables and limited control of the remaining ones was achieved without a sacrifice in scale. In situ studies have been conducted at existing weirs, channel dams, and spillways (Gameson, 1957; Mastropietro, 1968; Preul and Holler, 1969; Susag et al., 1967; Crevensten and Stoddard, 1974; Butts and Evans, 1978; Butts and Evans, 1980; Butts and Adkins, 1987; and Butts et al., 1987a, b), but none of these studies were conducted under controlled or even limited-control conditions.

Some experimental restraints or conditions were preset somewhat because of limitations set forth by Macaitis et al. (1984) in the MSD feasibility report on SEPA stations. The fall height of a SEPA station has been set at a minimum of 6 feet and at a maximum of 15 feet. The minimum fall reflects the maximum rise in the channel elevation historically observed during high water. The maximum height reflects the optimal lift of low-head, high-volume, single-stage screw pumps considered for use in pumping the large volume of flow to be diverted for aeration from the MSD waterways. Each station will be designed to fit on an approximately 1300 ft x 300 ft strip of land with the weir face aligned with the long dimension.

A weir length of 538 feet was originally specified, but current plans envision a 200- to 300-foot weir length. A 300-foot weir subjected to the design and maximum anticipated flow rates would result in design and maximum unit hydraulic loading flow rates of 1.9 cfs/ft (1.23 mgd/ft) and 2.53 cfs/ft (1.64 mgd/ft), respectively.

Factors and parameters that were readily controlled in the design and operation of the pilot weir system include fall height (up to 15 feet), profile geometry, weir face geometry, receiving depth, and unit hydraulic loading capacity. Some control over inlet DO could be exercised by

operating the pilot plant only when ambient DO concentrations in the waterway met experimental requirements. Stream water quality and the length of the receiving tank could not be controlled. The latter could not be accommodated because of excessive space requirements.

Pilot Plant Design

Schematic sketches of the basic pilot plant layout and flow routing schemes are shown on figure 6. Figure 7 shows typical inflow and receiving box designs. Figure 8 shows the weir-face configurations used. Provisions were made for routing the flow through single 10- and 15-foot drops and through two 5-foot steps or three 5-foot steps.

A step-weir has been shown to provide better aeration than a free-fall weir of equal height (see "Weir Aeration Theory and Concepts" in this report). However, no information is available that clearly defines the relative characteristics of each derived under similar full-scale operation. This study has been designed to provide data to determine if a step-weir is a significantly better aerator than a properly designed free-fall weir. A simple, free-fall weir is less costly to construct and requires less space. Consequently, monetary and physical considerations could weigh heavily in favor of using a free-fall weir in place of a stepped system if the difference between measured efficiencies is found to be small.

The pilot plant had to be designed to accommodate full-scale unit flow rates while using a minimum of construction material and space. Care had to be taken to insure that the anticipated maximum unit hydraulic loading rate could be properly contained and regulated. Heads (H) created above a sharp-crested weir at various flow rates are critical to the operation of an experimental weir box system and ultimately to the operation of the full-scale SEPA-station weirs. The maximum H-value anticipated to occur for the MSD design criteria was determined by using a published hydraulic chart (Chicago Pump Company, 1963) designed for estimating discharges over rectangular sharp-crested weirs. A reproduction of this chart is presented as Appendix A in this report. The chart shows that, for a maximum hydraulic loading on a weir of 1.64 mgd/ft, approximately 10 inches (0.83 ft) of head will be created above the weir. Consequently, a weir depth of 12 inches was selected. This allowed two inches of freeboard. The need to use removable flashboards to contain possible splashing and/or overflow was considered to be a possibility, but the need never materialized.

The reliability of the Chicago Pump Company chart was verified by a test conducted with the ISWS weir box setup (Butts and Adkins, 1987). The maximum unit flow rate that the ISWS setup could provide was 0.44 mgd/ft of weir, which produced an H-value of 4.5 inches; note that this value agrees closely with the 4.2 inches (0.35 ft) specified by the Chicago Pump Company design chart presented in Appendix A. The original MSD design criteria stipulated that the weir height (Z) was to be set at 1.5 feet. Note that in terms of hydraulic efficiency this would be appropriate as shown by the chart in Appendix A, since smaller values of Z produce lower heads. However, from the standpoint of oxygen absorption, this hydraulic characteristic would benefit only simple, free-fall weirs; step-weir efficiencies can be increased by increasing the weir overflow receiving depth (see "Weir Aeration Theory and Concepts" in this report).

For both the pilot study and the full-scale SEPA operation, a free admission of air should be maintained between the overflow and the vertical face of the weir to insure maximum aeration. A field test using the ISWS weir box system revealed that a nappe or free fall can be maintained for flows as low as 0.013 mgd/ft of weir. This appears to be consistent with the chart in Appendix A since the chart values start at 0.010 mgd/ft of weir.

Another unknown that had to be addressed in the design of the pilot plant was the extent of nappe projection from the face of the weir. A modicum of published data was available to aid in making this assessment for various flow and fall height conditions for a simple, sharp-crested weir. For the experimental setup, the receiving boxes had to be placed so that the overflows would spill into an area far enough back of the baffle plates to prevent splashing into the outfall recording area. Translated into SEPA weir consideration, the "deep" receiving pool had to be designed to catch the total overflow, but the "deep" pool width had to be kept to a minimum for economic reasons. The only data available for providing some insight into what might be required were some very crude measurements recorded during a test run using the SWS weir box setup. Very liberal extension of the experimental nappe curve developed indicated that the horizontal projection would extend outward about 2 feet for a 5-foot drop and somewhat over 2-1/2 feet for a 10-foot drop. The horizontal distance required to contain the nappe of a 15-foot fall could not be accurately estimated, but it appeared that it would be somewhat less than four feet.

The basic inflow box and receiving box designs are presented as figure 7. Two inflow boxes were used: one was used strictly for the 10-foot, free-fall weir, and one was selectively used to route flow to either the step-weir system or the 15-foot, free-fall weir. The boxes were constructed of 1-inch, 4' x 8' plywood concrete forms. The standard 4' x 8' plywood dimensions appeared to fit hydraulic requirements while providing convenience and economy in construction. Under-flow baffle plates with 5-inch bottom openings were installed in each box to minimize turbulence near the overflow weirs. Stilling wells, consisting of 8-inch plastic pipe, were used in each box to shelter the DO-temperature probes during a run. Figure 8 is a photographic frontal view of the step-weirs, and figure 9 is, a photographic frontal view of the 15- and 10-foot free-fall weirs. Figure 10 shows the details of the inside of the tank construction. Figure 11 shows the 10-foot, free-fall receiving tank in operation in the foreground and the 15-foot free-fall receiving tank inoperative in the background. Note the effectiveness of the baffle in reducing overflow turbulence. The tanks were supported by a bolted timber superstructure (figures 8, 9, and 12), and the insides of the tanks were stiffened with 2 x 4's on 12-inch centers. Steel rods, on 16-inch centers along both the short and long dimensions near the bottom of the tanks, tied the sides together to resist hydraulic pressure (figure 10). All seams and bolt holes were caulked with silicone sealant. Drains, controlled by gate valves, were provided for each tank.

Water was pumped from the Sanitary and Ship Canal to the pilot plant (figure 12) by means of a Jacuzzi Model 12LC water-lubricated, vertical-turbine pump powered by a 15 HP motor. The pump was of single-speed design, rated at 1000 gpm at 45-foot TDH (figure 13). Flow rates to the tanks were regulated by routing a certain portion of the pumpage through the waste discharge line shown diagrammatically on figure 6

and pictured being manipulated in figure 13. Flow rates to each individual receiving tank could be measured via an ultrasonic sensor connected to each inflow pipe. A Sam-Tech Inc. Model 5121 ultrasonic flow meter, transducer, and totalizer (figure 14) was used.

Six weir-face designs were used, as shown on figure 15. All weir plates were made of 1/4" plexiglass and were fastened to the face of the overflow box with C-clamps (figure 16). The basic weir plate, designated as M1, is 12 inches deep by 36 inches wide and is sized to produce experimental results within the range of unit hydraulic loads expected to be imposed upon a SEPA station. Weirs M2 and M3 are 12 and 24 inches narrower, respectively, and are designed to produce extremely high unit hydraulic loadings, i.e., above those sustained using the maximum pumping capacity in conjunction with the 36-inch-wide opening.

Weir faces A, B, and C shown on figure 15 were designed primarily to determine how flow partitioning affects aeration under full-scale conditions. If the overall weir width is considered to be 36 inches, then weir face B meets Nakasone's (1987) criterion that a partition width to weir width ratio of 0.25 is optimum. This ratio for weir face B is 0.125 and is less than optimum, while that for C is 0.33 and is greater than optimum. Besides partitioning the flow, these "toothed" weirs produce a secondary benefit in that additional unit-flow variability data can be generated, since the teeth are flow-restrictive.

Convenience of construction using standard plywood sheets limited the box depths to 4 feet. This resulted in a compromise in recommended receiving water depths. Nakasone's (1987) specification that optimization of the receiving depth (h') can be achieved by setting h' equal to $0.3h$ requires a total box depth in excess of 5.33 feet ($0.3 \times 15' + 0.83'$) for the 15-foot-high weir loaded at 1.64 mgd/ft. The 0.83'-value is derived from the chart presented in Appendix A. However, the Water Research Centre (1973) specification that the minimum depth should be equal to $0.1h + 0.06m$ necessitates a box depth of only 2.53 feet ($0.1 \times 15' + 0.2' + 0.83'$) plus some allowance for freeboard. The "design-box," having a 1-foot-deep weir (figure 15) cut from a tank depth of 4 feet (figure 7), provides a receiving water depth of 3.83 feet and a freeboard height of 0.17 feet for maximum experimental conditions. Nakasone's criterion, applied to 5-foot and 10-foot falls at 1.64 mgd/ft, produces optimum h' -values of 1.5 feet and 3.0 feet, respectively. The 10-foot fall requirement is slightly less than the 3.83 feet provided by the "design-box," and the 5-foot value is considerably less than that provided. Excessive depth, according to Nakasone, will result in less efficient oxygen transfer. Relative to the Water Research Centre maximum receiving water depth criterion, the "design-box" provides h' -values greatly in excess of that needed: $h' = 1.33$ feet for the 5-foot fall and $h' = 1.83$ feet for the 10-foot fall.

Equation 3 was used to make a cursory evaluation of the downstream pool length needed to effect maximum oxygen transfer for pilot plant and SEPA station weir designs. The maximum unit weir loading of 1.64 mgd/ft is equivalent to $848 \text{ m}^3/\text{hr}/\text{m}$, and for this rate, $H_c = (2/3)(0.83 \text{ ft}) = 0.55 \text{ ft} = 0.17 \text{ m}$. In terms of meters, D for the 15-foot and 10-foot free-fall weirs and the bottom 5-foot fall on the step-weir would be 4.572 m, 3.048 m, and 1.524 m, respectively. For the top and middle steps of the step-weir, D would be 1.271 m, slightly less than the bottom step value because of the

buildup of head on the intermediate receiving pools (boxes). The pool lengths L_0 (in feet) for the 15-, 10-, and 5-foot falls and the upper two steps are 22.7 ft, 21.6 ft, 19.9 ft, and 18.4 ft, respectively. Obviously, these lengths are too long for practical applications to the pilot plant, but they certainly should be considered for incorporation into the design of a SEPA station.

OperatinE Procedures

The pilot plant generally was operated on Mondays, Wednesdays, and Fridays, except for the first run and the last four runs, which were conducted on Tuesdays. Standard procedure consisted of operating the 15-foot and 10-foot free-fall weirs and the step-weir at flow rates of approximately 400, 800, and 1200 gpm using weir-face M1 (figure 15). A stopwatch was used in conjunction with known tank volumes to determine receiving-box detention times for these three flow rates, and the boxes were allowed two water changes before data were recorded during operational changes. This testing procedure was designed to provide data for evaluating the effects of changes in flow and vertical geometry on aeration.

A second phase of testing was instituted during the later stages of the experimental work to evaluate the effects of changing the transverse weir face geometry by using weirs A, B, and C (figure 15) and creating extremely high unit hydraulic loading by using weirs M2 and M3 (figure 15). The second phase of testing was limited to the 10-foot free-fall weir, since only the relative nature of the results involving weir-face design was of interest.

Dissolved oxygen and temperature measurements were made with YSI Model 58 digital dissolved oxygen meters equipped with YSI model 5795A submersible stirrers and YSI Model 5739 dissolved oxygen field probes. Four meters and stirrer-probes were used during a run; two were placed in the stilling well of an inflow box while two were placed in the stilling well of a receiving box. The two receiving-box probes were moved from step to step during step-weir experiments. The meters were calibrated on-site by using the Winkler method and fresh canal water. A fifth meter was always calibrated for stand-by use if needed.

The Butts method (Butts and Adkins, 1987) of using a calibrated weir box to determine the water quality factor (α) in equation 2 was employed during each run (figure 17). A small stream of canal water was pumped to the unit at the onset of and near the end of a pilot-plant run. Two DO probes were immersed in both the inflow and receiving boxes. This provided data for determining "water quality" at the start and end of each daily run.

Also, ambient DO saturation levels of the canal water were determined at the start and end of a run. A gallon of water was collected and aerated 15 minutes on-site by using compressed air and a stone diffuser. Deficit ratios were computed for both book and ambient DO saturation values. Book values were computed by using equation 4; ambient values for experiments conducted between the start and end of a daily run were proportionally adjusted by time and for temperature changes. All saturation measurements were determined in duplicate by using the Winkler method.

Other measurement or data recordings were made relative to critical water depth (H_c) on a weir, wind speed and direction, and head loss between boxes in the Butts control unit. At the end of a daily run, a gallon of canal water was retained for use in making laboratory chemistry analyses and algal enumeration. These analyses were performed according to Standard Methods procedures. The sequence of testing was varied daily to equalize the effect of possible temperature changes.

Data Reduction

The raw data were grouped for sequential analysis according to number of steps, fall height, unit-flow rate, and number of weir teeth (partitions). Three times as much data was available for the single 5-foot fall as for the single 15-foot fall since the three 5-foot steps making up the step-weir could be isolated and analyzed as individual 5-foot free-falls. Also, the step-weir data were divided into two sets of data for 2-step step-weirs having total falls of 10 feet. One set consists of data for the first step (inflow box) and the second or intermediate step, while the second set consists of data for the intermediate step and the final receiving tank. Significantly more data sets were available for the 10-foot free-fall weir than for the 15-foot free-fall weir since weir face designs M2 through C were used on runs with the 10-foot free-fall and not with the 15-foot free-fall.

Statistical methods involving stepwise regression techniques were used to develop design equations. Computer analyses were run by using three different parameters - r , b , and P_0 (output DO percent saturation) - as independent variables in conjunction with 11 dependent variables: number of steps, fall height, unit flow rate, number of teeth, input DO percent saturation, water temperature, chemical oxygen demand, suspended solids, methylene blue active substances, algae counts, and the British weir equation water quality factor (a). Data were collected on wind speed and wind direction, so these variables were available for use as two additional dependent variables. However, inclusion of these would have overextended the data handling capability of the computer program used, so they were eliminated from the analyses on the basis of relative importance. The computational program identifies each dependent variable in order of statistical importance, producing linear regression coefficients for use in developing design equations.

The experimental work was conducted to produce data that could be used to evaluate the efficiencies of the various weir setups by using either equation 1 or equation 2. Evaluations based solely on equation 1 produce results biased or influenced by changes in water quality. Theoretically, evaluations based upon equation 2 would remove this bias or influence. Equation 2 can be solved for "b" by using a-values derived from data generated using the Butts weir-box control unit. One-way analysis of variance (ANOVA) statistical tests were conducted at the 95% confidence level to determine if significant differences in aeration efficiencies (based on either "r" or "b" values) exist between various weir designs and modes of operation. Computations were based on averaging the two DO and temperature readings taken at each box location.

RESULTS

Twenty-seven daily experimental runs were completed from June 9, 1987 through October 6, 1987. The specific dates and the experimental conditions on those dates are presented in table 1. The first 16 runs were conducted primarily to generate data to evaluate the effects various flow rates have on weir-aeration and to compare the 10-foot and 15-foot free-fall weirs with the 3-step, 15-foot-high step-weir. The last 11 runs were conducted to generate data for comparing the aeration rates of partitioned (toothed) weirs with those for the 1-foot, 2-foot, and 3-foot rectangular weirs. The 1-foot and 2-foot rectangular weirs also provided an opportunity to increase unit hydraulic loadings significantly above those that could be attained across the "standard" 3-foot weir at maximum pumping capacity. Two special runs were conducted on July 6 and 8. The flows on these dates were evenly split between the 15-foot free-fall weir and the step-weir so that simultaneous data could be generated. Overall, the experimental schemes presented in table 1 provided information such that 534 individual weir aeration conditions could be isolated and analyzed.

The operation of the pilot plant was constrained somewhat after mid-August because of high water in Chicago-area streams and canals. Between late evening on August 13 and late afternoon on August 14, 9.35 inches of rain fell at O'Hare International Airport. Extensive flooding followed throughout the Chicago area.

Water quality conditions prevailing in the Sanitary and Ship Canal on the days on which runs were made are presented in table 2. A good mix of ambient DO concentrations occurred, ranging from a low of 0.49 mg/l on June 26 to a high of 5.52 mg/l on August 7. Note that, following the storm of August 13-14, a sharp drop in DO concentrations occurred, and these low DO values persisted until the end of August. The low DO values in late June occurred as water temperatures increased prior to the annual initiation of diversion of water from Lake Michigan (figure 2) for dilution and enhancement of Chicago-area streams and canals. Overall water quality in the canal, as gaged by the a-value in equation 1, could be classified as moderately polluted. The average a-value for the 27 dates, computed by using book-value DO saturation concentrations, was 1.03. The average computed on the basis of experimental (Exp.) DO saturation values was 1.24. The lowest a-values occurred immediately after the torrential rains hit the Chicago area on August 13. This reflects an increase in the polluttional nature of the water in the Sanitary and Ship Canal upon receipt of stormwater runoff and combined sewer overfalls. The August 13 storm produced runoff considerably in excess of that which TARP could handle.

The average α -value was 0.95 for the 53 experiments conducted relative to ambient DO, saturation. Only on two occasions were samples capable of being raised to corresponding clean-water (book-value) concentrations. In reality, this somewhat constrains the ultimate efficiency levels which can be produced by physical reaeration structures in or along Chicago-area waterways.

Wind speed and direction did not appear to affect the experimental results to a significant degree. The pilot plant was located in a fairly well-protected area. Double-digit wind speed (12 mph) was recorded on only one date. The wind direction, however, ranged over a 310 degree arc.

Rarely did the wind appear to cause excessive distortion at the waterfall nappes. Consequently, because of computer data input limitations to the statistical computation programs, wind-related variables were excluded from all statistical analyses.

Effects of Modes of Operation

Various modes of operation are illustrated by the photographs presented in Appendix B. Shown is the step-weir operating at a high unit flow rate. Also presented are photographs of the 10-foot free-fall weir operating at high and low unit flow rates for various water face designs.

The results of the effects of the three controlled variables - vertical geometry, weir face geometry, and unit flow rate - on aeration efficiencies as measured by "b" and "r" are summarized in tables 3 and 4. Careful examination of the b-value results in table 3 indicate that:

- 1) Aeration efficiencies for the 5-foot and 10-foot free-fall weirs and the 10-foot and 15-foot step-weirs do not appear to be significantly impacted by changes in unit flow rates.
- 2) At flow rates below 200 gpm/ft, aeration efficiencies are significantly reduced for the 15-foot free-fall weir.
- 3) Increases in fall-height improve aeration efficiencies of free-fall weirs significantly at moderate to high unit hydraulic loadings, but only slightly at unit hydraulic loadings of 200 gpm/ft or less.
- 4) A 2-step, 10-foot step-weir exhibits significantly greater aeration efficiencies over a full range of unit flows than does a 10-foot free-fall weir.
- 5) A 2-step, 10-foot step-weir exhibits slightly greater aeration efficiencies over a full range of unit flows than does a 15-foot free-fall weir.
- 6) A 3-step, 15-foot step-weir is, by far, a much more efficient aerator over a wide range of hydraulic loadings than is a 15-foot free-fall weir.

Similar conclusions, with the exception of number 5, can be arrived at using the average r-values presented in table 3. In the case of the exception, the r-values indicate that a 10-foot-high, 2-step step-weir would probably not provide better aeration than a 10-foot free-fall weir.

The results summarized in table 4 indicate that partitioning the 10-foot free-fall weir to create separate nappes does not appear to be advantageous relative to improving aeration. In fact, while not statistically significant for either "b" or "r" at the 5% level, partitioning appears to have a slight negative affect. The average r-values in table 4 tend to decrease steadily as the number of partitions increases. At the 90% confidence limits (10% level of significance), the hypothesis that the means are equal could be rejected. However, for a full-scale design, the possibility exists that, because of the long continuous nature

of the weir face, partitioning may be desirable to permit air to reach the back side of the nappe.

Design Regression Equations

The computer program used for developing a design regression equation, via the application of statistical stepwise regression techniques, was capable of handling 500 observations (lines of data) and 14 variables (columns of data). Thirty-four lines of data had to be eliminated since 534 observations were available. The data that were eliminated were selected from several dates for which some water quality data were missing. Chemical oxygen demand (COD), suspended solids (SS), and methylene blue active substances (MBAS) samples were not collected on June 11 and 19; the results given for these parameters in table 2 are extrapolations based on the results of those determined on the preceding and the following dates. All 534 observations for the 14 variables are listed in Appendix D. From these, 500 observations were used in the stepwise regression analyses. Included in the data are 11 independent and three dependent variables. The independent variables include: (1) number of steps, (2) water fall height, (3) unit flow, (4) number of teeth, (5) input DO in percent of saturation based on equation 4, (6) water temperature, (7) COD, (8) SS, (9) MBAS, (10) algae counts, and (11) the water quality factor "a" derived from equation 2. These 11 parameters were equated to the three dependent variables: (1) output DO in percent of saturation based on equation 4, (2) the weir aeration factor "b" derived from equation 2, and (3) the deficit ratio "r" derived from equation 1.

Tables 5, 6, and 7 summarize the significance of the relationship of the 11 independent variables, in stepwise fashion, to each of the three dependent variables. The b-value, when designated as the dependent variable, produced the lowest overall correlation coefficient of 0.818. The r-value, when designated as the dependent variable, produced a slightly better overall correlation coefficient of 0.851. However, when the output DO, in terms of percent of saturation, was equated to the independent variables, a significantly higher correlation coefficient of 0.945 resulted. Consequently, this formulation was chosen for use in the design analyses of a SEPA station.

The results presented in tables 5, 6, and 7 are interesting for a variety of reasons. First, the number-of-steps criterion appears as either the first or second rated independent variable in all three cases. Also, in all three cases, the water-fall-height criterion appears as either the second or third most important input variable. The input-DO-saturation criterion ranks second in importance when associated with the dam aeration coefficient (b) and ranks first when associated with the output-DO-saturation dependent variable. However, input-DO-saturation ranks only fifth relative to the deficit ratio (r), and its inclusion improves predictability very little as evidenced by the slight decrease in the standard error of estimate and the slight increase in the multiple correlation coefficient. This fact somewhat supports the theoretical contention that the deficit ratio is independent of the above-weir DO concentration. Also, the fact that the water quality factor (a) ranks third when associated with the deficit ratio indicates that general, overall water quality influences reaeration significantly, making "b" a better estimator

of weir reaeration since the derivation of "b" is partially predicated upon "a".

The 11 independent variables explain approximately two-thirds of the variability observed with "b" and three-fourths of that observed for "r", but they explain almost 90% of that observed for the output DO percent saturation (P_0). More important, however, is the fact that the three most significant independent variables associated with P_0 explain 87% of the variability and are factors that can be readily estimated or adjusted to meet design considerations. In other words, a weir could be designed to effect maximum aeration through variations in the number of steps or increases in the fall much more easily than through attempts to predict algal counts and water quality.

The regression coefficients associated with the following generalized linear equation for the three different dependent variable scenarios are summarized in table 8:

$$Y = A+B(P_i)+C(N)+D(h)+E(A)+F(a)+G(T)+H(n)+I(S)+J(M)+K(C)+L(q) \quad (5)$$

where Y is the dependent variable in the form of either "b", "r", or P_0 ; A is the intercept; and "B" through "L" are regression coefficients associated with the corresponding independent variables defined and symbolized in tables 5, 6, and 7.

When the appropriate coefficients from table 8 are used, the design formula can be written as:

$$P_0 = 0.32P_i + 4.13N + 0.81h + 54.78 \quad (6)$$

where P_0 is the output dissolved oxygen percent of saturation referenced to equation 4, P_i is the input dissolved oxygen percent of saturation referenced to equation 4, N is the number of steps, h is the water fall height in feet, and 54.78 is the intercept constant. The limits for which this equation was derived are P_i (2.0-93.1%), N (0-3), and h (5-15 ft). Also, while temperature is not included as a significant variable (sixth ranked, table 7) the application of the equation is theoretically limited to use between the temperature extremes for which the experiments were run. The minimum and maximum temperature values are 15.2°C and 27.6°C, respectively.

DISCUSSION

The results of this study indicate that properly designed weirs can effectively reaerate low-DO waters. Step-weirs are much more effective than free-fall weirs. However, to achieve maximum efficiency, the step-weir must be designed as such and not as a cascade. Efficiencies are increased in any type of weir system by providing optimal receiving depth below the fall. This study was not designed to evaluate receptacle depth effects; however, previous work by the principal author of this study and by others has established the fact that optimal depths range somewhere between 0.2 feet plus one-tenth of the fall height and 0.3 times the fall height. The

receiving boxes used during this study were designed accordingly, and this criterion should be used in designing a full-scale SEPA station.

The weir-aeration coefficient (b in equation 2) for a sharp-crested, free-falling weir has been defined as unity using clean water (a = 1.8 in equation 2) discharging into an optimal receiving depth. This is referred to as a standard or normal weir. However, note from table 3 that the b-values for a free-falling, sharp-crested weir do not appear to conform to the standard, but are greatly influenced by weir height and to a lesser extent by unit hydraulic loading. A 5-foot fall produced b-values slightly less than unity, while the 10-foot fall produced values about one-third greater, and the 15-foot fall produced values about two-thirds greater than 1.0. A two-step, 10-foot step-weir is essentially equivalent to a 15-foot, free-fall weir in terms of aeration efficiencies. The step-weir produced b-values over three times that of a "standard weir."

Theoretically the deficit ratio produced by a single free-fall weir can be used to predict the r-value of a step-weir made up of multiples of the single free-fall weir by raising the single-weir r-value to a power equal to the number of steps. In other words, $r_s = r^n$, where r_s is the deficit ratio of the step-weir, r is the deficit ratio of a simple free-fall weir, and n is the number of steps. Squaring the r-values in table 3 for the 5-foot weir yields the following theoretical r-values for a 2-step, 10-foot step-weir for the four given flow ranges: 3.72 (compared to measured 3.65), 3.76 (3.77), 4.00 (4.06), and 6.45 (5.12). Similarly, cubing the 5-foot weir values yields the following theoretical r-values for a 3-step, 15-foot step-weir: 7.19 (6.84), 7.30 (7.23), 8.00 (7.33), and 16.39 (13.70). The agreement between the theoretical and observed values ranges from very good to excellent. This is significant for two reasons: first, it shows that the experimental design was conceived in a careful and thoughtful manner and that the data generated are reliable, and second, it provides a means of confidently exploring the use of a 15-foot-high step-weir system made up of more than three steps. In other words, the data can be extrapolated to develop reliable alternative designs.

The r-values derived for the 5-, 10-, and 15-foot free-fall weirs for unit flows ranging between 325 gpm/ft and 600 gpm/ft (table 3) perfectly fit a theoretical line described by the equation

$$r_h = 1 + 0.2h \quad (7)$$

where r_h is the deficit ratio for any fall height h. The r-values from table 3 for the 200 gpm/ft to 325 gpm/ft flow range fit equation 7 very well; only the 15-foot value for the 100 gpm/ft to 200 gpm/ft flow range fails to agree closely with that predicted by equation 7. Note that $r = 1$, which is theoretically correct at zero head loss.

Equation 6 can be used as a starting point in a design analysis, but other factors such as those outlined and discussed above need to be considered. Table 9 lists predicted output DO percentages for various combinations of input DO percentages and number of steps for a 15-foot-high step-weir, computed by using equation 6. Note that supersaturated conditions start to appear beginning with N = 2 when P_i -values are high. This is not particularly significant, though, since SEPA stations would not be operated at such high input DO levels. Assuming a maximum water

temperature of 30°C, C_s from equation 4 would equal 7.44. Consequently, the maximum conceivable P_i -value would equal $(2.0/7.44)(100)$ or 27%. Examination of the data for $P_i = 27$ in table 9 reveals that significant increases in aeration could be achieved by using four or five steps as compared with using only three. Five steps appear to represent the upper limit since this design would result in an output DO of over 96% of saturation under the most critical conditions. At 30°C, P_0 would equal $(0.962)(7.44)$ or 7.16 mg/l. Also, further division into more steps would force the step-weir into less efficient cascade-like characteristics.

An entirely independent approach can be taken by using equations 1, 4, and 7 to analyze the possible benefits that can be derived from using a 5-step weir system. Five steps would produce an "h" of 3.0 feet for use in equation 7. Substituting this value in equation 7 produces an r_h -value equal to 1.6. Further, 1.6 to the fifth power equals 10.49. Substituting this r -value into equation 1 and using $C_g = 7.44$ (saturation at 30°C) and $C_A = 2.0$ mg/l results in an output DO (C_B) equal to 6.92 mg/l. This agrees very closely with the 7.16 mg/l value computed by using equation 6. Similar calculations using 1-, 2-, 3-, and 4-step weirs are summarized in table 10 and are compared to C_B -values computed by using equation 6. The two methods exhibit comparable results throughout.

Note that, at 30°C, the desired 4.0 mg/l instream value could easily be obtained. A 5-step weir would produce an instream value of approximately $(7.0 + 2.0)/2$ or 4.5 mg/l. At 25°C, an instream concentration of 4.9 mg/l could probably be achieved. These values are based on book or clean water saturation concentrations. Consequently, they are somewhat liberal projections; more realistic predictions could be made by including a α -factor. Using the average α -value of 0.95 for the 53 values given in table 2 for adjusting C_g to "dirty" water conditions, the instream DOs for 30°C and 25°C would more likely be equal to 4.3 mg/l and 4.6 mg/l, respectively.

Three basic sets of design specifications are presented in order of preference. Alternatives 1 and 2 were derived by using theoretical extensions of the observed data, while alternative 3 is based solely upon observed data.

Alternative 1

- Total weir height: 15 ft
- Total number of steps: 5
- Step height: 3 ft
- Receiving pool depth: 1.5 ft
- Receiving pool length: 18.5 ft
- Weir partitioning: none
- Unit hydraulic loading: 2.53 cfs/ft (1139 gpm/ft, 1.64 mgd/ft)
- Weir length: 300 ft

Alternative 2

- Total weir height: 15 ft
- Total number of steps: 4
- Step height: 3.75 ft
- Receiving pool depth: 2.0 ft
- Receiving pool length: 18.5 ft
- Weir partitioning: none

- Unit hydraulic loading: 2.53 cfs/ft (1139 gpm/ft, 1.64 mgd/ft)
- Weir length: 300 ft

Alternative 3

- Total weir height: 15 ft
- Total number of steps: 3
- Step height: 5 ft
- Receiving pool depth: 2.5 ft
- Receiving pool length: 18.5 ft
- Weir partitioning: none
- Unit hydraulic loading: 2.53 cfs/ft (1139 gpm/ft, 1.64 mgd/ft)
- Weir length: 300 ft

The receiving pool depths are somewhat greater than the optimum specification given in the literature as three-tenths of the fall height, and they are also somewhat greater than those observed as adequate by the principal author in other studies. However, the literature values and those derived as a result of the work done by the principal author came from small-scale laboratory experiments. During this study, receiving water depths somewhat greater than 3 feet appeared effective for the 5-foot falls. Consequently, the depths specified in all three alternatives were increased somewhat above the rule-of-thumb values. The SEPA station weir face should be constructed of steel plate to act as a sharp-crested weir to insure maximum aeration and hydraulic efficiencies. A broad-crested weir formed from concrete would not function satisfactorily. High unit hydraulic loadings are desirable for two reasons: first, this reduces construction and maintenance costs by reducing the weir length, and second, high unit loading may increase aeration efficiencies slightly. Although the data in table 3 show that no statistically significant differences exist in aeration efficiencies measured between 100 gpm/ft and 600 gpm/ft, a slight increase in aeration efficiencies with increase in flow is superficially discernible. The limited data available in the 740 gpm/ft to 1040 gpm/ft flow range indicate that very high unit loadings may, indeed, significantly increase efficiencies. More information is needed to verify this.

A 5.57-foot difference in elevation exists between the historical high water mark and the operational low. The difference between the high water elevation and the normal operating level is 4.80 feet. Inundation of the first step would occur with all three alternatives if the toe of the first step were referenced to the low water elevation. Referencing to the average or normal pool elevation would prevent inundation for only the 3-step system, and by merely 0.20 ft. At high water, the free-board on the second steps of the 5- and 4-step systems would be 0.43 ft and 1.93 ft, respectively. A rough estimate of the relative efficiencies of each alternative at high water can be made by using equation 6 and dividing each system into two separate entities. The 5-step system could be analyzed as a 9-foot-high, 3-step step-weir and a 0.43-foot free-fall weir; the 4-step system as a 7.5-foot high, 2-step step-weir and a 1.93-foot free-fall weir; and the 3-step system as a 5-foot free-fall weir and a 4.43-foot free-fall weir. For $C_b = 2.0$ at a water temperature of 30°C, the resultant P_0 -values for the inundated 5-, 4-, and 3-step step systems referenced to low water would be 87.5%, 83.4%, and 79.3%. A 5-step step-weir system still provides the best efficiency even under high-water conditions. The 87.5% figure,

however, represents a 9% reduction in aeration efficiency relative to that which would occur for the 5-step system during low water.

SUMMARY AND CONCLUSIONS

1. A full-scale weir-system pilot plant was designed and built to generate data for use in designing sidestream elevated pool aeration (SEPA) stations. The experimental design proved to be good, and excellent results were achieved.
2. Evaluations were made of the relative efficiencies of 10-foot-high, 2-step step-weirs; 15-foot-high, 3-step step-weirs; and 5-, 10-, and 15-foot free-fall weirs. The step weirs proved to be significantly better aerators than free-fall weirs of comparable heights.
3. Evaluations were made of the effects various unit hydraulic loadings have on aeration. Aeration data were grouped under three flow ranges: 100-200 gpm/ft, 200-325 gpm/ft, and 325-600 gpm/ft. Although the aeration efficiencies, as measured by the British dam weir aeration coefficient (b), appeared to increase slightly with increased flow, this increase proved to be statistically insignificant at the 95% confidence level. A limited amount of data was generated at the 740-1040 gpm/ft flow range, and significant increases in efficiencies were observed; however, more information is needed at this elevated hydraulic loading rate to verify this phenomenon.
4. Evaluations were made of the effects partitioning the weir face has on aeration. The "standard" rectangular weir opening of 36 inches was partitioned by using 4-inch rectangular teeth. Experiments were run using one, two, and three teeth (two, three, and four partitions), and no statistically significant differences could be discerned between any of these designs and the "standard" 3-foot unpartitioned rectangular weir.
5. Two independent methods of evaluating and designing a SEPA station were developed. Statistical methods using stepwise regression techniques were used to develop an empirical formula relating the output dissolved oxygen (DO) in terms of percentage of saturation to: (1) the input DO in terms of percentage of saturation, (2) the number of steps, and (3) the fall height in feet. A second more theoretical method was developed around the concept of the deficit ratio (r). Both methods produced comparable results.
6. Three alternative step-weir systems were proposed for use as part of the SEPA station design. The first alternative (the recommended system) consists of a 15-foot-high, 5-step, step-weir loaded at 2.53 cfs/ft (1139 gpm/ft, 1.64 mgd/ft) with no weir-face partitioning, and having a 1.5-foot receiving pool depth and an 18.5-foot receiving pool length. The second alternative consists of a 4-step, step-weir system, while the third alternative consists of a 3-step, step-weir system. The recommended order of consideration is based only on aeration efficiencies. Costs should also be considered in the choosing of the final design configuration.

7. The effects of high water levels on proposed SEPA station operation were evaluated. Significant reduction in aeration would occur if a station were subjected to historical high water levels. However, this reduction would be minimized (kept to about 9%) by using a 5-step, step-weir design.

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FIGURES AND TABLES

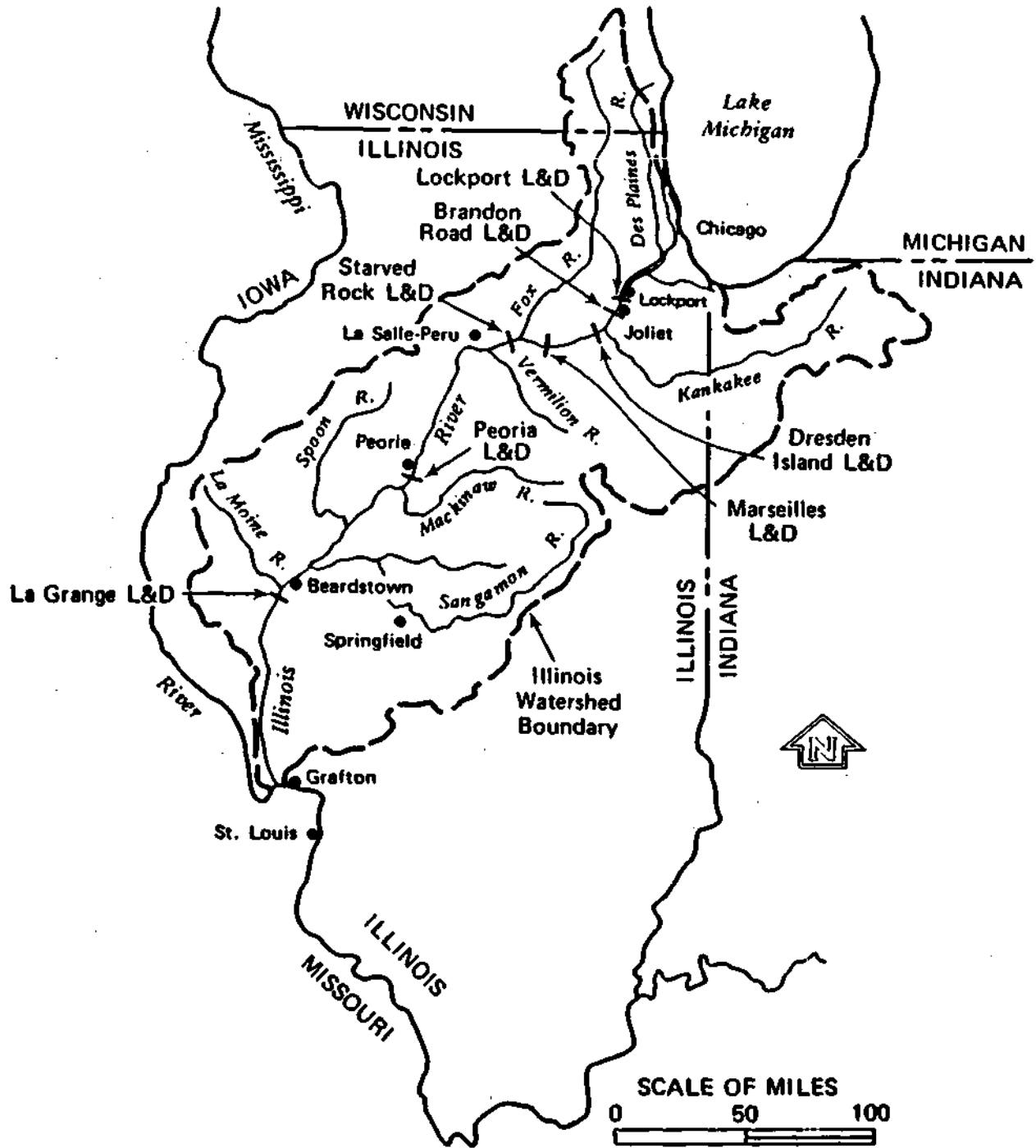


Figure 1. Illinois Waterway and drainage area

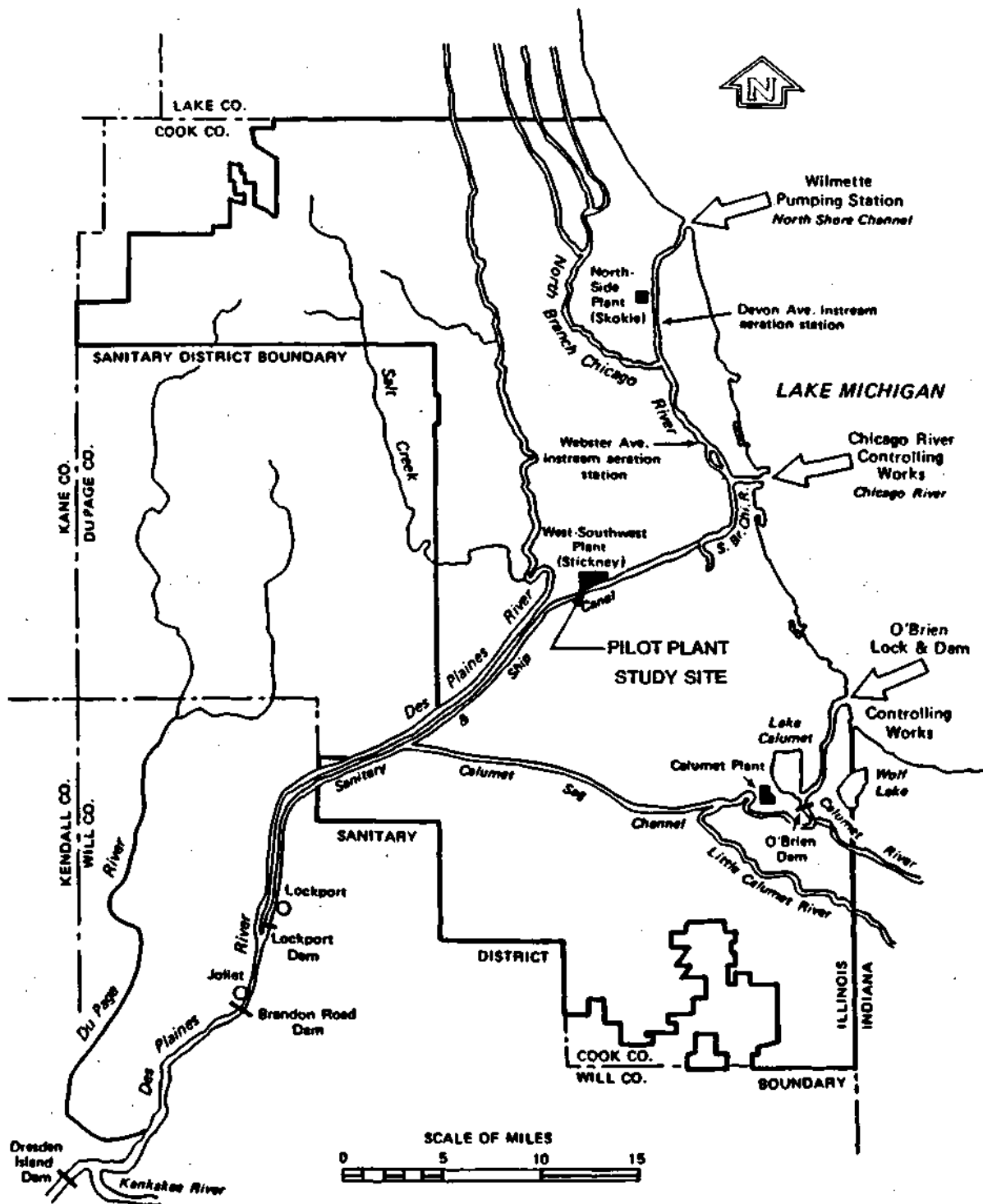


Figure 2. Chicago-area drainage system and Lake Michigan diversion inlets

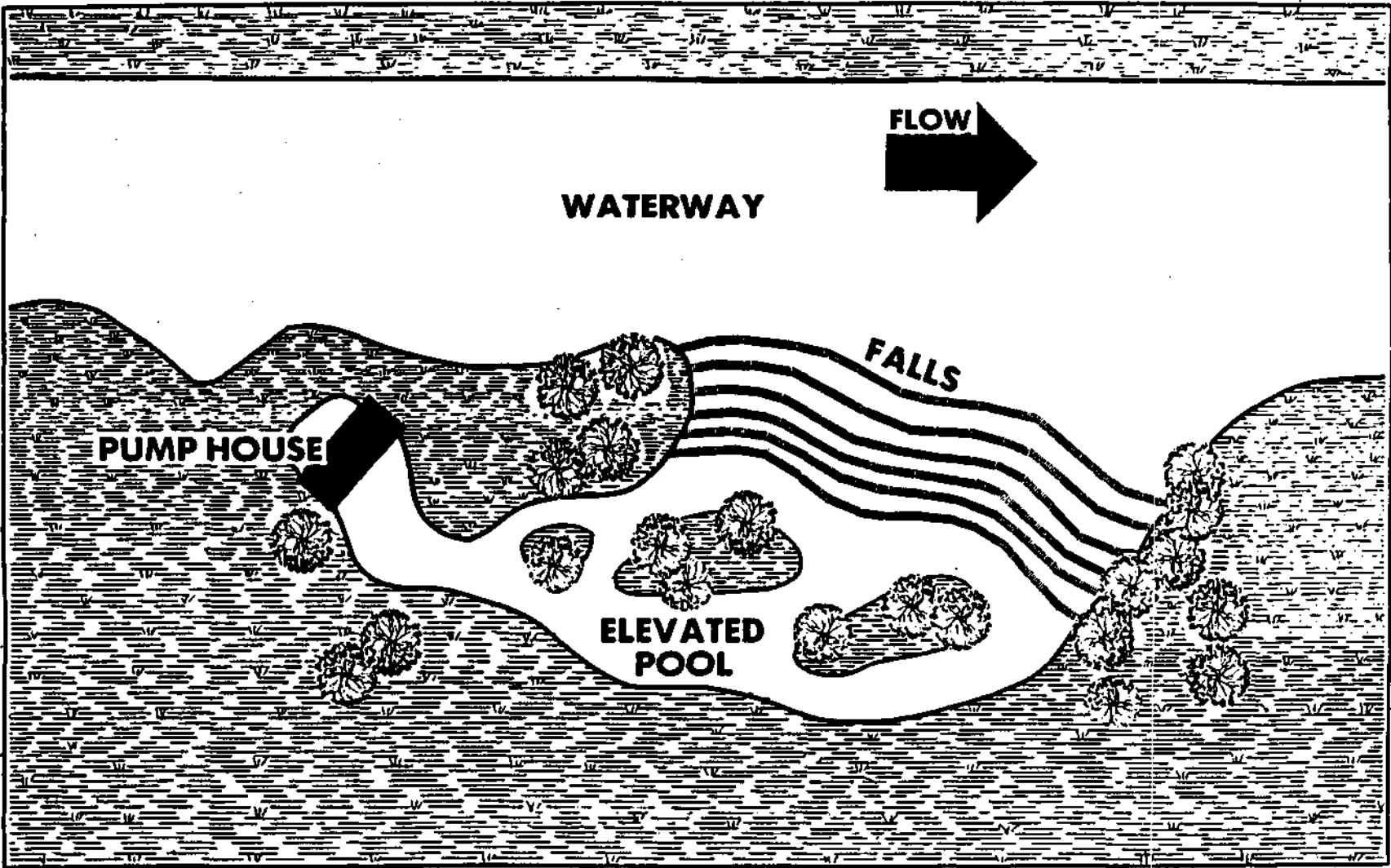


Figure 3. Slidestream elevated pool aeration station

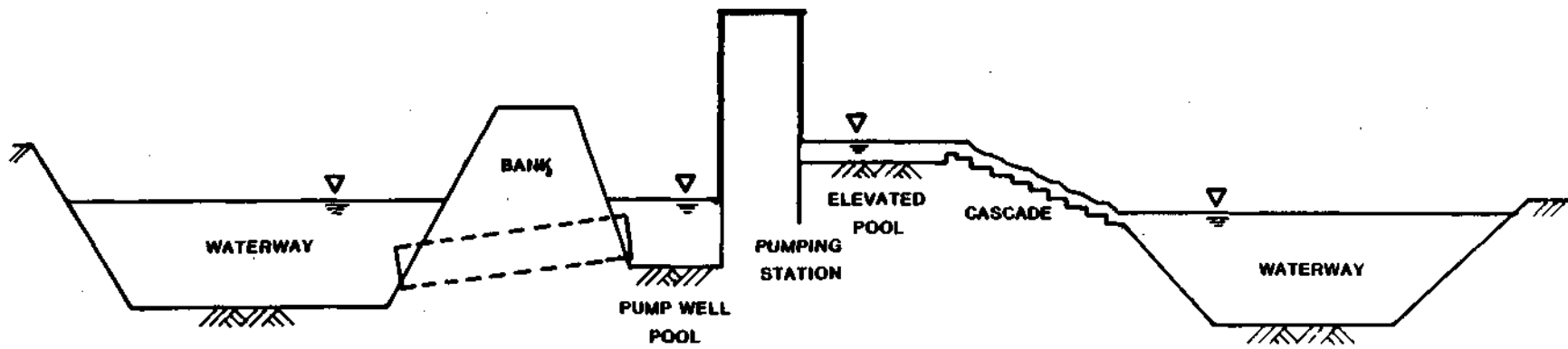


Figure 4. Schematic profile of a sidestream elevated pool aeration station

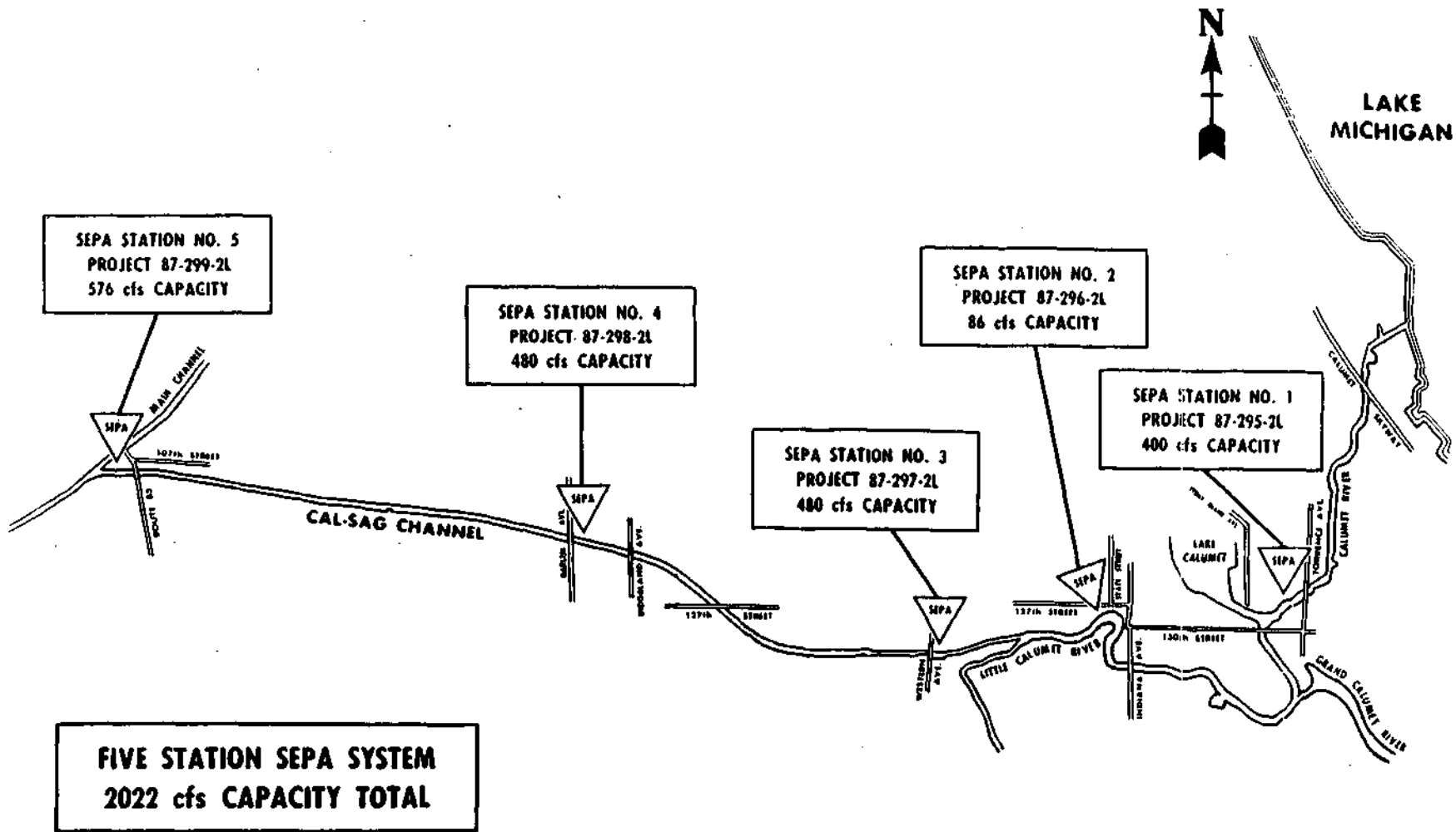


Figure 5. Proposed sidestream elevated pool aeration (SEPA) system

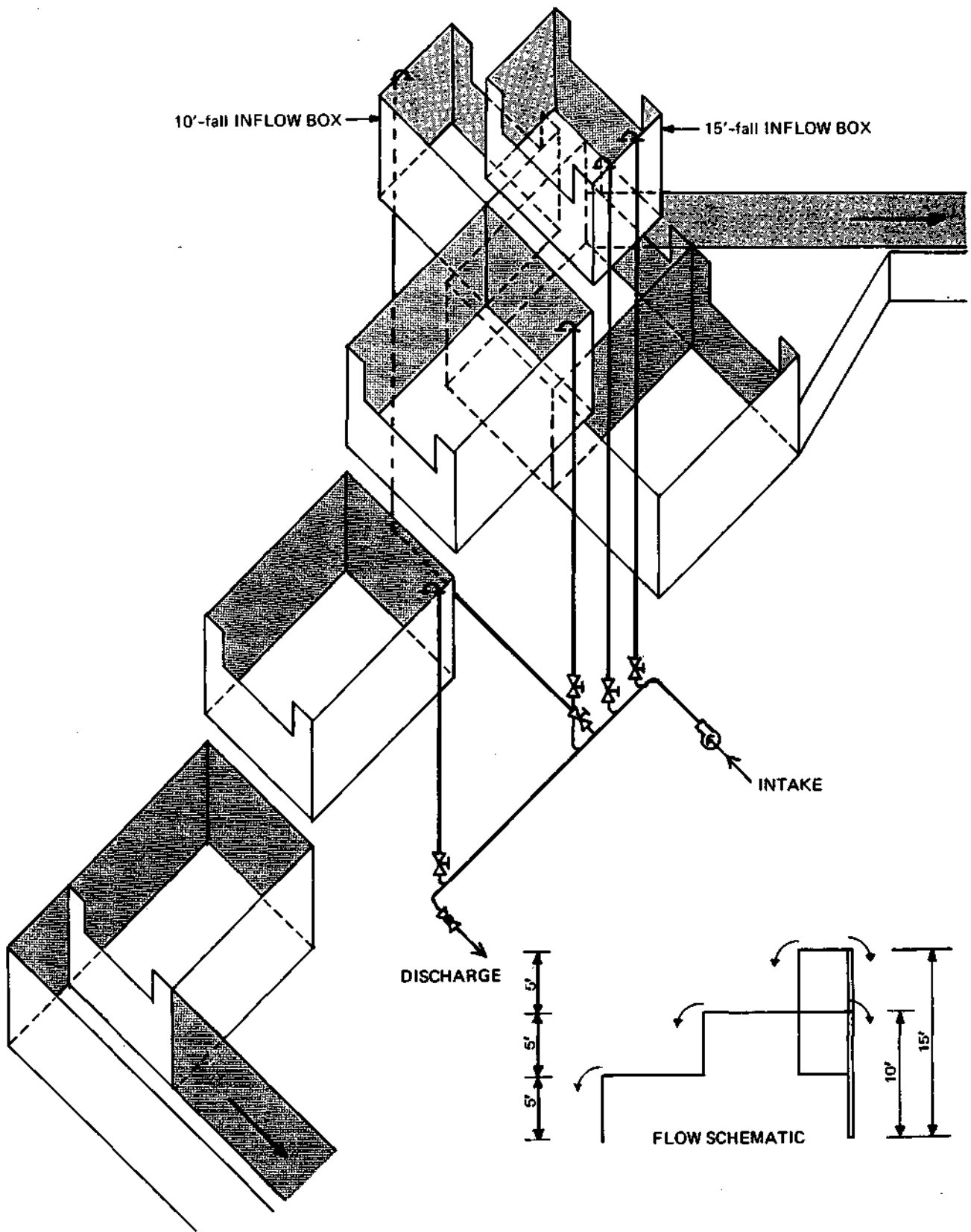


Figure 6. Schematic of SEPA pilot plant setup

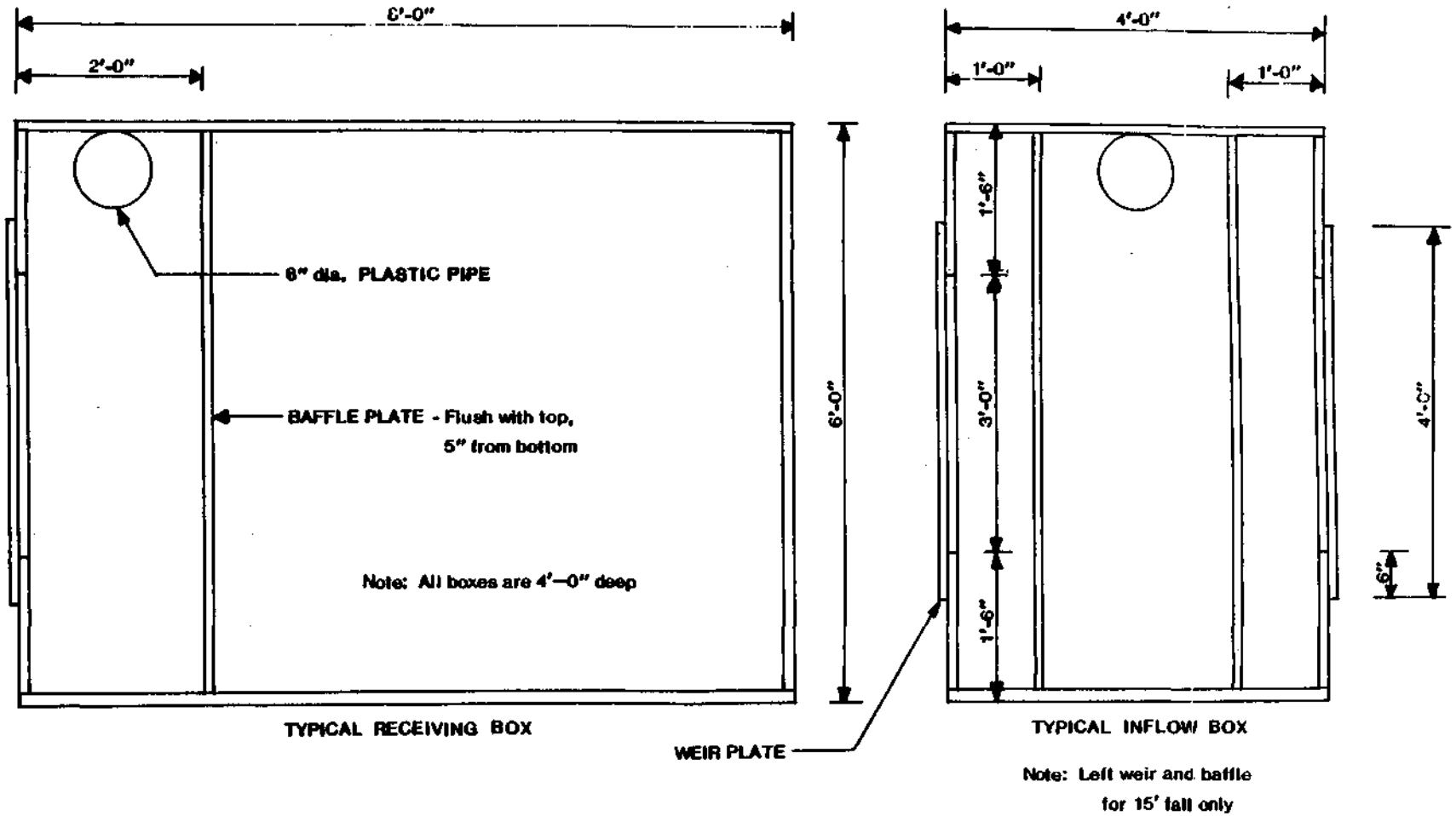


Figure 7. Plan view of SEPA pilot plant weir boxes

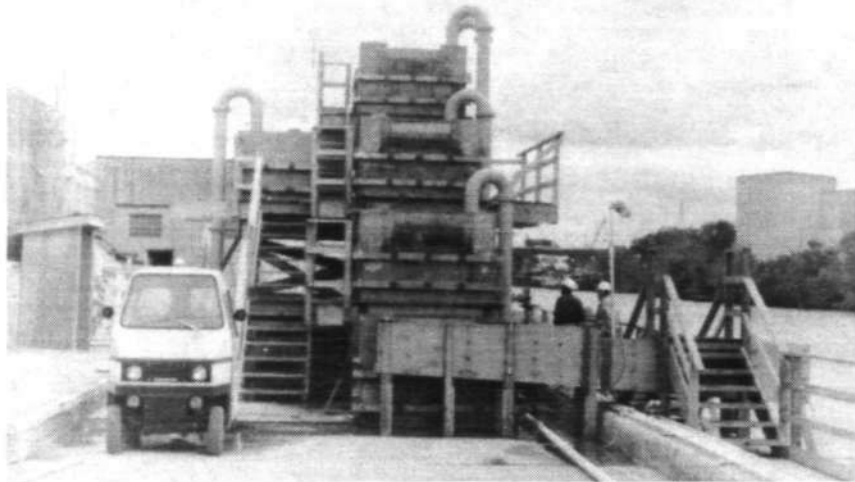


Figure 8. Pilot plant, showing front view of step-weir

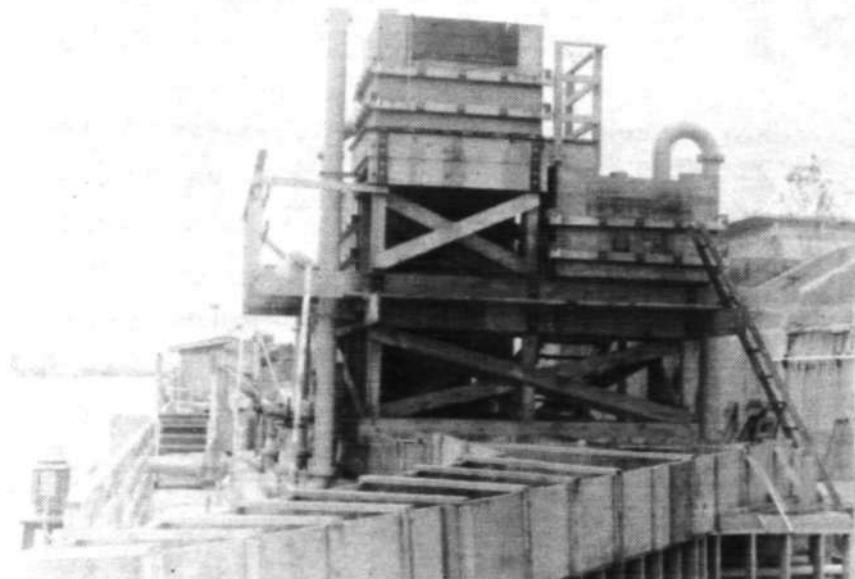


Figure 9. Pilot plant, showing front view of 10-foot and 15-foot free-fall weirs

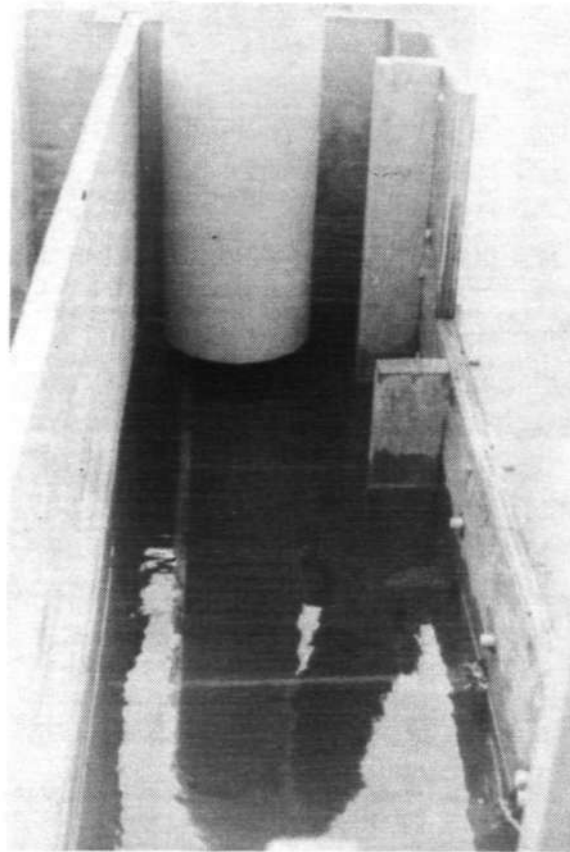


Figure 10. Inside of weir box

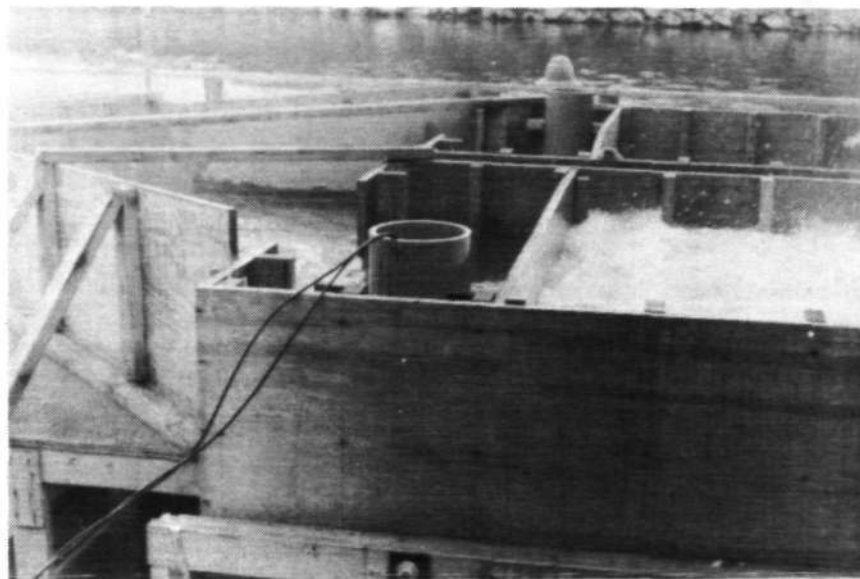


Figure 11. 10-foot free-fall weir receiving tank In operation

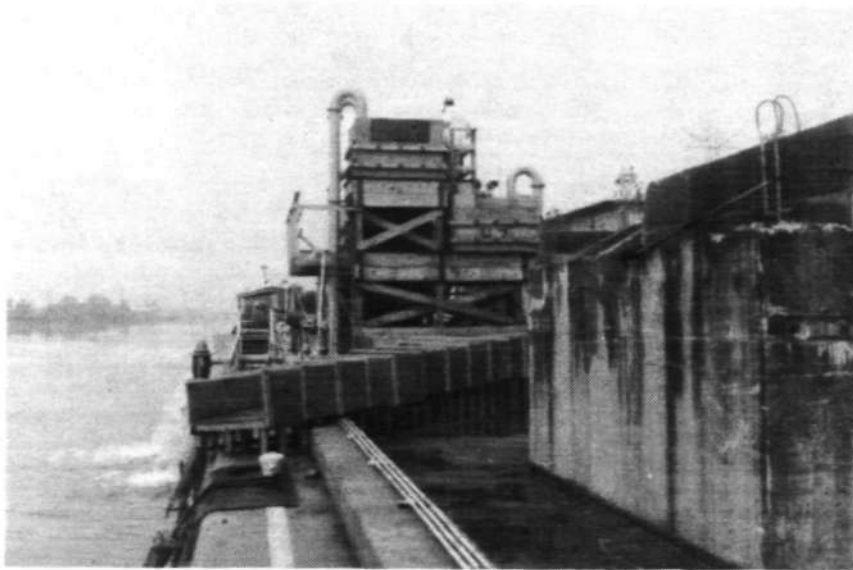
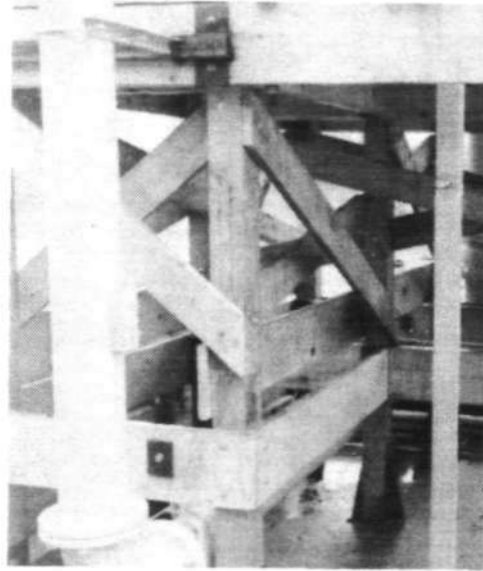


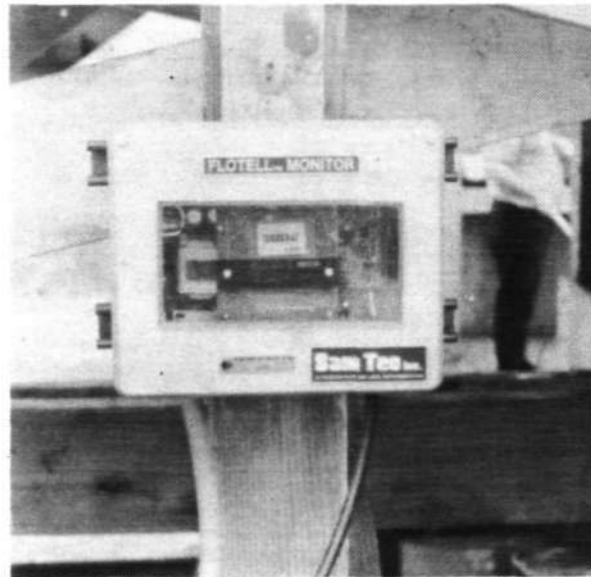
Figure 12. Overall view of the pilot plant, looking downstream along the Sanitary and Ship Canal



Figure 13. Pumping and piping arrangement, showing flow adjustment via a bypass waste line



a. Sonic Device



b. Totalizing Meter

Figure 14. Flow measuring and metering devices

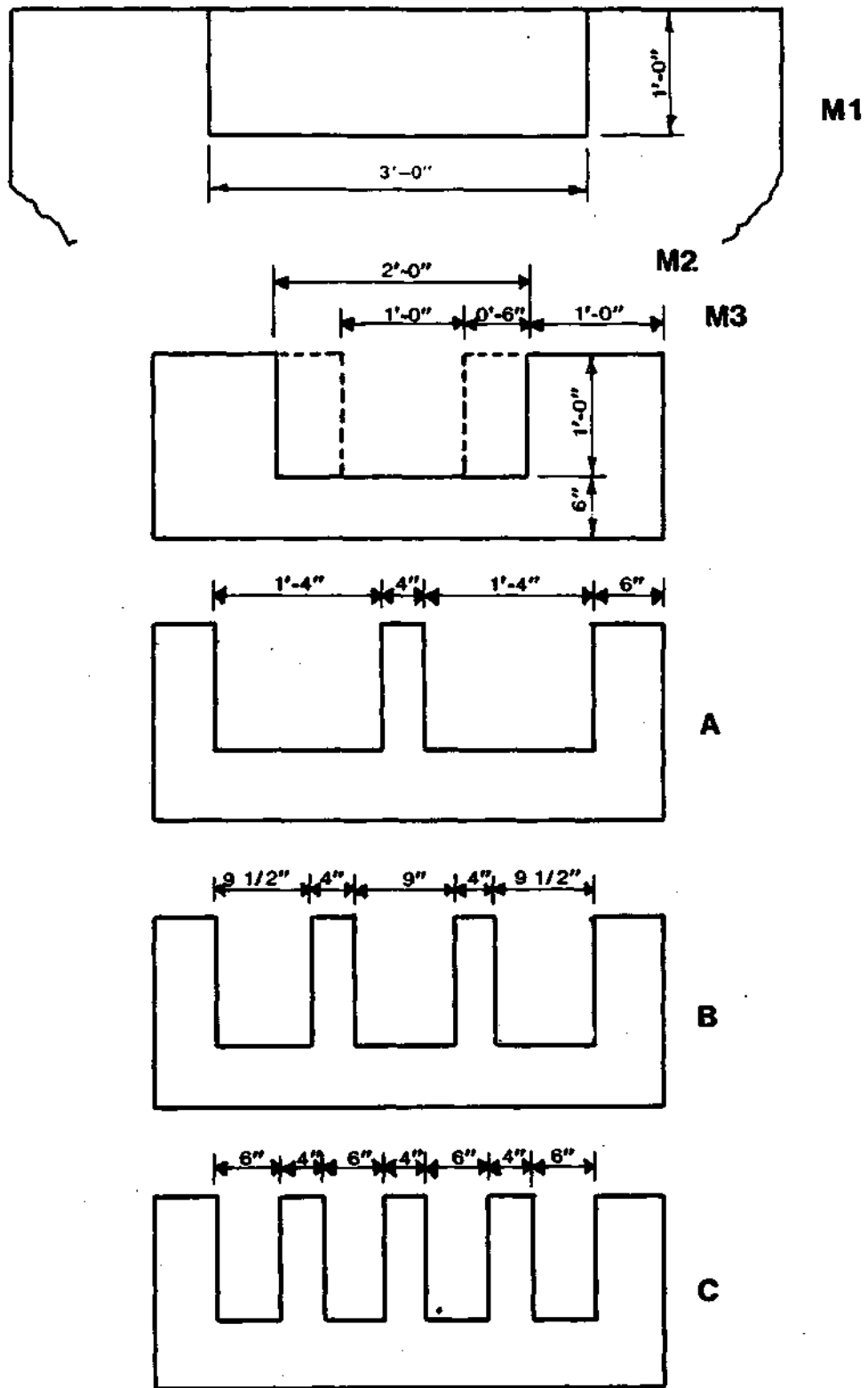


Figure 15. Unpartitioned and partitioned weir plates



**Figure 16. Clamping partitioned weir plate
in place on 10-foot free-fall weir**

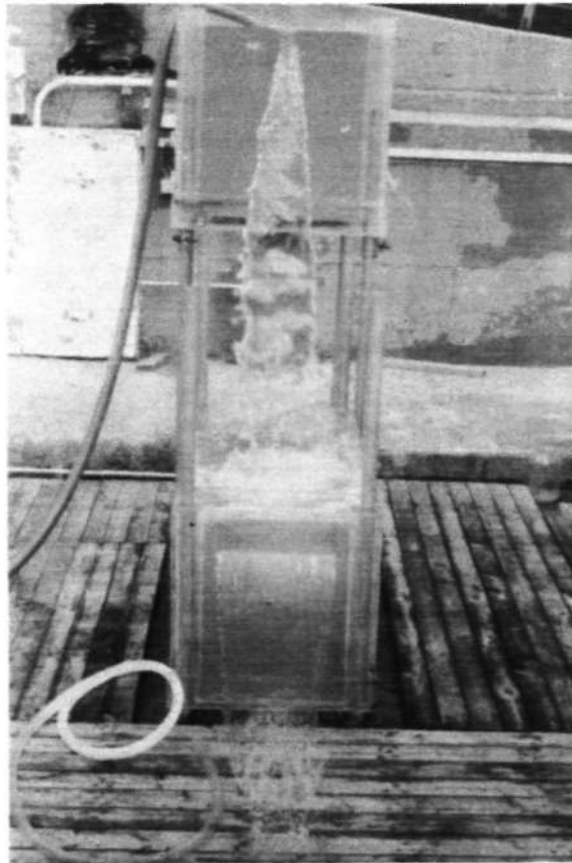


Figure 17. Butts weir-box control

Table 1. Pilot Plant Operational Conditions by Date

1987 Date	Weir face type	Flow rates (gpm) for weir operation modes of		
		15-ft free	10-ft free	5-ft steps
6/09	rect. -3'	1142, 812, 470	1062, 800, 432	1186, 800, 503
6/11	-3'	1292, 662, 388	1179, 821, 380	- 771, 331
6/15	-3'	1118, 606, 387	1125, 762, 450	1100, 822, 405
6/19	-3'	1213, 855, 400	1260, 866, 555	1072, 855, 300
6/22	-3'	1142, 755, 340	1000, 850, 370	1080, 780, 308
6/24	-3'	1100, 972, 336	1085, 875, 375	1110, 970, 333
6/26	-3'	1089, 817, 412	1167, 832, 385	1231, 946, 406
6/29	-3'	1100, 833, 415	1118, 775, 439	1104, 758, 430
7/01	-3'	1270, 820, 400	1151, 829, 488	1280, 833, 382
7/06	-3'	1100, 880, 447	1156, 880, 408	1180, 787, 420
7/08	-3'	1250, 824, 409	1180, 820, 400	1210, 807, 396
7/10	-3'	1143, 800, 459	1176, 844, 402	1248, 790, 403
7/13	-3'	1196, 814, 400	1184, 830, 475	1095, 824, 416
7/17	-3'	1247, 800, 400	1253, 847, 442	1147, 788, 390
7/20	-3'	1186, 800, 385	1161, 850, 421	1000, 767, 410
7/22	-3'	1250, 813, 386	1215, 883, 400	1072, 822, 428
8/07	-3'	- - -	1141, - 555	- - -
	-2'	- - -	1135, 740, 360	- - -
	-1'	- - -	1100 1000, -	- - -
	teeth -1	- - -	1054, - 520	- - -
	-2	- - -	- 892, 432	- - -
	-3	- - -	- 760, 370	- - -
8/10	rect. -3'	- - -	1155 1095, 575	- - -
	-2'	- - -	1100, 780, 340	- - -
	teeth -1	- - -	1028, - 540	- - -
	-2	- - -	930, - 450	- - -
	-3	- - -	- 816, 383	- - -
8/12	rect. -3'	- - -	1120, 666 -	- - -
	-2'	- - -	1150, 740, 420	- - -
	-1'	- - -	990, - -	- - -
	teeth -1	- - -	980, - 530	- - -
	-2	- - -	900, - 435	- - -
	-3	- - -	880, - 452	- - -
8/17	rect. -3'	- - -	1205, - 654	- - -
	-2'	- - -	1140, 975, 416	- - -
	-1'	- - -	1075, - -	- - -
	teeth -1	- - -	1020, - 622	- - -
	-2	- - -	925, - 462	- - -
	-3	- - -	- 880, 375	- - -
8/18	rect. -3'	- - -	1200, - 690	- - -
	-2'	- - -	1075, 800, 366	- - -
	-1'	- - -	1016, - -	- - -
	teeth -1	- - -	1066, - 566	- - -
	-2	- - -	1010, - 537	- - -
	-3	- - -	- 733, 560	- - -
8/28	rect. -3'	- - -	1110, - 550	- - -
	-2'	- - -	1190, 836, 410	- - -
	-1'	- - -	1090, 740 -	- - -

Concluded on next page

Table 1. Concluded

1987 Date	Weir face type	Flow rates (gpm) for weir operation modes of								
		15-ft free			10-ft free			5-ft steps		
8/31	teeth -1	-	-	-	1021,	-	490	-	-	-
	-2	-	-	-	-	888,	411	-	-	-
	-3	-	-	-	-	847,	409	-	-	-
	rect. -3'	-	-	-	1115,	-	540	-	-	-
	-2'	-	-	-	1095,	840,	402	-	-	-
	-1'	-	-	-	1040,	-	-	-	-	-
9/01	teeth -1	-	-	-	1108,	-	545	-	-	-
	-2	-	-	-	944,	-	441	-	-	-
	-3	-	-	-	-	780,	380	-	-	-
	rect. -3'	-	-	-	1191,	-	579	-	-	-
	-2'	-	-	-	-	814,	424	-	-	-
	-1'	-	-	-	1026,	-	468	-	-	-
9/08	teeth -1	-	-	-	1058,	-	544	-	-	-
	-2	-	-	-	955,	-	448	-	-	-
	-3	-	-	-	-	813,	401	-	-	-
	rect. -3'	-	-	-	1126,	-	567	-	-	-
	-2'	-	-	-	-	808,	411	-	-	-
	teeth -1	-	-	-	1006,	-	495	-	-	-
9/15	-2	-	-	-	910,	-	439	-	-	-
	-3	-	-	-	-	852,	412	-	-	-
	rect. -3'	-	-	-	1102,	-	515	1000,	-	-
	-2'	-	-	-	-	730,	352	-	-	-
	-1'	-	-	-	-	-	-	1000,	-	-
	teeth -1	-	-	-	1050	-	490	-	-	-
10/06	-2	-	-	-	-	860,	421	-	-	-
	-3	-	-	-	-	735,	360	-	-	-
	rect. -3'	-	-	-	1190,	-	480	1040,	-	-
	-2'	-	-	-	-	880,	444	-	-	-
	-1'	-	-	-	-	-	-	1040,	-	-
	teeth -1	-	-	-	1060	-	526	-	-	-
Special runs	-2	-	-	-	960	-	470	-	-	-
	-3	-	-	-	-	866,	440	-	-	-
	7/06 rect. -3'	-	-	612	-	-	-	-	-	612
7/08 -3'	-	-	600	-	-	-	-	-	600	

Table 2. Sanitary and Ship Canal Water Quality during Daily Sampling Runs

1987 Date	DO (mg/l)		Exp. DO Sat. (mg/l)		Temperature (°C)		COD (mg/l)	SS (mg/l)	MBAS (mg/l)	Algae (no/ml)	Equation 2 a-values				B-values	
	Start	Stop	Start	Stop	Start	Stop					Start	Stop	Start	Stop	Start	Stop
6/09	2.48	4.56	8.08	8.32	21.6	21.9	12	7	0.04	628	1.37	1.60	1.91	2.15	0.92	0.95
6/11	4.08	4.09	7.88	8.18	22.3	21.9	19	7	0.05	1108	0.98	1.33	1.37	1.74	0.92	0.95
6/15	1.88	3.78	7.88	7.51	23.1	23.8	25	6	0.05	1025	1.01	0.80	1.23	1.70	0.93	0.88
6/19	1.86	2.08	8.29	7.70	24.7	24.4	21	9	0.06	918	1.02	0.93	0.96	1.14	1.02	0.93
6/22	3.43	0.17	8.09	8.08	22.8	24.1	18	12	0.07	810	0.96	1.16	1.21	1.33	0.94	0.95
6/24	0.98	0.70	7.62	7.55	25.6	25.5	27	14	0.04	794	1.08	0.94	1.32	1.10	0.93	0.93
6/26	0.49	1.35	7.87	7.85	24.2	24.1	19	12	0.03	976	1.11	1.37	0.93	1.06	0.92	0.94
6/29	3.07	2.72	8.27	8.21	21.9	22.1	24	5	0.06	348	1.01	1.17	1.30	1.38	0.93	0.95
7/01	4.38	4.54	8.31	8.24	22.7	22.9	19	8	0.04	670	0.97	1.01	1.10	1.18	0.97	0.97
7/06	3.42	3.36	8.20	8.22	22.9	22.9	15	19	0.02	331	1.17	1.34	1.09	1.23	0.97	0.97
7/08	4.07	4.05	7.94	7.96	24.7	24.8	4	8	0.05	1000	1.10	1.01	1.33	1.15	0.96	0.97
7/10	3.28	3.67	7.22	7.28	27.6	27.6	6	8	0.03	889	0.99	0.84	1.38	1.08	0.92	0.94
7/13	2.17	2.00	7.30	7.50	27.2	26.4	17	5	0.13	1467	0.93	0.78	1.26	1.11	0.91	0.93
7/17	3.74	3.68	7.90	7.89	23.1	23.2	24	12	0.02	556	1.06	1.07	1.35	1.37	0.93	0.94
7/20	5.08	5.27	7.95	7.93	23.7	23.5	9	15	0.02	1245	1.12	0.98	1.36	1.22	0.97	0.96
7/22	5.44	5.38	7.85	7.85	25.4	25.4	0	11	0.02	689	0.88	0.99	1.19	1.24	0.96	0.95
8/07	5.52	5.52	8.05	-	23.9	24.0	16	19	0.02	67	1.01	-	1.28	-	0.96	-
8/10	5.26	4.89	8.05	7.98	23.9	24.0	4	28	0.01	423	0.96	0.90	1.30	1.11	0.95	0.96
8/12	4.64	4.68	8.03	7.95	26.4	26.3	86	19	0.01	556	0.92	0.86	1.27	0.95	0.94	0.98
8/17	1.37	2.06	8.05	8.05	24.4	24.8	49	22	0.10	78	0.81	0.86	0.92	0.98	0.94	0.95
8/18	0.56	0.72	8.23	8.05	24.6	24.7	42	15	0.05	2244	0.89	0.90	1.00	1.03	0.94	0.94
8/28	0.61	0.69	8.60	8.63	20.3	20.3	30	17	0.23	3933	0.87	0.91	0.99	0.98	0.94	0.96
8/31	0.89	0.65	8.60	8.63	20.1	20.2	22	24	0.03	1556	1.03	1.07	1.23	1.25	0.93	0.94
9/01	2.63	2.77	7.98	8.58	20.9	20.9	22	9	0.02	645	1.02	0.71	1.59	0.75	0.87	0.93
9/08	3.49	3.57	7.68	8.55	21.1	21.1	10	9	0.03	1023	0.91	0.87	1.57	1.00	0.87	0.96
9/15	3.84	3.84	8.60	8.63	21.9	21.7	39	15	0.03	667	1.20	1.27	1.25	1.38	0.99	0.98
10/06	5.35	5.69	10.15	10.18	15.2	15.2	52	6	0.02	512	1.00	1.02	1.14	1.02	0.97	1.00

Note: The B-values are computed by using equation 6 for determining DO saturation; to adjust these values for the pilot plant elevation above mean sea level (MSL), divide by 0.979.

COD - chemical oxygen demand; SS - suspended solids; MBAS - methylene blue active substances.

Table 3. Statistical Comparisons of Mean Values for the Various Experimental Schemes

Number of steps	Height (ft)	Average value within flow ranges (gpm/ft) of				Degrees of freedom		F-values			Null hypothesis					
		100-200	200-325	325-600	740-1040	f ₁	f ₂	Comp	F(.10)	F(.05)	Accept		Reject			
													F(.10)	F(.05)	F(.10)	F(.05)
<u>b-values</u>																
1	5	0.90	0.91	0.98	1.69*	2	144	0.78	2.30	3.00	X	X				
1	10	1.30	1.35	1.42	1.23	2	98	1.42	2.36	3.10	X	X				
1	15	1.28	1.62	1.64	-	2	47	5.52	2.44	4.01			X	X		
2	10	1.58	1.67	1.87	2.41*	2	96	1.89	2.37	3.18	X	X				
3	15	3.14	3.35	3.54	6.68*	2	48	2.24	2.42	3.20	X	X				
				(3.83)												
<u>r-values</u>																
1	5	1.93	1.94	2.00	2.54*	2	144	0.53	2.30	3.00	X	X				
1	10	3.02	3.20	3.00	2.72	2	98	2.56	2.36	3.10		X	X			
1	15	3.38	4.00	4.06	-	2	47	5.53	2.44	4.01			X	X		
2	10	3.65	3.77	4.06	5.12*	2	96	1.38	2.37	3.18	X	X				
3	15	6.84	7.23	7.33	13.70*	2	48	1.46	2.42	3.20	X	X				
				(8.04)												

Note: The null hypothesis is an assumption that the means are equal. F-values are ratios used to statistically test the null hypothesis; computed values must be less than the book values, F(.10) and F(.05), for the null hypothesis to be true. The two values shown in parentheses are mean values including a very high outlier for each. Values shown with asterisks were not included in ANOVA analyses because of limited data points.

Table 4. Statistical Comparisons of the Mean Values of Partitioned, One-Step, 10-Foot-High Weirs for Flows Ranging between 170 and 450 gpm/ft

Parameter	Number of teeth				Degrees of freedom		F-values			Null hypothesis						
	0	1	2	3	f ₁	f ₂	Comp	F(.10)	F(.05)	Accept		Reject				
													F(.10)	F(.05)	F(.10)	F(.05)
No. values	73	22	22	22												
Avg. b	1.36	1.44	1.34	1.28	3	135	2.00	2.08	2.60	X	X					
Avg. r	3.14	3.12	2.94	2.90	3	135	2.39	2.08	2.60		X	X				

Table 5. Summary of Results of Stepwise Regression Analyses
Relating the British Dam Aeration Coefficient (b)
to Appendix D Data

Step No.	Parameter addition	Parameter symbol	Standard error of estimate	Multiple correlation coefficient. R	Explained variation R ²
1	Number of steps	N	0.6317	0.7305	0.5337
2	Input DO saturation (%)	P _i	0.5922	0.7688	0.5911
3	Water fall height (ft)	h	0.5779	0.7819	0.6114
4	Unit flow rate (gpm/ft)	q	0.5630	0.7949	0.6319
5	Algae counts (No./ml)	A	0.5523	0.8040	0.6465
6	Water temperature (°C)	T	0.5452	0.8100	0.6561
7	Water quality factor, a	a	0.5398	0.8146	0.6636
8	Suspended solids (mg/l)	S	0.5380	0.8164	0.6666
9	Number of teeth	n	0.5366	0.8179	0.6689
10	Chemical oxygen demand (mg/l)	C	0.5367	0.8182	0.6695
11	Surfactants as MBAS (mg/l)	M	0.5371	0.8184	0.6697

Table 6. Summary of Results of Stepwise Regression Analyses
Relating the Deficit Ratio (r) to
Appendix D Data

Step No.	Parameter addition	Parameter symbol	Standard error of estimate	Multiple correlation coefficient. R	Explained variation R ²
1	Number of steps	N	1.2530	0.7491	0.5611
2	Water fall height (ft)	h	1.0853	0.8194	0.6714
3	Water quality factor, a	a	1.0637	0.8276	0.6850
4	Suspended solids (mg/l)	S	1.0451	0.8346	0.6965
5	Input DO saturation (%)	P _i	1.0301	0.8398	0.7053
6	Unit flow rate (gpm/ft)	q	1.0173	0.8447	0.7136
7	Algae counts (No./ml)	A	1.0049	0.8492	0.7211
8	Chemical oxygen demand (mg/l)	C	1.0032	0.8501	0.7226
9	Number of teeth	n	1.0029	0.8505	0.7233
10	Water temperature (°C)	T	1.0025	0.8509	0.7241
11	Surfactants as MBAS (mg/l)	M	1.0034	0.8510	0.7242

Table 7. Summary of Results of Stepwise Regression Analyses
 Relating the Output DO Percent Saturation (P_0)
 to Appendix D Data

Step No.	Parameter addition	Parameter symbol	Standard error of estimate	Multiple correlation coefficient. R	Explained variation R^2
1	Input DO saturation (%)	P_i	5.6062	0.7606	0.5785
2	Number of steps	N	3.7866	0.8989	0.8081
3	Water fall height (ft)	h	3.1347	0.9321	0.8688
4	Algae counts (No./ml)	A	2.8931	0.9426	0.8884
5	Water quality factor, a	a	2.8684	0.9437	0.8905
6	Water temperature (°C)	T	2.8585	0.9442	0.8915
7	Number of teeth	n	2.8464	0.9448	0.8927
8	Suspended solids (mg/l)	S	2.8367	0.9453	0.8936
9	Surfactants as MBAS (mg/l)	M	2.8378	0.9454	0.8937
10	Chemical oxygen demand (mg/l)	C	2.8401	0.9454	0.8938
11	Unit flow rate (gpm/ft)	q	2.8420	0.9454	0.8939

Table 8. Summary of Stepwise Regression Coefficients
Associated with Each Independent Step-Equation

Dependent variable	Step no.	Inter- cept	Independent variable regression coefficients																
			A	B	C	D	E	F	G	H	I	J	K	L					
P ₀	1	70.84	.27																
	2	61.74	.28	6.19															
	3	54.78	.32	4.13	.81														
	4	58.30	.30	4.09	.75	-.0020													
	5	55.16	.30	4.03	.76	-.0019	2.94												
	6	58.47	.30	4.06	.76	-.0019	2.25	-.11											
	7	60.18	.30	3.97	.77	-.0019	1.92	-.14	-67.8										
	8	59.85	.30	4.06	.76	-.0019	1.94	-.15	-82.3	.05									
	9	60.03	.30	4.06	.76	-.0018	1.88	-.15	-78.3	.05	-1.08								
	10	59.59	.30	4.06	.76	-.0018	1.98	-.14	-79.5	.05	-1.11	.004							
	11	59.89	.30	4.06	.76	-.0018	1.95	-.15	-81.8	.05	-1.10	.005	-.0004						
b	1	0.16		1.01															
	2	0.63	-.009	0.99															
	3	0.20	-.006	0.86	.050														
	4	-0.50	-.006	0.87	.051														.00073
	5	0.27	-.008	0.87	.046	-.00019													.00074
	6	1.15	-.008	0.87	.046	-.00018		-.038											.00061
	7	2.10	-.008	0.89	.045	-.00022	-.63	-.049											.00058
	8	2.01	-.008	0.91	.043	-.00021	-.62	-.052		.0096									.00054
	9	2.27	-.008	0.89	.044	-.00021	-.67	-.056	-10.69	.0116									.00051
	10	2.13	-.008	0.90	.045	-.00021	-.63	-.053	-11.32	.0113				.0016					.00048
	11	2.16	-.008	0.90	.045	-.00020	-.64	-.053	-10.72	.0109	-.16	.0016		.0016					.00048
r	1	0.52		2.12															
	2	-0.75		1.55	.21														
	3	-2.33		1.51	.22			1.57											
	4	-2.89		1.59	.21			1.66			.038								
	5	-2.36	-.008	1.64	.18			1.77			.034								
	6	-2.64	-.008	1.64	.18			1.77			.031								.00095
	7	-1.82	-.011	1.64	.17	-.00029	1.46				.028								.00097
	8	-2.02	-.010	1.65	.18	-.00027	1.52				.027			.0050					.00086
	9	-1.88	-.010	1.64	.18	-.00026	1.50		-12.01	.029				.0056					.00083
	10	-1.09	-.010	1.64	.18	-.00027	1.33	-.025	-14.11	.031				.0045					.00077
	11	-1.07	-.010	1.64	.18	-.00027	1.32	-.025	-13.47	.031	-.17	.0046		.0046					.00077

Table 9. Predicted Output Dissolved Oxygen Percentages (P_0)
 Derived by Using Equation 6
 for 15-Foot Step-Weirs

P_i	P_0 -values for N-values of				
	1	2	3	4	5
0	71.1	75.2	79.3	83.5	87.6
5	72.7	76.8	80.9	85.1	89.2
10	74.3	78.4	82.5	86.7	90.8
15	75.9	80.0	84.1	88.3	92.4
20	77.5	81.6	85.7	89.9	94.0
27	79.7	83.8	88.0	92.1	96.2
30	80.7	84.8	88.9	93.1	97.2
40	83.9	88.0	92.1	96.3	100.4
50	87.1	91.2	95.3	99.5	104.6
60	90.3	94.4	98.5	102.7	106.8
70	93.5	97.6	101.7	105.9	110.0
80	96.7	100.8	104.9	109.1	113.2
90	99.9	104.0	108.1	112.3	116.4

Note: P_0 and P_i are, respectively, the output and input dissolved oxygen percentages of saturation referenced to equation 4. N is the number of steps in a weir system.

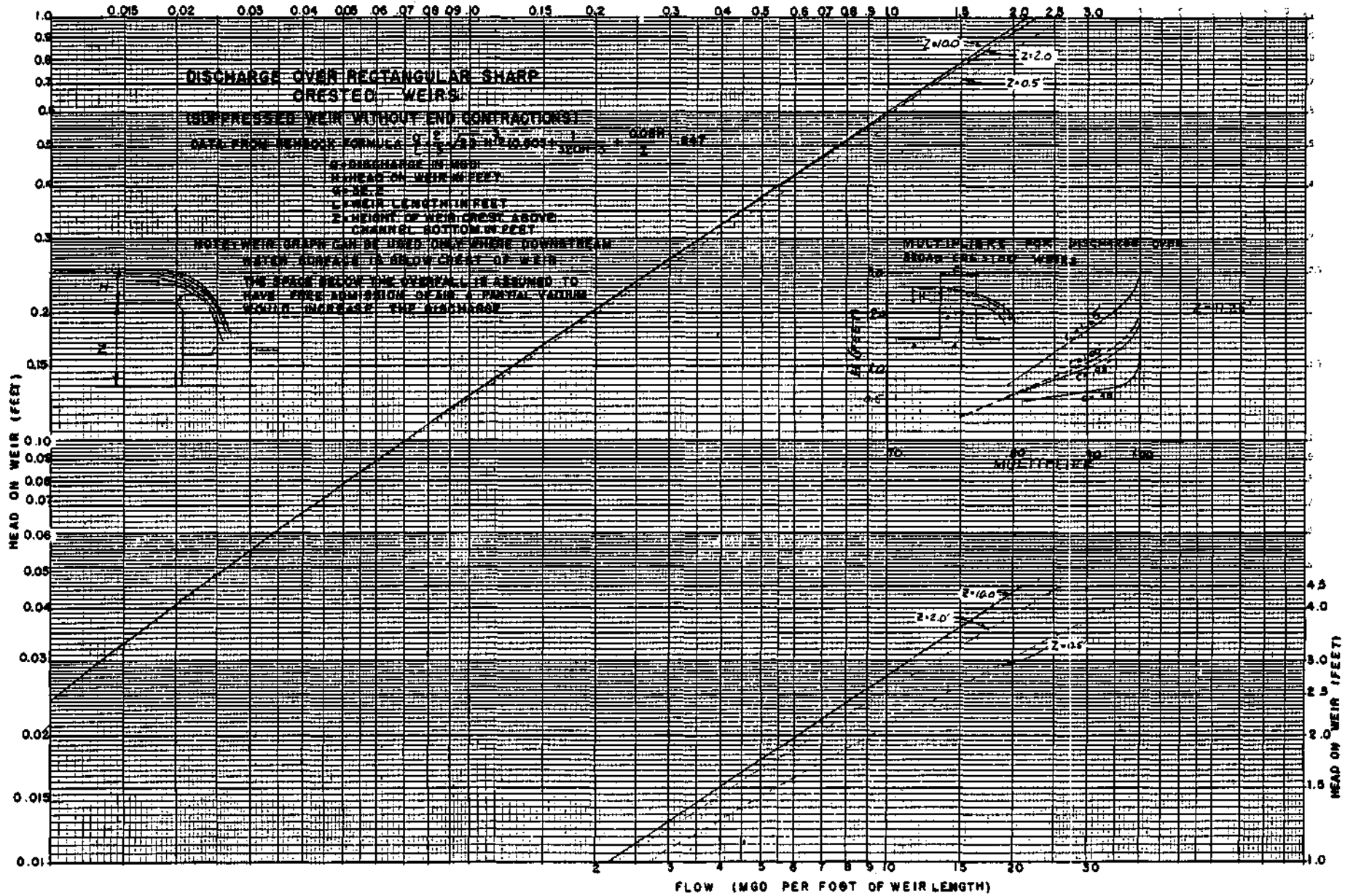
Table 10. Predicted Output Dissolved Oxygen Concentrations
 for Various Steps Associated with a 15-Foot-High Weir:
 $C_s = 7.44$ mg/l at 30°C

<u>No. of steps, n</u>	<u>h (ft.)</u>	<u>r_h eq. 7</u>	<u>r_h^n</u>	<u>Output DO, C_B (mg/l)</u>	
				<u>Eqs. 1,4,7</u>	<u>Eqs. 4,6</u>
1	15	4	4.00	6.08	5.92
2	7.5	2.5	6.25	6.57	6.23
3	5	2.0	8.00	6.76	6.54
4	3.75	1.75	9.38	6.86	6.85
5	3	1.6	10.49	6.92	7.16

Appendix A

Chicago Pump Company Hydraulic Chart
for
Discharge Over Rectangular Sharp-Crested Weirs

FLOW (MGD PER FOOT OF WEIR LENGTH)

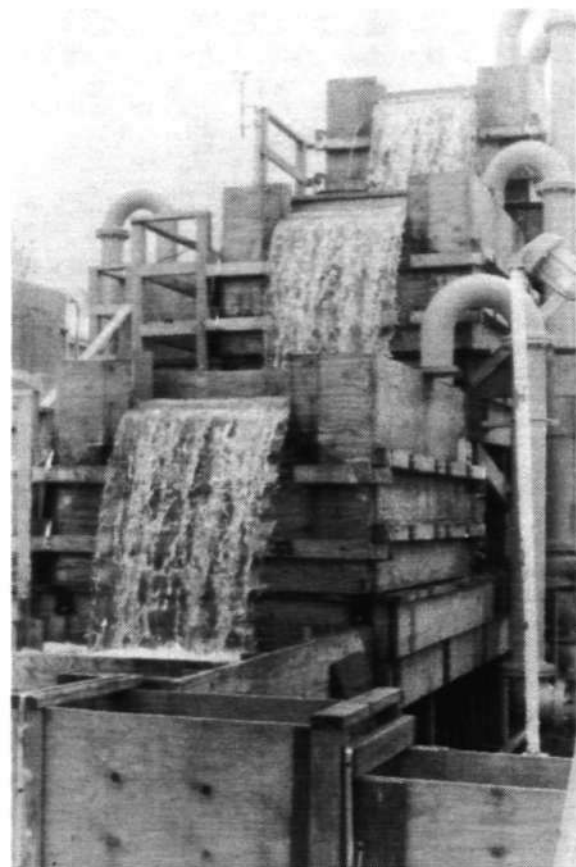


Appendix B

Photographs Showing Various Modes of Operation

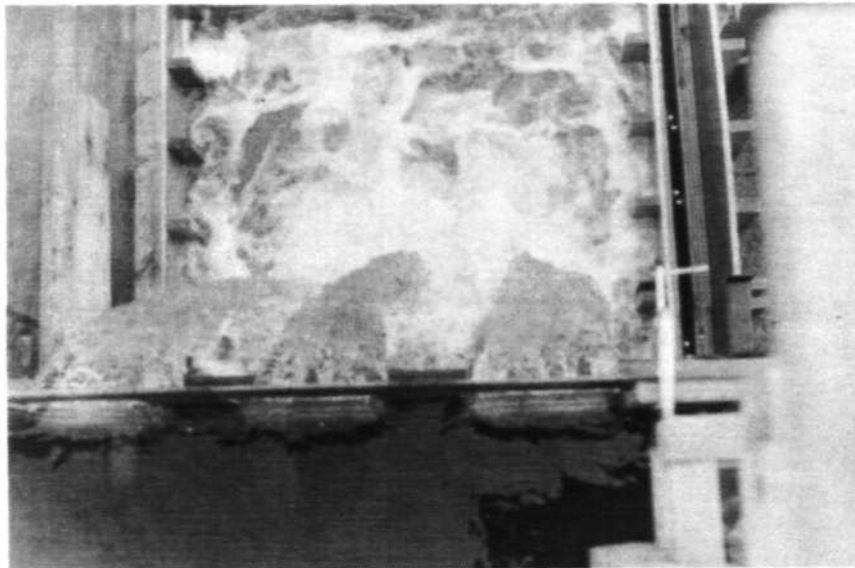


Front view of 15-foot step-weir

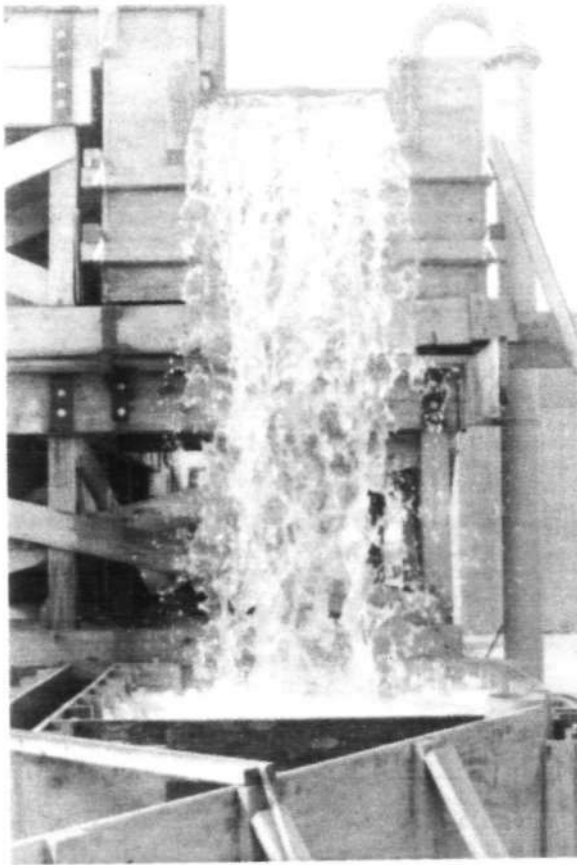


Angular view of 15-foot step-weir

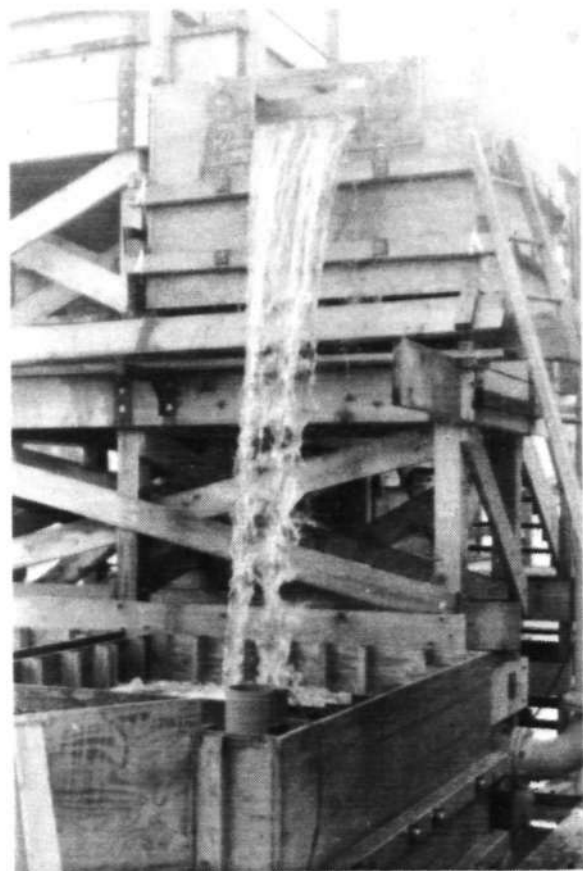
**Side view of 3-foot-wide,
15-foot free-fall weir**



Top view of partitioned 10-foot free-fall weir



Front view of 3-foot-wide,
10-foot free-fall weir at high flow



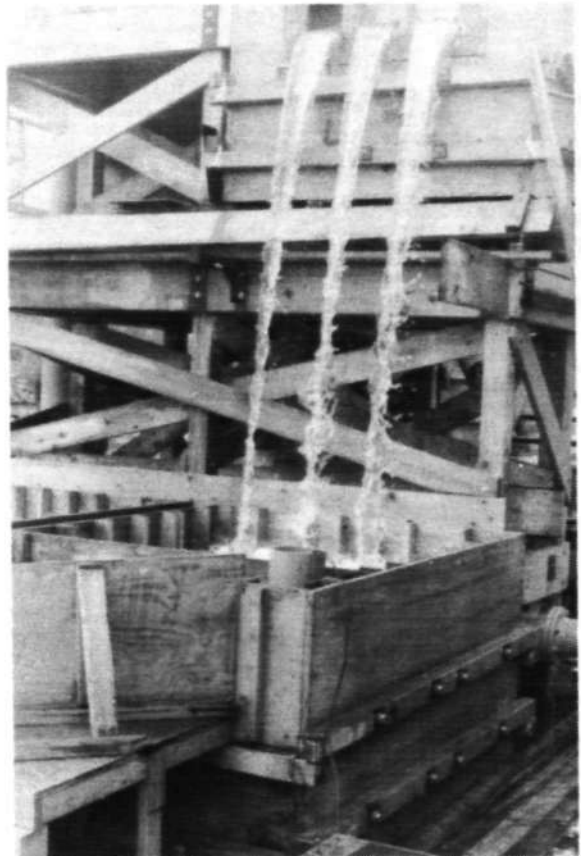
Front view of 2-foot-wide,
10-foot free-fall weir at medium flow



**Front view of two-partition,
10-foot free-fall weir at high flow**

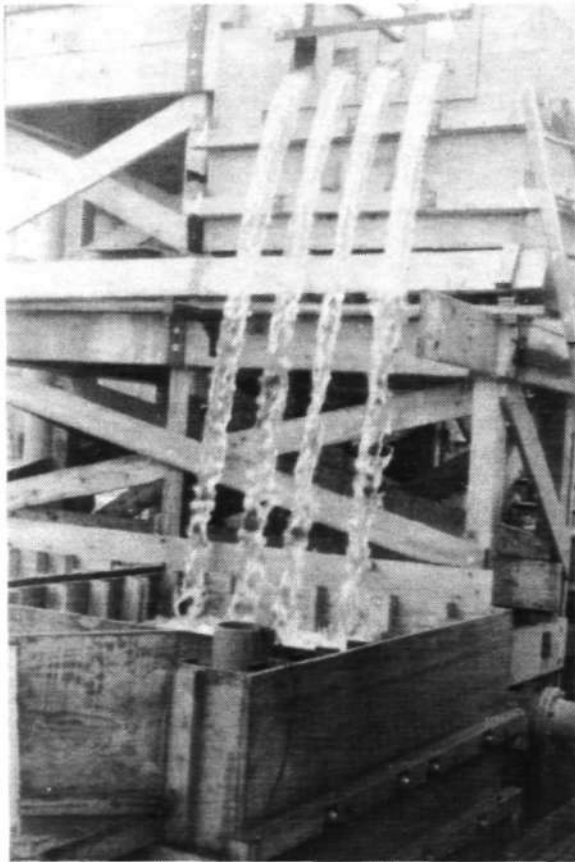


**Front view of three-partition,
10-foot free-fall weir at high flow**



**Front view of three-partition,
10-foot free-fall weir at low flow**

**Front view of four-partition,
10-foot free-fall weir at high flow**



**Front view of four-partition,
10-foot free-fall weir at low flow**

Appendix C

ANOVA Results for b-values and r-values for
Flow Ranges Grouped By Weir Geometric Designs

Appendix C-1. 5-Foot Free-Fall; No Partitions

Appendix C-1a
b-values

		b-values for flow ranges in gpm/ft of				
		100 - 168	253 - 323	333 - 427	1000-1040*	
0.952	1.430	0.960	1.383	0.984	0.703	1.373
0.717	0.916	0.730	0.924	0.804	1.255	1.276
0.365	0.657	0.470	0.582	0.393	0.982	1.409
1.059	1.347	1.045	1.403	1.068	0.421	4.021
0.660	1.000	0.955	1.019	0.971	1.234	0.997
0.495	0.583	0.715	0.621	0.635	0.687	1.084
1.260	1.373	1.211	1.293	1.075	0.356	
0.692	0.990	0.836	0.966	0.793	0.562	
0.366	0.537	0.550	0.381	0.474	1.447	
1.251	1.162	1.151	1.036	1.588	0.921	
0.733	0.813	0.793	0.896	1.182	0.658	
0.380	0.349	0.441	0.362	0.869	1.374	
1.456	1.669	1.630	1.550	1.374	1.085	
1.095	1.027	1.084	1.016	0.858	0.458	
0.590	0.499	0.398	0.549	0.697	1.411	
1.450	1.330	1.370	1.431	1.268	0.989	
0.875	0.871	0.904	0.958	0.758	0.620	
0.412	0.326	0.482	0.375	0.482	1.373	
1.265	1.613	1.157	1.257	1.354	1.276	
0.821	0.705	0.848	0.998	0.996	1.409	
0.429	0.456	0.456	0.495	0.434	1.738	
1.170	1.834	1.233	1.753	1.279	1.202	
0.823	0.845	0.850	1.068	1.059	1.074	
0.487	0.675	0.508	0.552	0.524	0.985	
				1.357	1.568	
				1.092		
n =	48	48	51	6		
avg. =	0.898	0.909	0.983	1.693		

* Not included in the ANOVA test

Appendix C-lb
r-values

r-values for flow ranges in gpm/ft of

	100 - 168	253 - 323	333 - 427	1000-1040*		
2.302	2.360	2.286	2.326	2.295	1.776	2.668
1.980	1.870	1.976	1.884	2.058	2.304	2.550
1.498	1.623	1.629	1.558	1.517	2.018	2.710
2.362	2.455	2.221	2.535	2.033	1.436	4.352
1.849	2.080	2.115	2.115	1.897	2.296	1.083
1.637	1.630	1.834	1.679	1.615	1.720	1.902
2.135	2.462	2.133	2.360	2.057	1.373	
1.623	2.053	1.783	2.014	1.779	2.384	
1.330	1.571	1.516	1.400	1.465	1.869	
2.193	2.263	2.113	2.106	2.505	1.496	
1.698	1.883	1.766	1.955	2.120	2.526	
1.362	1.378	1.427	1.387	1.824	1.972	
2.490	2.381	2.600	2.332	2.372	1.694	
2.120	1.412	2.064	1.873	1.843	2.344	
1.603	2.399	1.391	1.471	1.685	2.062	
2.449	1.916	2.404	2.510	2.373	1.448	
1.874	1.548	1.927	2.011	1.819	2.322	
1.411	2.649	1.494	1.632	1.520	1.926	
2.430	1.722	2.291	2.257	2.473	1.580	
1.927	1.468	1.945	2.000	2.083	2.668	
1.483	2.681	1.507	1.496	1.472	2.550	
2.323	1.772	2.364	2.620	2.232	2.710	
1.929	1.615	1.939	1.994	2.021	2.446	
1.550	1.850	1.561	1.513	1.506	2.000	
				2.499	1.894	
				2.206		
n =	48	48		51		6
avg. -	1.929	1.944		2.002		2.544

* Not included in the ANOVA test

Appendix C-2. 10-Foot Free-Fall; No Partitions

Appendix C-2a
b-values

b-values for flow ranges in gpm/ft of

<u>123 - 230</u>		<u>254 - 400</u>		<u>405 - 595</u>	<u>740 - 1100</u>
1.336	1.198	1.818	1.203	1.258	1.136
0.995	1.186	0.556	1.141	1.259	0.891
1.286	1.271	1.110	1.491	1.243	0.891
1.425	1.174	1.257	1.414	1.381	1.528
1.515	1.265	1.242	1.338	1.190	1.093
1.623	0.930	1.407	1.355	1.837	1.038
1.365	1.189	1.446	1.746	1.516	1.169
1.276	1.299	1.528	1.643	1.637	1.375
1.104	1.322	1.138	0.570	1.188	1.940
1.216	1.234	1.532	1.258	1.074	
1.219	1.417	1.394	1.322	1.095	
1.197	1.197	1.314	1.417	1.150	
1.444	1.367	1.641	1.459	1.381	
1.390	1.057	1.654	1.538	2.046	
1.374	1.384	1.531	1.213	1.969	
1.946		1.032	1.546	1.169	
1.254		1.352	1.370	1.818	
1.303		1.358	1.219		
1.721		1.425	1.242		
1.517		1.556	1.310		
1.815		1.616	1.557		
0.523		1.026	1.261		
0.976		1.114	1.630		

n = 38
avg. = 1.298

46
1.354

17
1.424

9
1.229

Appendix C-2b
r-values

r-values for flow ranges in gpm/ft of					
<u>123 - 230</u>		<u>254 - 400</u>		<u>405 - 595</u>	<u>740 - 1100</u>
3.174	2.879	3.415	2.496	3.037	2.535
2.559	2.878	2.322	3.343	3.138	2.453
2.974	3.390	2.687	3.172	2.998	2.453
3.139	3.125	3.003	2.846	2.816	3.242
3.264	2.937	3.298	2.852	2.657	2.543
3.393	2.447	3.469	4.326	2.522	2.518
2.802	2.879	3.122	4.164	3.163	2.574
2.783	3.397	3.518	2.378	3.260	3.104
2.608	3.322	2.895	3.037	3.406	3.135
2.793	3.000	3.784	3.395	2.666	
2.593	3.150	3.413	3.511	2.753	
2.572	3.029	3.055	3.180	2.613	
3.277	3.392	3.386	3.504	2.489	
3.210	2.677	3.989	2.929	3.189	
3.060	2.838	3.492	3.826	3.202	
3.218		2.685	3.388	3.637	
2.724		3.089	2.925	3.415	
2.773		3.057	2.950		
4.297		3.072	3.086		
3.931		3.334	3.304		
3.460		3.391	3.138		
2.290		2.492	3.912		
2.584		2.634	2.937		
n =	38	46		17	9
avg. =	3.022	3.200		2.998	2.729

Appendix C-3. 15-Foot Free-Fall; No Partitions

Appendix C-3a
b-values

Appendix C-3b
r-values

b-values for flow ranges			r-values for flow ranges		
In gpm/ft of			in gpm/ft of		
<u>112 - 157</u>	<u>200 - 293</u>	<u>363 - 417</u>	<u>112 - 157</u>	<u>200 - 293</u>	<u>363 - 417</u>
0.577	0.706	0.825	2.506	2.511	3.078
0.784	1.315	1.277	2.561	3.537	3.397
1.272	1.247	1.278	2.830	2.823	2.865
1.252	1.504	1.394	3.294	3.792	3.617
1.346	1.814	1.983	3.660	4.468	4.737
1.448	1.597	1.760	3.693	4.024	4.397
1.212	1.432	1.450	3.169	3.675	3.747
1.592	1.939	1.819	4.056	4.677	4.395
1.189	1.379	1.520	3.080	3.400	3.632
1.517	1.808	1.796	4.032	4.637	4.636
1.193	1.636	1.658	3.442	4.286	4.306
1.319	1.566	1.608	3.256	4.029	3.648
1.451	2.198	1.569	3.507	4.648	3.826
1.469	1.554	1.830	3.787	3.599	4.465
1.538	1.712	2.696	3.875	4.036	6.197
1.393	1.758	1.784	3.411	4.332	3.998
	2.113			5.020	
	1.870			4.187	
<hr/>	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>
n = 16	18	16	16	18	16
avg. = 1.285	1.619	1.640	3.385	3.999	4.059

Appendix C-4. 2-Step, 10-Foot Step-Weir; No Partitions

Appendix C-4a
b-values

Appendix C-4b
r-values

	b-values for flow ranges in gpm/ft of			r-values for flow ranges in gpm/ft of				
	100-200	257-315	333-416	1000-1040*	100-200	257-315	333-416	1000-1040*
	1.180	2.618	1.772	2.993	2.967	5.278	4.723	6.802
	0.901	1.469	1.010	3.048	4.369	3.393	3.122	6.909
	1.640	1.643	1.847	2.791	3.027	4.517	3.856	4.714
	0.987	1.036	1.336	0.790	3.465	3.218	3.064	2.051
	1.713	1.981	1.695		2.158	4.696	3.659	
	0.805	1.545	1.024		3.724	3.879	2.606	
	1.789	1.878	2.846		2.312	3.805	5.311	
	0.863	1.169	1.894		4.588	2.704	3.866	
	2.248	1.769	2.149		2.664	3.733	4.372	
	1.031	0.984	1.342		4.683	2.520	3.106	
	2.040	2.785	1.920		2.858	5.367	4.316	
	1.032	1.193	1.022		4.481	2.871	2.764	
	1.928	2.220	2.389		2.989	4.633	5.153	
	1.103	1.147	1.190		4.412	2.878	3.067	
	2.248	1.944	2.278		3.035	4.455	4.511	
	1.341	0.811	1.328		5.106	2.930	3.042	
	2.380	2.029	2.558		3.389	4.585	5.513	
	1.385	1.148	1.654		4.650	3.027	3.918	
	2.202	2.210	2.202		2.899	4.383	4.650	
	1.147	1.265	1.147		4.648	2.935	2.899	
	2.198	2.496	1.760		4.261	5.360	3.950	
	1.879	1.460	0.813		2.595	3.550	2.362	
	0.920	2.235	2.455		4.405	4.753	4.457	
	2.578	1.085	1.274		2.612	2.820	2.796	
	1.220	1.828	2.402		4.560	4.118	5.043	
	2.141	1.005	1.355		4.597	2.709	3.282	
	1.170	2.456	2.548		2.966	4.369	4.983	
	2.179	1.287	1.271		4.563	2.764	2.986	
	0.934	2.402	2.320		2.528	5.045	4.472	
	2.565	1.355	1.367		4.750	3.282	3.043	
	1.278	0.993	3.234		2.862	2.237	7.331	
		1.245	3.058			2.993	6.994	
		2.867	2.929			5.222	4.893	
		1.356	2.097			3.016	3.788	
n =	31	34	34	4	31	34	34	4
avg. =	1.581	1.673	1.867	2.406	3.649	3.766	4.056	5.119

* Not included in the ANOVA test

Appendix C-5. 3-Step, 15-Foot Step-Weir; No Partitions

Appendix C-5a
b-values

Appendix C-5b
r-values

	b-values for flow ranges in gpm/ft of				r-values for flow ranges in gpm/ft of			
	100-168	200-323	333-427	1000-1040*	100-168	200-323	333-427	1000-1040*
	2.383	2.647	2.617	8.020	6.831	7.357	7.164	18.432
	2.670	3.642	3.015	5.342	7.151	8.613	6.227	8.967
	2.235	2.838	2.478		4.607	5.768	5.360	
	2.385	2.496	5.113		5.071	5.325	9.687	
	4.071	3.676	3.617		8.461	7.464	7.368	
	3.058	3.226	2.870		6.475	6.920	6.560	
	2.939	2.865	3.377		6.945	6.712	7.585	
	2.936	3.106	3.553		6.943	7.157	6.791	
	3.617	3.393	4.442		7.161	6.827	9.792	
	3.784	4.081	3.055		8.320	8.998	6.679	
	3.638	3.001	2.353		7.940	6.653	5.424	
	2.503	4.480	3.587		5.872	9.668	6.666	
	3.525	3.620	3.938		6.221	7.735	8.436	
	3.245	2.462	3.546		7.116	5.705	7.217	
	3.106	3.529	3.614		6.697	6.428	7.067	
	4.072	3.832	8.402		7.672	8.236	19.449	
		3.209	5.544			6.754	9.266	
		4.175				7.902		
n =	16	18	17	2	16	18	17	2
avg. =	3.135	3.349	3.831 (3.545)	6.681	6.843	7.235	8.043 (7.331)	13.699

* Not included in the ANOVA test

Note: values in parentheses indicate averages excluding outlier values;
8.402 for b, 19.499 for r.

Appendix C-6. 10-Foot Free-Fall Weir; Partitioned; Flows 170 - 450 gpm/ft

Appendix C-6a
b-values

Appendix C-6b
r-values

	b-values for teeth number				r-values for teeth number						
	0	1	2	3	0	1	2	3			
0.570	1.303	1.491	1.195	1.037	0.931	2.378	2.773	3.343	2.950	2.691	2.517
1.258	1.721	1.414	1.590	1.449	1.386	3.037	4.297	3.172	3.419	3.152	3.031
1.322	1.517	1.837	1.655	1.455	1.452	3.395	3.931	3.163	3.588	3.227	3.208
1.417	1.815	1.338	1.132	1.251	1.000	3.511	3.460	2.846	2.515	2.687	2.389
1.459	1.186	1.355	1.098	1.068	1.043	3.180	2.878	2.852	2.607	2.565	2.522
1.538	0.556	1.746	1.234	1.121	1.133	3.504	2.322	4.326	2.631	2.487	2.513
1.213	1.110	1.643	1.379	1.360	1.310	2.929	2.687	4.164	3.155	3.106	3.012
1.546	1.257	1.696		1.436	1.360	3.826	3.003		3.166	2.946	2.966
1.370	1.258	1.320		1.242	1.259	3.388	3.037		2.757	2.666	2.706
1.219	1.242	1.637		1.531	1.457	2.925	3.298		4.024	3.863	3.750
1.242	1.407	1.935		1.468	1.468	2.950	3.469		3.554	2.928	2.928
1.310	1.446	1.531		1.027	0.910	3.086	3.122		3.339	2.675	2.482
1.557	1.528	1.567		1.393	1.334	3.304	3.518		3.441	3.060	2.966
1.261	1.138	1.458		1.473	1.403	3.138	2.895		2.937	3.264	3.120
1.630	1.532	1.159		1.234	1.080	3.912	3.784		2.700	2.679	2.484
1.203	1.394	1.234		1.136	1.056	2.937	3.413		2.631	2.663	2.542
1.336	1.314	1.475		1.227	1.231	3.174	3.055		3.310	1.934	2.650
0.995	1.641	1.770		1.432	1.440	2.559	3.386		3.175	3.224	3.219
1.286	1.259	1.320		1.564	1.446	2.974	3.138		2.757	3.073	3.038
1.425	1.654	1.698		1.258	1.237	3.139	3.989		4.151	2.681	2.669
1.515	1.243	1.793		1.570	1.543	3.264	2.998		3.371	3.949	3.926
1.623	1.531	0.896		1.717	1.585	3.393	3.492		2.462	3.264	3.085
1.365	1.032					2.802	2.685				
1.276	1.352					2.783	3.089				
1.104	1.358					2.608	3.057				
1.216	1.425					2.793	3.072				
1.219	1.556					2.593	3.334				
1.197	1.616					2.572	3.391				
1.444	1.381					3.277	2.816				
1.390	1.026					3.210	2.492				
1.374	1.114					3.060	2.634				
1.946	1.169					3.218	2.522				
1.254	1.141					2.724	2.496				
n=	73	22	22	22		73	22	22	22		
avg. =	1.358	1.444	1.339	1.276		3.136	3.120	2.945	2.897		

Appendix D

Data Used in the Stepwise Regression Analyses

No. of steps	Fall ft.	Flow gpm/ ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
1	5	395	0	28.4	68.8	21.6	12	7	0.04	628	1.37	0.984	2.295
1	5	395	0	68.8	84.9	21.6	12	7	0.04	628	1.37	0.804	2.058
1	5	395	0	84.9	90.1	21.5	12	7	0.04	628	1.37	0.393	1.517
1	5	367	0	27.8	63.6	23.3	25	6	0.05	1025	0.97	1.068	2.033
1	5	367	0	63.6	79.7	23.3	25	6	0.05	1025	0.97	0.971	1.897
1	5	367	0	79.7	86.5	23.5	25	6	0.05	1025	0.97	0.635	1.615
1	5	357	0	26.9	63.2	24.4	21	9	0.06	918	0.96	1.075	2.057
1	5	357	0	63.2	80.0	24.3	21	9	0.06	918	0.96	0.793	1.779
1	5	357	0	80.0	86.4	24.3	21	9	0.06	918	0.96	0.474	1.465
1	5	360	0	40.1	76.2	22.7	18	12	0.07	810	0.96	1.588	2.505
1	5	360	0	76.2	88.7	22.7	18	12	0.07	810	0.96	1.182	2.120
1	5	360	0	88.7	93.8	22.7	18	12	0.07	810	0.96	0.869	1.824
1	5	370	0	09.5	61.9	25.6	27	14	0.04	794	0.94	1.370	2.372
1	5	370	0	61.9	79.3	25.6	27	14	0.04	794	0.94	0.858	1.843
1	5	370	0	79.3	87.7	25.6	27	14	0.04	794	0.94	0.697	1.685
1	5	410	0	09.6	62.0	24.2	19	12	0.03	976	1.06	1.268	2.373
1	5	410	0	62.0	79.2	24.1	19	12	0.03	976	1.06	0.758	1.819
1	5	410	0	79.2	86.3	24.0	19	12	0.03	976	1.06	0.482	1.520
1	5	368	0	31.5	72.3	21.9	24	5	0.06	348	1.12	1.354	2.473
1	5	368	0	72.3	86.8	21.9	24	5	0.06	348	1.12	0.996	2.083
1	5	368	0	86.8	91.0	21.9	24	5	0.06	348	1.12	0.434	1.472
1	5	427	0	51.8	78.5	22.7	19	8	0.04	670	0.98	1.279	2.232
1	5	427	0	78.5	89.3	22.7	19	8	0.04	670	0.98	1.059	2.021
1	5	427	0	89.3	92.9	22.7	19	8	0.04	670	0.98	0.524	1.506
1	5	393	0	38.5	75.4	22.9	15	19	0.02	331	1.12	1.357	2.499
1	5	393	0	75.4	88.8	22.9	15	19	0.02	331	1.12	1.092	2.206
1	5	393	0	88.8	93.7	22.9	15	19	0.02	331	1.12	0.703	1.776
1	5	403	0	49.3	78.1	24.7	4	8	0.05	1000	1.01	1.255	2.304
1	5	403	0	78.1	89.1	24.7	4	8	0.05	1000	1.01	0.982	2.018
1	5	403	0	89.1	92.4	24.6	4	8	0.05	1000	1.01	0.421	1.436
1	5	416	0	50.2	78.3	27.9	6	8	0.03	889	0.95	1.234	2.296
1	5	416	0	78.3	87.4	27.9	6	8	0.03	889	0.95	0.687	1.720
1	5	416	0	87.4	90.8	27.9	6	8	0.03	889	0.95	0.356	1.373
1	5	365	0	24.5	68.3	26.7	17	5	0.13	1467	0.82	1.568	2.384
1	5	365	0	68.3	83.1	26.6	17	5	0.13	1467	0.82	0.985	1.869
1	5	365	0	83.1	88.7	26.6	17	5	0.13	1467	0.82	0.562	1.496

No. of steps	Fall ft.	Flow gpm/ ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
1	5	382	0	41.7	76.9	23.1	24	12	0.02	556	1.06	1.447	2.526
1	5	382	0	76.9	88.3	23.2	24	12	0.02	556	1.06	0.921	1.972
1	5	382	0	88.3	93.1	23.1	24	12	0.02	556	1.06	0.658	1.694
1	5	333	0	62.0	83.8	23.5	9	15	0.02	1245	0.98	1.374	2.344
1	5	333	0	83.8	92.1	23.5	9	15	0.02	1245	0.98	1.085	2.062
1	5	333	0	92.1	94.6	23.6	9	15	0.02	1245	0.98	0.458	1.448
1	5	357	0	64.5	84.6	24.7	1	11	0.02	689	0.91	1.411	2.322
1	5	357	0	84.6	92.1	24.6	1	11	0.02	689	0.91	0.989	1.926
1	5	357	0	92.1	95.0	24.6	1	11	0.02	689	0.91	0.620	1.580
1	5	333	0	44.0	79.8	21.8	39	15	0.03	667	1.26	1.373	2.668
1	5	333	0	79.8	92.4	21.8	39	15	0.03	667	1.26	1.276	2.550
1	5	333	0	92.4	97.1	21.8	39	15	0.03	667	1.26	1.409	2.710
1	5	347	0	35.3	80.5	15.2	52	6	0.02	512	1.02	1.738	2.446
1	5	347	0	80.5	90.2	15.2	52	6	0.02	512	1.02	1.202	2.000
1	5	347	0	90.2	94.8	15.2	52	6	0.02	512	1.02	1.074	1.894
1	5	1000	0	44.6	79.3	21.9	39	15	0.03	667	1.26	1.373	2.668
1	5	1000	0	79.3	91.9	21.8	39	15	0.03	667	1.26	1.276	2.550
1	5	1000	0	91.9	97.0	21.8	39	15	0.03	667	1.26	1.409	2.710
1	5	1040	0	52.4	89.0	15.2	52	6	0.02	512	1.02	4.021	4.352
1	5	1040	0	89.0	89.9	15.2	52	6	0.02	512	1.02	0.997	1.083
1	5	1040	0	89.9	94.5	15.2	52	6	0.02	512	1.02	1.084	1.902
1	5	267	0	29.1	69.0	21.5	12	7	0.04	628	1.40	0.960	2.286
1	5	267	0	69.0	84.3	21.5	12	7	0.04	628	1.40	0.730	1.976
1	5	267	0	84.3	90.4	21.5	12	7	0.04	628	1.40	0.470	1.629
1	5	257	0	48.3	78.7	23.3	19	7	0.05	1108	1.17	1.045	2.221
1	5	257	0	78.7	90.0	23.3	19	7	0.05	1108	1.17	0.955	2.115
1	5	257	0	90.0	94.6	23.3	19	7	0.05	1108	1.17	0.715	1.834
1	5	274	0	28.2	63.6	23.3	25	6	0.05	1025	0.94	1.211	2.133
1	5	274	0	63.6	79.6	23.3	25	6	0.05	1025	0.94	0.836	1.783
1	5	274	0	79.6	86.5	23.4	25	6	0.05	1025	0.94	0.550	1.516
1	5	295	0	22.5	63.4	24.2	21	9	0.06	918	0.95	1.151	2.113
1	5	295	0	63.4	79.3	24.2	21	9	0.06	918	0.95	0.793	1.766
1	5	295	0	79.3	85.4	24.2	21	9	0.06	918	0.95	0.441	1.427
1	5	260	0	37.3	75.9	22.8	18	12	0.07	810	0.99	1.630	2.600
1	5	260	0	75.9	88.3	22.8	18	12	0.07	810	0.99	1.084	2.064
1	5	260	0	88.3	91.6	22.8	18	12	0.07	810	0.99	0.398	1.391
1	5	323	0	9.3	62.2	25.4	27	14	0.04	794	0.98	1.370	2.404
1	5	323	0	62.2	80.5	25.4	27	14	0.04	794	0.98	0.904	1.927
1	5	323	0	80.5	86.9	25.4	27	14	0.04	794	0.98	0.482	1.494
1	5	315	0	6.1	59.3	24.2	19	12	0.03	976	1.10	1.157	2.291
1	5	315	0	62.0	79.1	24.1	19	12	0.03	976	1.10	0.848	1.945
1	5	315	0	79.1	86.2	24.0	19	12	0.03	976	1.10	0.456	1.507
1	5	253	0	31.5	71.1	22.0	24	5	0.06	348	1.14	1.233	2.364
1	5	253	0	71.1	85.1	21.9	24	5	0.06	348	1.14	0.850	1.939
1	5	253	0	85.1	90.5	21.9	24	5	0.06	348	1.14	0.508	1.561

No. of steps	Fall ft.	Flow gpm/ ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
1	5	278	0	51.3	79.1	22.7	19	8	0.04	670	0.97	1.383	2.326
1	5	278	0	79.1	89.0	22.6	19	8	0.04	670	0.97	0.924	1.884
1	5	278	0	89.0	92.9	22.6	19	8	0.04	670	0.97	0.582	1.558
1	5	262	0	39.3	76.0	22.9	15	19	0.02	331	1.11	1.403	2.535
1	5	262	0	76.0	88.6	22.9	15	19	0.02	331	1.11	1.019	2.115
1	5	262	0	88.6	93.2	22.9	15	19	0.02	331	1.11	0.621	1.679
1	5	269	0	50.3	79.0	24.8	4	8	0.05	1000	1.02	1.293	2.360
1	5	269	0	79.0	89.6	24.7	4	8	0.05	1000	1.02	0.966	2.014
1	5	269	0	89.6	92.6	24.7	4	8	0.05	1000	1.02	0.381	1.400
1	5	263	0	46.5	74.7	27.7	6	8	0.03	889	0.97	1.036	2.106
1	5	263	0	74.7	87.0	27.7	6	8	0.03	889	0.97	0.896	1.955
1	5	263	0	87.0	90.7	27.7	6	8	0.03	889	0.97	0.362	1.387
1	5	275	0	24.9	67.8	26.5	17	5	0.13	1467	0.80	1.550	2.332
1	5	275	0	67.8	82.8	26.5	17	5	0.13	1467	0.80	1.016	1.873
1	5	275	0	82.8	88.3	26.5	17	5	0.13	1467	0.80	0.549	1.471
1	5	263	0	42.8	77.2	23.2	24	12	0.02	556	1.06	1.431	2.510
1	5	263	0	77.2	88.7	23.2	24	12	0.02	556	1.06	0.958	2.011
1	5	263	0	88.7	93.1	23.2	24	12	0.02	556	1.06	0.375	1.632
1	5	256	0	61.5	82.9	23.6	9	15	0.02	1245	1.00	1.257	2.257
1	5	256	0	82.9	91.4	23.7	9	15	0.02	1245	1.00	0.998	2.000
1	5	256	0	91.4	94.3	23.7	9	15	0.02	1245	1.00	0.495	1.496
1	5	274	0	61.3	85.0	24.8	1	11	0.02	689	0.90	1.753	2.620
1	5	274	0	85.0	92.5	25.2	1	11	0.02	689	0.90	1.068	1.994
1	5	274	0	92.5	95.0	25.1	1	11	0.02	689	0.90	0.552	1.513
1	5	168	0	31.7	70.3	21.5	12	7	0.04	628	1.43	0.952	2.302
1	5	168	0	70.3	85.0	21.5	12	7	0.04	628	1.43	0.717	1.980
1	5	168	0	85.0	90.0	21.4	12	7	0.04	628	1.43	0.365	1.498
1	5	110	0	47.0	77.6	21.9	19	7	0.05	1108	1.33	1.059	2.362
1	5	110	0	77.6	87.9	21.9	19	7	0.05	1108	1.33	0.660	1.849
1	5	110	0	87.9	92.6	21.9	19	7	0.05	1108	1.33	0.495	1.637
1	5	135	0	39.3	71.6	22.9	25	6	0.05	1025	0.91	1.260	2.135
1	5	135	0	71.6	82.5	22.9	25	6	0.05	1025	0.91	0.692	1.623
1	5	135	0	82.5	92.7	22.9	25	6	0.05	1025	0.91	0.366	1.330
1	5	100	0	25.1	65.9	24.3	21	9	0.06	918	0.93	1.251	2.193
1	5	100	0	65.9	79.9	24.3	21	9	0.06	918	0.93	0.733	1.698
1	5	100	0	79.9	85.3	24.2	21	9	0.06	918	0.93	0.380	1.362
1	5	103	0	29.9	71.8	22.9	18	12	0.07	810	1.03	1.456	2.490
1	5	103	0	71.8	86.7	22.9	18	12	0.07	810	1.03	1.095	2.120
1	5	103	0	86.7	91.7	22.9	18	12	0.07	810	1.03	0.590	1.603
1	5	111	0	8.6	62.7	25.5	27	14	0.04	794	0.96	1.450	2.449
1	5	111	0	62.7	80.1	25.4	27	14	0.04	794	0.96	0.875	1.874
1	5	111	0	80.1	85.9	25.4	27	14	0.04	794	0.96	0.412	1.411
1	5	135	0	5.8	61.4	24.1	19	12	0.03	976	1.11	1.265	2.430
1	5	135	0	61.4	80.0	24.0	19	12	0.03	976	1.11	0.821	1.927
1	5	135	0	80.0	86.5	24.0	19	12	0.03	976	1.11	0.429	1.483

No. of steps	Fall ft.	Flow gpm/ ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
1	5	143	0	31.4	70.5	22.0	24	5	0.06	348	1.17	1.170	2.323
1	5	143	0	70.5	84.7	22.0	24	5	0.06	348	1.17	0.823	1.929
1	5	143	0	84.7	90.1	22.0	24	5	0.06	348	1.17	0.487	1.550
1	5	127	0	51.2	79.4	22.6	19	8	0.04	670	0.97	1.430	2.360
1	5	127	0	79.4	89.0	22.6	19	8	0.04	670	0.97	0.916	1.870
1	5	127	0	89.0	93.3	22.5	19	8	0.04	670	0.97	0.657	1.623
1	5	140	0	39.4	75.3	22.9	15	19	0.02	331	1.09	1.347	2.455
1	5	140	0	75.3	88.1	22.9	15	19	0.02	331	1.09	1.000	2.080
1	5	140	0	88.1	92.4	22.9	15	19	0.02	331	1.09	0.583	1.630
1	5	132	0	50.8	80.1	24.8	4	8	0.05	1000	1.03	1.373	2.462
1	5	132	0	80.1	90.3	24.7	4	8	0.05	1000	1.03	0.990	2.053
1	5	132	0	90.3	93.9	24.7	4	8	0.05	1000	1.03	0.537	1.571
1	5	134	0	42.1	74.5	27.6	6	8	0.03	889	0.99	1.162	2.263
1	5	134	0	74.5	86.4	27.5	6	8	0.03	889	0.99	0.813	1.883
1	5	134	0	86.4	90.2	27.5	6	8	0.03	889	0.99	0.349	1.378
1	5	139	0	25.1	68.5	26.4	17	5	0.13	1467	0.78	1.669	2.381
1	5	139	0	68.5	83.0	26.4	17	5	0.13	1467	0.78	1.027	1.850
1	5	139	0	83.0	88.0	26.4	17	5	0.13	1467	0.78	0.499	1.412
1	5	130	0	44.1	76.1	23.1	24	12	0.02	556	1.06	1.330	2.399
1	5	130	0	76.7	87.8	23.1	24	12	0.02	556	1.06	0.871	1.916
1	5	130	0	87.8	92.1	23.1	24	12	0.02	556	1.06	0.326	1.548
1	5	137	0	60.7	85.2	23.7	9	15	0.02	1245	1.02	1.613	2.649
1	5	137	0	85.2	91.4	23.8	9	15	0.02	1245	1.02	0.705	1.722
1	5	137	0	91.4	94.1	23.8	9	15	0.02	1245	1.02	0.456	1.468
1	5	143	0	67.1	87.8	25.3	1	11	0.02	689	0.88	1.834	2.681
1	5	143	0	87.8	93.1	25.1	1	11	0.02	689	0.88	0.845	1.772
1	5	143	0	93.1	95.7	25.0	1	11	0.02	689	0.88	0.675	1.615
1	10	550	0	60.0	87.8	24.0	4	28	0.01	423	0.92	1.516	3.260
1	10	575	0	58.0	87.7	26.3	86	19	0.01	556	0.86	1.637	3.406
1	10	570	0	24.2	71.6	24.8	49	22	0.10	78	0.85	1.188	2.666
1	10	568	0	66.0	87.6	24.0	16	19	0.02	67	1.01	1.074	2.753
1	10	538	0	8.7	65.1	24.7	42	15	0.05	2244	0.90	1.095	2.613
1	10	595	0	6.8	62.5	20.3	30	17	0.23	3933	0.87	1.150	2.489
1	10	558	0	8.1	71.2	20.2	22	24	0.03	1556	1.07	1.381	3.189
1	10	468	0	31.2	79.0	20.9	22	9	0.02	645	0.71	2.046	3.202
1	10	440	0	56.4	88.0	15.6	52	6	0.02	512	1.01	1.969	3.637
1	10	397	0	51.0	92.1	15.3	52	6	0.02	512	1.01	1.818	3.415
1	10	740	0	7.5	63.5	20.3	30	17	0.23	3933	0.91	1.136	2.535
1	10	354	0	51.9	79.3	21.8	12	7	0.04	628	1.54	0.556	2.322
1	10	393	0	47.3	80.5	22.2	19	7	0.05	1108	0.98	1.110	2.687
1	10	375	0	22.1	74.1	23.0	25	6	0.05	1025	1.01	1.257	3.003
1	10	420	0	24.6	75.2	24.4	21	9	0.06	918	0.99	1.258	3.037
1	10	333	0	4.2	71.0	23.8	18	12	0.07	810	1.15	1.242	3.298
1	10	362	0	13.3	75.0	25.5	27	14	0.04	794	1.05	1.407	3.469
1	10	389	0	16.2	73.1	24.2	19	12	0.03	976	0.90	1.446	3.122

No. of steps	Fall ft.	Flow qpm/ ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
1	10	373	0	35.7	81.7	21.9	24	5	0.06	348	1.07	1.528	3.518
1	10	384	0	53.2	83.8	22.9	19	8	0.04	670	1.01	1.138	2.895
1	10	385	0	39.5	83.7	22.9	15	19	0.02	331	1.15	1.532	3.784
1	10	369	0	50.2	85.4	24.7	4	8	0.05	1000	1.05	1.394	3.413
1	10	392	0	46.2	82.4	27.7	6	8	0.03	889	0.89	1.314	3.055
1	10	395	0	25.4	78.0	26.9	17	5	0.13	1467	0.84	1.641	3.386
1	10	418	0	43.4	82.0	23.2	24	12	0.02	556	1.07	1.259	3.138
1	10	387	0	60.6	90.1	23.7	9	15	0.02	1245	1.12	1.654	3.989
1	10	405	0	64.5	88.1	24.1	1	11	0.02	689	0.99	1.243	2.998
1	10	380	0	66.1	90.3	23.9	16	19	0.02	67	1.01	1.531	3.492
1	10	370	0	65.8	87.3	24.0	16	19	0.02	67	1.01	1.032	2.685
1	10	385	0	63.0	88.0	23.9	4	28	0.01	423	0.96	1.352	3.089
1	10	390	0	64.1	88.3	24.0	4	28	0.01	423	0.94	1.358	3.057
1	10	365	0	58.7	86.5	24.0	4	28	0.01	423	0.90	1.425	3.072
1	10	373	0	57.2	87.1	26.3	86	19	0.01	556	0.88	1.556	3.334
1	10	318	0	57.5	87.4	26.3	86	19	0.01	556	0.87	1.616	3.391
1	10	402	0	16.5	70.3	24.4	49	22	0.10	78	0.81	1.381	2.816
1	10	488	0	23.5	71.2	24.8	49	22	0.10	78	0.85	1.190	2.657
1	10	400	0	6.7	62.6	24.6	42	15	0.05	2244	0.89	1.026	2.492
1	10	400	0	8.9	65.4	24.6	42	15	0.05	2244	0.89	1.114	2.634
1	10	418	0	7.8	63.4	20.3	30	17	0.23	3933	0.87	1.169	2.522
1	10	370	0	6.0	62.2	20.4	30	17	0.23	3933	0.88	1.141	2.496
1	10	420	0	7.2	72.3	20.2	22	24	0.03	1556	1.06	1.491	3.343
1	10	397	0	29.7	77.8	20.8	22	9	0.02	645	1.02	1.414	3.172
1	10	407	0	31.1	78.2	20.9	22	9	0.02	645	0.78	1.837	3.163
1	10	375	0	39.5	78.7	21.2	10	9	0.03	1023	0.91	1.338	2.846
1	10	404	0	40.2	78.9	21.2	10	9	0.03	1023	0.90	1.355	2.852
1	10	365	0	46.1	87.6	21.9	39	15	0.03	667	1.23	1.746	4.326
1	10	367	0	46.5	87.2	21.9	39	15	0.03	667	1.25	1.643	4.164
1	10	267	0	53.3	80.4	21.8	12	7	0.04	628	1.57	0.570	2.378
1	10	289	0	25.2	74.8	24.3	21	9	0.06	918	0.98	1.258	3.037
1	10	283	0	4.6	71.8	23.7	18	12	0.07	810	1.13	1.322	3.395
1	10	292	0	13.4	75.4	25.4	27	14	0.04	794	1.06	1.417	3.511
1	10	277	0	18.5	74.4	24.2	19	12	0.03	976	0.92	1.459	3.180
1	10	258	0	32.9	80.9	21.8	24	5	0.06	348	1.06	1.538	3.504
1	10	276	0	52.0	83.1	22.9	19	8	0.04	670	1.01	1.213	2.929
1	10	293	0	38.4	83.9	22.9	15	19	0.02	331	1.16	1.546	3.826
1	10	273	0	50.4	85.4	24.7	4	8	0.05	1000	1.06	1.770	3.388
1	10	254	0	22.0	73.4	23.0	25	6	0.05	1025	1.00	1.219	2.925
1	10	274	0	41.8	80.2	22.2	19	7	0.05	1105	1.01	1.242	2.950
1	10	281	0	48.2	83.2	27.7	6	8	0.03	889	1.00	1.310	3.086
1	10	277	0	25.5	77.5	27.0	17	5	0.13	1467	0.86	1.557	3.304
1	10	282	0	43.4	81.9	23.2	24	12	0.02	556	1.07	1.261	3.138
1	10	283	0	60.9	90.0	23.7	9	15	0.02	1245	1.11	1.630	3.912
1	10	294	0	67.4	88.9	24.9	1	11	0.02	689	0.97	1.203	2.937

No. of steps	Fall ft.	Flow gpm/ ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
1	10	185	0	66.3	89.4	23.9	16	19	0.02	67	1.01	1.336	3.174
1	10	180	0	65.9	86.7	24.0	16	19	0.02	67	1.01	0.995	2.559
1	10	192	0	64.2	88.0	23.9	4	28	0.01	423	0.95	1.286	2.974
1	10	170	0	60.5	87.5	24.0	4	28	0.01	423	0.93	1.425	3.139
1	10	222	0	57.9	88.7	26.3	86	19	0.01	556	0.88	1.515	3.264
1	10	210	0	57.7	87.5	26.3	86	19	0.01	556	0.87	1.623	3.393
1	10	218	0	17.8	70.7	24.4	49	22	0.10	78	0.81	1.365	2.802
1	10	208	0	23.4	72.5	24.8	49	22	0.10	78	0.85	1.276	2.783
1	10	230	0	5.2	63.6	24.6	42	15	0.05	2244	0.89	1.104	2.608
1	10	183	0	6.3	66.4	24.8	42	15	0.05	2244	0.90	1.216	2.793
1	10	205	0	6.8	64.0	20.3	30	17	0.23	3933	0.88	1.219	2.593
1	10	183	0	5.8	63.3	20.4	30	17	0.23	3933	0.88	1.197	2.572
1	10	201	0	7.3	71.7	20.2	22	24	0.03	1556	1.06	1.444	3.277
1	10	270	0	8.1	71.2	20.2	22	24	0.03	1556	1.07	1.390	3.210
1	10	193	0	29.7	77.0	20.8	22	9	0.02	645	1.00	1.374	3.060
1	10	212	0	31.1	78.6	20.8	22	9	0.02	645	0.76	1.946	3.218
1	10	189	0	40.4	78.0	21.2	10	9	0.03	1023	0.91	1.254	2.724
1	10	206	0	40.7	78.5	21.2	10	9	0.03	1023	0.90	1.303	2.773
1	10	176	0	46.3	87.5	21.9	39	15	0.03	667	1.24	1.721	4.297
1	10	172	0	45.7	86.2	21.8	39	15	0.03	667	1.25	1.517	3.931
1	10	222	0	57.1	87.6	16.0	52	6	0.02	512	1.01	1.815	3.460
1	10	144	0	52.5	79.3	21.9	12	7	0.04	628	1.60	0.523	2.290
1	10	127	0	47.9	79.8	22.3	19	7	0.05	1108	1.04	0.976	2.584
1	10	150	0	25.4	74.1	23.1	25	6	0.05	1025	0.99	1.198	2.879
1	10	185	0	27.1	74.7	24.4	21	9	0.06	918	0.97	1.186	2.878
1	10	123	0	2.0	71.2	24.0	18	12	0.07	810	1.16	1.271	3.390
1	10	125	0	12.1	71.9	25.6	27	14	0.04	794	1.08	1.174	3.125
1	10	128	0	20.2	72.9	24.1	19	12	0.03	976	0.94	1.265	2.937
1	10	146	0	35.4	80.7	21.9	24	5	0.06	348	1.01	0.930	2.447
1	10	163	0	53.4	83.8	22.8	19	8	0.04	670	1.00	1.189	2.879
1	10	136	0	40.1	82.3	22.9	15	19	0.02	331	1.17	1.299	3.397
1	10	133	0	50.2	85.0	24.7	4	8	0.05	1000	1.07	1.322	3.322
1	10	134	0	45.5	81.8	27.7	6	8	0.03	889	0.93	1.234	3.000
1	10	158	0	25.4	76.4	27.0	17	5	0.13	1467	0.88	1.417	3.150
1	10	147	0	43.2	81.2	23.2	24	12	0.02	556	1.06	1.197	3.029
1	10	140	0	60.3	88.3	23.7	9	15	0.02	1245	1.09	1.367	3.392
1	10	133	0	67.7	88.0	24.8	1	11	0.02	689	0.96	1.057	2.677
1	10	160	0	47.7	80.5	15.2	52	6	0.02	512	1.02	1.384	2.838
1	10	1100	0	66.2	86.3	24.0	16	19	0.02	67	1.01	0.891	2.453
1	10	1000	0	66.2	86.3	24.0	16	19	0.02	67	1.01	0.891	2.453
1	10	990	0	58.6	87.2	26.3	86	19	0.01	556	0.86	1.528	3.242
1	10	1075	0	25.1	70.5	24.8	49	22	0.10	78	0.86	1.093	2.543
1	10	1016	0	5.1	62.3	24.6	42	15	0.05	2244	0.89	1.038	2.518
1	10	1090	0	7.6	64.1	20.3	30	17	0.23	3933	0.91	1.169	2.574
1	10	1040	0	10.1	72.4	20.1	22	24	0.03	1556	1.03	1.375	3.104

No. of steps	Fall ft.	Flow gpm/ ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
1	10	1026	0	31.1	70.0	20.8	22	9	0.02	645	0.73	1.940	3.135
1	10	395	1	65.5	98.3	24.0	16	19	0.02	67	1.01	1.195	2.950
1	10	385	1	60.5	88.1	24.0	4	28	0.01	423	0.94	1.590	3.419
1	10	367	1	58.3	88.4	26.4	86	19	0.01	556	0.91	1.655	3.588
1	10	382	1	21.0	68.6	24.5	49	22	0.10	78	0.82	1.132	2.515
1	10	399	1	6.3	64.0	24.6	42	15	0.05	2244	0.89	1.098	2.607
1	10	382	1	5.7	62.6	20.3	30	17	0.23	3933	0.89	1.234	2.631
1	10	415	1	8.9	71.1	20.2	22	24	0.03	1556	1.05	1.379	3.155
1	10	396	1	29.9	79.4	20.9	22	9	0.02	645	0.85	1.696	3.166
1	10	377	1	40.5	78.3	21.2	10	9	0.03	1023	0.88	1.320	2.757
1	10	393	1	44.2	86.2	21.9	39	15	0.03	667	1.20	1.637	4.024
1	10	397	1	51.1	87.0	15.2	52	6	0.02	512	1.01	1.935	3.554
1	10	195	1	65.8	86.1	24.0	16	19	0.02	67	1.01	0.896	2.462
1	10	202	1	60.7	88.2	23.9	4	28	0.01	423	0.95	1.531	3.339
1	10	199	1	58.5	87.9	26.4	86	19	0.01	556	0.91	1.567	3.441
1	10	233	1	18.7	72.4	24.5	49	22	0.10	78	0.81	1.458	2.937
1	10	212	1	6.8	65.5	24.7	42	15	0.05	2244	0.89	1.159	2.700
1	10	184	1	5.5	64.0	20.3	30	17	0.23	3933	0.89	1.234	2.631
1	10	204	1	8.7	72.4	20.2	22	24	0.03	1556	1.06	1.475	3.310
1	10	204	1	30.0	77.9	20.9	22	9	0.02	645	0.81	1.770	3.175
1	10	185	1	40.9	78.8	21.2	10	9	0.03	1023	0.88	1.320	2.757
1	10	184	1	43.7	86.5	21.9	39	15	0.03	667	1.20	1.698	4.151
1	10	196	1	53.6	86.2	15.2	52	6	0.02	512	1.01	1.793	3.371
1	10	383	2	66.0	87.3	24.0	16	19	0.02	67	1.01	1.037	2.691
1	10	399	2	58.6	86.9	24.0	4	28	0.01	423	0.92	1.449	3.152
1	10	386	2	58.2	87.1	26.4	86	19	0.01	556	0.90	1.455	3.227
1	10	418	2	22.5	71.1	24.5	49	22	0.10	78	0.82	1.251	2.687
1	10	433	2	9.3	64.6	24.6	42	15	0.05	2244	0.89	1.068	2.565
1	10	381	2	6.5	62.4	20.3	30	17	0.23	3933	0.89	1.121	2.487
1	10	447	2	8.4	70.5	20.1	22	24	0.03	1556	1.04	1.360	3.106
1	10	410	2	30.3	76.4	20.8	22	9	0.02	645	0.90	1.436	2.946
1	10	391	2	40.9	77.8	21.1	10	9	0.03	1023	0.88	1.242	2.666
1	10	369	2	44.5	85.6	21.9	39	15	0.03	667	1.21	1.531	3.863
1	10	412	2	51.1	85.9	15.2	52	6	0.02	512	1.00	1.468	2.928
1	10	185	2	66.0	87.3	24.0	16	19	0.02	67	1.01	1.027	2.675
1	10	193	2	59.5	86.7	24.0	4	28	0.01	423	0.91	1.393	3.060
1	10	187	2	58.6	87.3	26.4	86	19	0.01	556	0.90	1.473	3.264
1	10	198	2	21.8	70.8	24.6	49	22	0.10	78	0.83	1.234	2.679
1	10	230	2	8.6	65.7	24.6	42	15	0.05	2244	0.89	1.136	2.663
1	10	176	2	6.0	64.3	20.3	30	17	0.23	3933	0.89	1.227	1.934
1	10	189	2	9.4	71.8	20.2	22	24	0.03	1556	1.05	1.432	3.224
1	10	192	2	29.6	77.1	20.8	22	9	0.02	645	0.88	1.564	3.073
1	10	188	2	40.6	77.8	21.2	10	9	0.03	1023	0.88	1.258	2.681
1	10	181	2	43.5	85.7	21.9	39	15	0.03	667	1.22	1.570	3.949
1	10	202	2	52.3	85.4	15.2	52	6	0.02	512	1.01	1.717	3.264

No. of steps	Fall ft.	Flow gpm/ ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
1	10	380	3	65.8	86.4	24.0	16	19	0.02	67	1.01	0.931	2.517
1	10	408	3	58.7	86.4	24.0	4	28	0.01	423	0.90	1.386	3.031
1	10	440	3	57.6	86.8	26.3	86	19	0.01	556	0.89	1.452	3.208
1	10	440	3	22.9	67.7	24.7	49	22	0.10	78	0.84	1.000	2.389
1	10	367	3	5.0	62.3	24.6	42	15	0.05	2244	0.89	1.043	2.522
1	10	424	3	6.4	62.7	20.3	30	17	0.23	3933	0.90	1.133	2.513
1	10	390	3	10.1	70.1	20.1	22	24	0.03	1556	1.04	1.310	3.012
1	10	407	3	28.9	76.0	20.8	22	9	0.02	645	0.96	1.360	2.966
1	10	426	3	40.2	77.8	21.2	10	9	0.03	1023	0.89	1.259	2.706
1	10	368	3	43.8	85.0	21.9	39	15	0.03	667	1.22	1.457	3.750
1	10	433	3	53.6	84.1	15.2	52	6	2.02	512	1.00	1.468	2.928
1	10	185	3	65.7	86.1	24.0	16	19	0.02	67	1.01	0.910	2.482
1	10	192	3	59.1	86.2	24.0	4	28	0.01	423	0.91	1.334	2.966
1	10	226	3	57.9	86.5	26.3	86	19	0.01	556	0.89	1.403	3.120
1	10	188	3	21.7	68.5	24.7	49	22	0.10	78	0.84	1.080	2.484
1	10	280	3	5.4	62.8	24.6	42	15	0.05	2244	0.89	1.056	2.542
1	10	205	3	6.0	64.5	20.3	30	17	0.23	3933	0.90	1.231	2.650
1	10	190	3	9.8	72.0	20.1	22	24	0.03	1556	1.04	1.440	3.219
1	10	201	3	29.2	76.7	20.8	22	9	0.02	645	0.94	1.446	3.038
1	10	206	3	40.7	77.7	21.2	10	9	0.03	1023	0.89	1.237	2.669
1	10	180	3	43.7	85.6	21.9	39	15	0.03	667	1.23	1.543	3.926
1	10	220	3	52.8	84.7	15.2	52	16	0.02	512	1.01	1.585	3.085
1	15	381	0	55.5	85.5	21.8	12	7	0.04	628	1.46	0.825	3.078
1	15	431	0	42.4	83.0	23.3	19	7	0.05	1108	1.07	1.277	3.397
1	15	373	0	58.6	85.6	23.3	25	6	0.05	1025	0.82	1.278	2.865
1	15	404	0	22.6	78.6	24.7	21	9	0.06	918	1.02	1.394	3.617
1	15	381	0	23.4	83.8	23.1	18	12	0.07	810	1.06	1.983	4.737
1	15	367	0	14.4	80.6	25.4	27	14	0.04	794	1.03	1.760	4.397
1	15	363	0	17.2	78.0	24.1	19	12	0.03	976	1.04	1.480	3.747
1	15	367	0	34.2	85.1	21.9	24	5	0.06	348	1.08	1.819	4.395
1	15	423	0	52.0	86.9	22.7	19	8	0.04	670	0.98	1.520	3.632
1	15	367	0	37.4	86.4	22.9	15	19	0.02	331	1.14	1.796	4.636
1	15	417	0	49.8	88.3	24.7	4	8	0.05	1000	1.08	1.658	4.306
1	15	381	0	47.2	85.5	27.7	6	8	0.03	889	0.84	1.608	3.648
1	15	399	0	27.6	81.1	27.2	17	5	0.13	1467	0.93	1.569	3.826
1	15	416	0	42.8	87.2	23.2	24	12	0.02	556	1.06	1.830	4.465
1	15	395	0	58.1	93.2	23.7	9	15	0.02	1245	1.07	2.696	6.197
1	15	417	0	61.5	90.3	24.2	1	11	0.02	689	0.92	1.784	3.998
1	15	271	0	52.8	83.3	21.8	12	7	0.04	628	1.48	0.706	2.811
1	15	221	0	41.1	83.4	22.2	19	7	0.05	1108	1.11	1.315	3.537
1	15	202	0	49.7	82.3	23.9	25	6	0.05	1025	0.81	1.247	2.823
1	15	285	0	24.6	80.1	24.7	21	9	0.06	918	1.01	1.504	3.792
1	15	252	0	18.2	81.7	23.2	18	12	0.07	810	1.07	1.814	4.468
1	15	324	0	14.2	78.7	25.4	27	14	0.04	794	1.01	1.597	4.024
1	15	272	0	21.2	78.6	24.2	19	12	0.03	976	1.02	1.432	3.675

No. of steps	Fall ft.	Flow gpm/ ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
1	15	278	0	34.0	85.9	21.9	24	5	0.06	348	1.10	1.939	4.677
1	15	273	0	53.2	86.3	22.7	19	8	0.04	670	0.99	1.379	3.400
1	15	293	0	39.6	86.9	22.9	15	19	0.02	331	1.13	1.808	4.637
1	15	275	0	49.3	88.2	24.7	4	8	0.05	1000	1.09	1.636	4.286
1	15	204	0	41.5	85.4	22.9	15	19	0.02	331	1.09	1.566	4.029
1	15	200	0	49.4	86.9	24.8	4	8	0.05	1000	1.01	2.198	4.648
1	15	267	0	47.6	85.4	27.7	6	8	0.03	889	0.85	1.554	3.599
1	15	271	0	26.0	81.7	27.2	17	5	0.13	1467	0.91	1.712	4.036
1	15	267	0	43.7	87.0	23.2	24	12	0.02	556	1.06	1.758	4.332
1	15	267	0	58.6	91.8	23.6	9	15	0.02	1245	1.06	2.113	5.020
1	15	271	0	63.3	91.2	24.3	1	11	0.02	689	0.93	1.870	4.187
1	15	157	0	52.8	81.2	21.8	12	7	0.04	628	1.51	0.577	2.506
1	15	129	0	46.5	79.2	22.4	19	7	0.05	1108	1.14	0.784	2.561
1	15	129	0	45.2	80.7	23.7	25	6	0.05	1025	0.80	1.272	2.830
1	15	133	0	22.4	76.5	24.4	21	9	0.06	918	1.00	1.252	3.294
1	15	113	0	11.1	75.7	23.4	18	12	0.07	810	1.10	1.346	3.660
1	15	112	0	13.6	76.7	25.5	27	14	0.04	794	0.99	1.448	3.693
1	15	137	0	20.3	75.5	24.1	19	12	0.03	976	0.98	1.212	3.169
1	15	138	0	34.4	83.9	21.9	24	5	0.06	348	1.11	1.592	4.056
1	15	133	0	51.5	84.3	22.7	19	8	0.04	670	0.99	1.189	3.080
1	15	149	0	38.9	84.8	22.9	15	19	0.02	331	1.13	1.517	4.032
1	15	136	0	49.5	85.3	24.7	4	8	0.05	1000	1.10	1.193	3.422
1	15	153	0	47.5	83.9	27.6	6	8	0.03	889	0.87	1.319	3.256
1	15	133	0	25.5	78.8	27.1	17	5	0.13	1467	0.89	1.451	3.507
1	15	133	0	43.4	85.1	23.2	24	12	0.02	556	1.06	1.469	3.787
1	15	128	0	58.8	89.4	23.7	9	15	0.02	1245	1.04	1.538	3.875
1	15	129	0	65.2	89.8	24.2	1	11	0.02	689	0.95	1.393	3.411
2	10	395	0	28.4	84.9	21.6	12	7	0.04	628	1.37	1.772	4.723
2	10	395	0	68.8	90.1	21.6	12	7	0.04	628	1.37	1.010	3.122
2	10	367	0	27.8	79.7	23.5	25	6	0.05	1025	0.97	1.847	3.856
2	10	367	0	63.6	86.5	23.5	25	6	0.05	1025	0.97	1.336	3.064
2	10	357	0	26.9	80.0	24.3	21	9	0.06	918	0.96	1.695	3.659
2	10	357	0	63.2	86.4	24.3	21	9	0.06	918	0.96	1.024	2.606
2	10	360	0	40.1	88.7	22.7	18	12	0.07	810	0.96	2.846	5.311
2	10	360	0	76.2	93.8	22.7	18	12	0.07	810	0.96	1.894	3.866
2	10	370	0	9.5	79.3	25.6	27	14	0.04	794	0.94	2.149	4.372
2	10	370	0	61.9	87.7	25.6	27	14	0.04	794	0.94	1.342	3.106
2	10	410	0	9.6	79.2	24.1	19	12	0.03	976	1.06	1.920	4.316
2	10	410	0	62.0	86.3	24.0	19	12	0.03	976	1.06	1.022	2.764
2	10	368	0	31.5	86.8	21.9	24	5	0.06	348	1.12	2.389	5.153
2	10	368	0	72.3	91.0	21.9	24	5	0.06	348	1.12	1.190	3.067
2	10	427	0	51.8	89.3	22.7	19	8	0.04	670	0.98	2.278	4.511
2	10	427	0	78.5	92.9	22.7	19	8	0.04	670	0.98	1.328	3.042
2	10	393	0	38.5	88.8	22.9	15	19	0.02	331	1.12	2.558	5.513
2	10	393	0	75.4	93.7	22.9	15	19	0.02	331	1.12	1.654	3.918

No. of steps	Fall ft.	Flow gpm/ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
2	10	403	0	49.3	89.1	24.7	4	8	0.05	1000	1.01	2.102	4.650
2	10	403	0	78.1	92.4	24.7	4	8	0.05	1000	1.01	1.147	2.899
2	10	416	0	50.2	87.4	27.9	6	8	0.03	889	0.95	1.760	3.950
2	10	416	0	78.3	90.8	27.9	6	8	0.03	889	0.95	0.813	2.362
2	10	365	0	24.5	83.1	27.7	17	5	0.13	1467	0.82	2.455	4.457
2	10	365	0	68.3	88.7	27.6	17	5	0.13	1467	0.82	1.274	2.796
2	10	382	0	41.7	88.3	23.1	24	12	0.02	556	1.06	2.402	5.043
2	10	382	0	76.9	93.1	23.1	24	12	0.02	556	1.06	1.355	3.282
2	10	333	0	62.0	92.1	23.5	9	15	0.02	1245	0.98	2.548	4.983
2	10	333	0	83.8	94.6	23.5	9	15	0.02	1245	0.98	1.271	2.986
2	10	357	0	64.5	92.1	24.7	1	11	0.02	689	0.91	2.320	4.472
2	10	357	0	84.6	95.0	24.6	1	11	0.02	689	0.91	1.367	3.043
2	10	333	0	44.0	92.4	21.8	39	15	0.03	667	1.27	3.234	7.331
2	10	333	0	79.8	97.1	21.8	39	15	0.03	667	1.27	3.058	6.994
2	10	347	0	35.3	90.2	15.2	52	6	0.02	512	1.02	2.929	4.893
2	10	347	0	80.5	94.8	15.2	52	6	0.02	512	1.02	2.097	3.788
2	10	267	0	29.1	84.3	21.5	12	7	0.04	628	1.40	1.643	4.517
2	10	267	0	69.0	90.4	21.5	12	7	0.04	628	1.40	1.036	3.218
2	10	257	0	48.3	90.0	23.3	19	7	0.05	1108	1.17	1.981	4.696
2	10	257	0	78.7	94.6	23.3	19	7	0.05	1108	1.17	1.545	3.879
2	10	274	0	28.2	79.6	23.3	25	6	0.05	1025	0.94	1.878	3.805
2	10	274	0	63.6	86.5	23.4	25	6	0.05	1025	0.94	1.169	2.704
2	10	295	0	22.5	79.3	24.2	21	9	0.06	918	0.95	1.769	3.733
2	10	295	0	63.4	85.4	24.2	21	9	0.06	918	0.95	0.984	2.520
2	10	260	0	37.3	88.3	22.8	18	12	0.07	810	0.99	2.785	5.367
2	10	260	0	75.9	91.6	22.8	18	12	0.07	810	0.99	1.193	2.871
2	10	323	0	9.3	80.5	25.4	27	14	0.04	794	0.98	2.220	4.633
2	10	323	0	62.2	86.9	25.4	27	14	0.04	794	0.98	1.147	2.878
2	10	315	0	6.1	79.1	24.1	19	12	0.03	976	1.10	1.944	4.455
2	10	315	0	62.0	86.2	24.1	19	12	0.03	976	1.10	0.811	2.930
2	10	253	0	31.5	85.1	21.9	24	5	0.06	348	1.14	2.029	4.585
2	10	253	0	71.1	90.5	21.9	24	5	0.06	348	1.14	1.148	3.027
2	10	278	0	51.3	89.0	22.6	19	8	0.04	670	0.97	2.210	4.383
2	10	278	0	79.1	92.9	22.6	19	8	0.04	670	0.97	1.265	2.935
2	10	262	0	39.3	88.6	22.9	15	19	0.02	331	1.11	2.496	5.360
2	10	262	0	76.0	93.2	22.9	15	19	0.02	331	1.11	1.460	3.550
2	10	269	0	50.3	89.6	24.7	4	8	0.05	1000	1.02	2.235	4.753
2	10	269	0	79.0	92.6	24.7	4	8	0.05	1000	1.02	1.085	2.820
2	10	263	0	46.5	87.0	27.7	6	8	0.03	889	0.97	1.828	4.118
2	10	263	0	74.7	90.7	27.7	6	8	0.03	889	0.97	1.005	2.709
2	10	275	0	24.9	82.8	26.5	17	5	0.13	1467	0.80	2.456	4.369
2	10	275	0	67.8	88.3	26.5	17	5	0.13	1467	0.80	1.287	2.764
2	10	263	0	42.8	88.7	23.2	24	12	0.02	556	1.06	2.402	5.045
2	10	263	0	77.2	93.1	23.2	24	12	0.02	556	1.06	1.355	3.282
2	10	256	0	61.5	91.4	23.6	9	15	0.02	1245	1.00	0.993	2.237

No. of steps	Fall ft.	Flow gpm/ ft.	No. teeth	DO Sat a		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
2	10	256	0	82.9	94.3	23.7	9	15	0.02	1245	1.00	1.245	2.993
2	10	274	0	61.3	92.5	24.7	1	11	0.02	689	0.90	2.867	5.222
2	10	274	0	85.0	95.0	25.2	1	11	0.02	689	0.90	1.356	3.016
2	10	168	0	31.7	85.0	21.5	12	7	0.04	628	1.43	1.180	4.560
2	10	168	0	70.3	90.0	21.5	12	7	0.04	628	1.43	0.901	2.967
2	10	110	0	47.0	87.9	21.9	19	7	0.05	1108	1.33	1.640	4.369
2	10	110	0	77.6	92.6	21.9	19	7	0.05	1108	1.33	0.987	3.027
2	10	135	0	39.3	82.5	22.9	25	6	0.05	1025	0.91	1.713	3.465
2	10	135	0	71.6	92.7	22.9	25	6	0.05	1025	0.91	0.805	2.158
2	10	100	0	25.1	79.9	24.3	21	9	0.06	918	0.93	1.789	3.724
2	10	100	0	65.9	85.3	24.3	21	9	0.06	918	0.93	0.863	2.312
2	10	303	0	29.9	86.7	22.9	18	12	0.07	810	1.03	2.618	5.278
2	10	303	0	71.8	91.7	22.9	18	12	0.07	810	1.03	1.469	3.393
2	10	111	0	8.6	80.1	25.4	27	14	0.04	794	0.96	2.248	4.588
2	10	111	0	62.7	85.9	25.4	27	14	0.04	794	0.96	1.031	2.664
2	10	135	0	5.8	80.0	24.1	19	12	0.03	976	1.11	2.040	4.683
2	10	135	0	61.4	86.5	24.0	19	12	0.03	976	1.11	1.032	2.858
2	10	143	0	31.4	84.7	22.0	24	5	0.06	348	1.17	1.928	4.481
2	10	143	0	70.5	90.1	22.0	24	5	0.06	348	1.17	1.103	2.989
2	10	127	0	51.2	89.0	22.6	19	8	0.04	670	0.97	2.248	4.412
2	10	127	0	79.4	93.3	22.6	19	8	0.04	670	0.97	1.341	3.035
2	10	140	0	39.4	88.1	22.9	15	19	0.02	331	1.09	2.380	5.106
2	10	140	0	75.3	92.4	22.9	15	19	0.02	331	1.09	1.385	3.389
2	10	132	0	50.8	90.3	24.7	4	8	0.05	1000	1.03	2.202	4.650
2	10	132	0	80.1	93.9	24.7	4	8	0.05	1000	1.03	1.147	2.899
2	10	200	0	49.4	89.1	24.8	4	8	0.05	1000	1.01	2.198	4.648
2	10	134	0	42.1	86.4	27.6	6	8	0.03	889	0.99	1.879	4.261
2	10	134	0	74.5	90.2	27.5	6	8	0.03	889	0.99	0.920	2.595
2	10	139	0	25.1	83.0	26.4	17	5	0.13	1467	0.78	2.578	4.405
2	10	139	0	68.5	88.0	26.4	17	5	0.13	1467	0.78	1.220	2.612
2	10	130	0	44.1	87.8	23.1	24	12	0.02	556	1.06	2.141	4.597
2	10	130	0	76.7	92.1	23.1	24	12	0.02	556	1.06	1.170	2.966
2	10	137	0	60.7	91.4	23.8	9	15	0.02	1245	1.02	2.179	4.563
2	10	137	0	85.2	94.1	23.8	9	15	0.02	1245	1.02	0.934	2.528
2	10	143	0	67.1	93.1	25.2	1	11	0.02	689	0.88	2.565	4.750
2	10	143	0	87.8	95.7	25.1	1	11	0.02	689	0.88	1.278	2.862
2	10	1000	0	44.6	91.9	21.9	39	15	0.03	667	1.26	2.993	6.802
2	10	1000	0	79.3	97.0	21.8	39	15	0.03	667	1.26	3.048	6.909
2	10	1040	0	52.4	89.9	15.2	52	6	0.02	512	1.02	2.791	4.714
2	10	1040	0	89.0	94.5	15.2	52	6	0.02	512	1.02	0.790	2.051
3	15	395	0	28.4	90.1	21.6	12	7	0.04	628	1.37	2.617	7.164
3	15	367	0	27.8	86.5	23.5	25	6	0.05	1025	0.97	3.015	6.227
3	15	357	0	26.9	86.4	24.3	21	9	0.06	918	0.96	2.478	5.360
3	15	360	0	40.1	93.8	22.7	18	12	0.07	810	0.96	5.113	9.687
3	15	370	0	9.5	87.7	25.6	27	14	0.04	794	0.94	3.617	7.368

No. of steps	Fall ft.	Flow gpm/ ft.	No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
				In	Out								
3	15	410	0	9.6	86.3	24.1	19	12	0.03	976	1.06	2.870	6.560
3	15	368	0	31.5	91.0	21.9	24	5	0.06	348	1.12	3.377	7.585
3	15	427	0	51.8	92.9	22.7	19	8	0.04	670	0.98	3.353	6.791
3	15	393	0	38.5	93.7	22.9	15	19	0.02	331	1.12	4.442	9.798
3	15	403	0	49.3	92.4	24.7	4	8	0.05	1000	1.01	3.055	6.679
3	15	416	0	50.2	90.8	27.9	6	8	0.03	889	0.95	2.353	5.424
3	15	365	0	24.5	88.7	26.6	17	5	0.13	1467	0.82	3.587	6.666
3	15	382	0	41.7	93.1	23.1	24	12	0.02	556	1.06	3.938	8.436
3	15	333	0	62.0	94.6	23.5	9	15	0.02	1245	0.98	3.546	7.217
3	15	357	0	64.5	95.0	24.7	1	11	0.02	689	0.91	3.614	7.067
3	15	333	0	44.0	97.1	21.8	39	15	0.03	667	1.27	8.402	19.449
3	15	347	0	35.3	94.8	15.2	52	6	0.02	512	1.02	5.544	9.266
3	15	267	0	29.1	90.4	21.5	12	7	0.04	628	1.40	2.647	7.357
3	15	257	0	48.3	94.6	23.3	19	7	0.05	1108	1.17	3.642	8.613
3	15	274	0	28.6	86.5	23.4	25	6	0.05	1025	0.94	2.838	5.768
3	15	295	0	22.5	85.4	24.2	21	9	0.06	918	0.95	2.496	5.325
3	15	260	0	37.3	91.6	22.8	18	12	0.07	810	0.99	3.676	7.464
3	15	323	0	9.3	86.9	25.4	27	14	0.04	794	0.98	3.226	6.920
3	15	315	0	6.1	86.2	24.1	9	12	0.03	976	1.10	2.865	6.712
3	15	253	0	31.5	90.5	21.9	24	5	0.06	348	1.14	3.106	7.157
3	15	278	0	51.3	92.9	22.6	19	8	0.04	670	0.97	3.393	6.827
3	15	262	0	39.3	93.2	22.9	15	19	0.02	331	1.11	4.081	8.998
3	15	269	0	50.3	92.6	24.7	4	8	0.05	1000	1.02	3.001	6.653
3	15	204	0	41.5	93.8	22.9	15	19	0.02	331	1.09	4.480	9.668
3	15	200	0	49.4	93.5	24.8	4	8	0.05	1000	1.01	3.620	7.735
3	15	168	0	31.7	90.0	21.5	12	7	0.04	628	1.43	2.383	6.831
3	15	263	0	46.5	90.7	27.7	6	8	0.03	889	0.97	2.462	5.705
3	15	275	0	24.9	88.3	26.5	17	5	0.13	1467	0.80	3.529	6.428
3	15	263	0	42.8	93.1	23.2	24	12	0.02	556	1.06	3.832	8.236
3	15	256	0	61.5	94.3	23.6	9	15	0.02	1245	1.00	3.209	6.754
3	15	274	0	61.3	95.0	24.8	1	11	0.02	689	0.90	4.175	7.902
3	15	110	0	47.0	92.6	21.9	19	7	0.05	1108	1.33	2.670	7.151
3	15	135	0	39.3	92.7	22.9	25	7	0.05	1025	0.91	2.235	4.607
3	15	100	0	25.1	85.3	24.3	21	9	0.06	918	0.93	2.385	5.071
3	15	103	0	29.9	91.7	22.9	18	12	0.07	810	1.03	4.071	8.461
3	15	111	0	8.6	85.9	25.4	27	14	0.04	794	0.96	3.058	6.475
3	15	135	0	5.8	86.5	24.1	19	12	0.03	976	1.11	2.939	6.945
3	15	143	0	31.4	90.1	22.0	24	5	0.06	348	1.17	2.936	6.943
3	15	127	0	51.2	93.3	22.6	19	8	0.04	670	0.97	3.617	7.161
3	15	140	0	39.4	92.4	22.9	15	19	0.02	331	1.09	3.784	8.320
3	15	132	0	50.8	93.9	24.7	4	8	0.05	1000	1.03	3.638	7.940
3	15	134	0	42.1	90.2	27.5	6	8	0.03	889	0.99	2.503	5.872
3	15	139	0	25.1	88.0	26.4	17	5	0.13	1467	0.78	3.525	6.221
3	15	130	0	44.1	92.1	23.1	24	12	0.02	556	1.06	3.245	7.116
3	15	137	0	60.7	94.1	23.8	9	15	0.02	1245	1.02	3.106	6.697

No. of steps	Flow		No. teeth	DO Sat %		Temp °C	COD mg/l	SS mg/l	MBAS mg/l	Algae no/ml	a	b	r
	ft.	gpm/ ft.		In	Out								
3	15	143	0	67.1	95.7	25.1	1	11	0.02	689	0.88	4.072	7.672
3	15	1000	0	44.6	97.0	21.9	39	15	0.03	667	1.26	8.020	18.432
3	15	1040	0	52.4	94.5	15.2	52	6	0.02	512	1.02	5.342	8.967