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SWS Contract Report 423

AERATION CHARACTERISTICS OF STARVED ROCK DAM TAINTER GATE FLOW CONTROLS

by Thomas A. Butts and Harvey R. Adkins

Prepared for the
Illinois Department of Energy and Natural Resources

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CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Concluded on next page

ABSTRACT

The dissolved oxygen (DO) concentrations in the 74-mile-long Peoria pool (Illinois River) are greatly influenced by Tainter gate flow releases at the Starved Rock lock and dam located at the head of the pool. A study was conducted to determine if downstream DO resources can be improved by manipulating the Tainter gate openings to improve aeration. Nineteen calibration runs were made during the summer and early fall of 1985 to determine the effects several variables have on aeration. The factors evaluated were: river flow, head loss, water quality, diel DO variations, gate submergence, gate opening height, and number of gates open. A statistical evaluation of the data revealed that the aeration efficiency is dictated primarily by the gate opening height; i.e., the dam aeration coefficient was found to be directly proportional to the size of the opening. The aeration coefficient for a gate open 4 feet is four times greater than that for a gate open 1 foot. A gate management plan was developed that uses gate opening manipulation to improve downstream DOs without conflicting with navigational interests.

Descriptors: Water Quality, Water Pollution Effects, Water Pollution Abatement, Water Management, Dam Aeration, Dissolved Oxygen

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INTRODUCTION

The Illinois Pollution Control Board (IPCB) dissolved oxygen (DO) standards, as administered by the Illinois Environmental Protection Agency (IEPA), are not being met consistently along several major reaches of the Illinois Waterway. Undesirably low DO levels still occur routinely, particularly during low summer flows, in spite of the fact that hundreds of millions of dollars have been expended over the last 20 years to reduce point source waste loads. General use water quality standards are applicable to the Illinois Waterway below the 1-55 bridge. Section 302.206 of Subpart B of the IPCB <u>Rules and Regulations</u> C1986) states:

> Dissolved oxygen CSTORET number 00300) shall not be less than 6.0 mg/l during at least 16 hours of any 24 hour period, nor less than 5.0 mg/l at any time.

Dissolved oxygen surveys conducted in the Peoria pool by the Water Quality Section (WQS) of the State Water Survey (SWS) during the summers of 1982 and 1983 show that DO concentrations often drop below 5.0 mg/l even during relatively high summer flows. In the LaGrange pool below Peoria, concentrations as low as 3.5 mg/l were observed during 1983 summer low flow conditions. Simulations made by using the Water Quality Section's biochemical oxygen demand (BOD)-DO computer model have clearly demonstrated that significant improvements in DO levels cannot be achieved by requiring additional organic waste load (BOD) reductions at the point sources. Most treatment plants along the waterway are presently achieving 90 to 95 percent BOD reductions. In addition, since 1971 ammonia input to the waterway (another cause of oxygen depletion) has been reduced over 50 percent. Additional treatment would not produce a commensurate improvement in DO levels. The only plant along the waterway amenable to a large-scale upgrading is the Metropolitan Sanitary District of Greater Chicago Calumet plant. Butts et al. (1983) have shown that upgrading the effluent of this plant to 7 mg/l BOD and 2 mg/l ammonia would improve the DO level in the critical reach of the Peoria pool by only 0.6 mg/l during low flow conditions.

Cause of the Problem

The reason the improvement in DO has not been commensurate with the reduction of waste inputs is that the waste assimilative capacity of the waterway has been drastically reduced due to the physical alterations of the natural stream channel over the last 50 years. Dam construction, dredging, and channelization have slowed flows and increased water depths, thereby reducing the natural reaeration capacity, i.e., the ability of the water to replenish oxygen from the air that has been lost to biological oxidation. Also, the pools and deepened channels have created sediment traps. These trapped sediments often exert a significant sediment oxygen demand (SOD). In some pools, the reaeration capacity is barely adequate to supply the oxygen needed to stabilize the SOD.

General Effects of Dams

Dams are built across streams for a multiplicity of reasons ranging from aesthetics (as exemplified by small channel dams in parks) to flow and navigation control. Regardless of the purpose of the dam, all affect water quality to some degree. The manifestations can be both positive and negative, and some effects may be subtle and indirect while others may be obvious and direct.

One of the most obvious and direct effects dams have on water quality is the creation of abrupt changes in dissolved oxygen (DO) concentrations. When potential DO problems appear likely in the establishment of a new dam, design consideration should be given to maximizing aeration efficiency, and at established sites operating procedures should be geared to maximizing reaeration in a practical manner.

Dissolved oxygen concentrations must be maintained at or above regulatory standards to promote balanced, high-quality aquatic ecosystems. An aquatic environment completely devoid of DO is referred to as anaerobic while a system which is capable of sustaining even a trace of DO is referred to as aerobic. The quality of fish life is often a good indicator of aerobic conditions. Some "rough" fish, such as carp, bullheads, and bowfin, can survive for extended periods at DOs less than 1.0 mg/l. Less hardy "rough" fish such as buffalo fish, drum, and gar can exist comfortably in waters with DOs in the 2.0 to 4.0 mg/l range. Warm water game fish, such as crappie, largemouth bass, and white bass, need sustained DO concentrations of 5.0 mg/l or greater to survive. Other game fish such as walleye, northern pike, and smallmouth bass need sustained DO levels in excess of 6.0 mg/l while some cold water species, like trout, need DO levels of 7.0 mg/l or greater to prevent stress.

Not only can fishes be categorized by DO needs, but the organisms on which these various fish classes feed exhibit commensurate DO needs. For example, mayflies, on which trout and walleye feed heavily, need DO levels greater than 5.0 mg/l to function. Sludge worms, on the other hand, can survive in anaerobic bottom muds and are heavily utilized as a source of food by the lowly bullhead.

To fully appreciate the need for an efficient aeration design or operating procedure at a dam site, a person needs to understand the basic ecological and environmental consequences dams have on aquatic systems. Weirs and dams create pools which have DO levels inherently above or below those normally expected in a free-flowing stream of similar water quality. If the water is nutrient-rich but not grossly polluted, excessive algal growths can be expected to occur in the pools, resulting in wide fluctuations of diurnal DO levels. Also, supersaturation may occur in the pools during the day, resulting in wide fluctuations of diurnal DO levels.

This supersaturation may occur during the day because of algal cell photosynthesis, whereas during the night almost total depletion may occur because of the respiratory needs of the algae. Essentially the pools act as biological incubators for plankton. However, in the absence of sustained photosynthetic oxygen production, DO concentrations may often fall below desired levels since the waste assimilative capacities of the pools are often much lower than those of free-flowing reaches of the same stream. Several factors account for this.

One is that the physical reaeration capability of a pool is much lower than that of a free-flowing reach of similar length. Reaeration is directly related to stream velocity and inversely related to depth. Consequently, since pooling decreases velocity and increases depth, natural physical aeration in a pool proceeds at a much slower rate. Butts et al. (1973) showed that for the Rock River in Illinois the average reaeration constant for an 11-mile pool was only 11 percent of the average of the one calculated for the preceding 11-mile upstream free-flowing reach.

The problem of low aeration rates in pools is compounded by the fact that more oxygen is used in the pool than in a free-flowing reach since the detention time is increased as a result of lower velocities. This enables microorganisms suspended in the water and micro- and macroorganisms indigenous to the bottom sediments in the pools to use more of the DO resources in a given area to satisfy respiratory needs. The detention time in the afore-mentioned Rock River pool was 2.23 days compared with the free-flowing reach time of travel of only 0.68 days.

Also, dams promote the accumulation of sediments upstream. If these sediments are polluted or laden with organic material, additional strain is put on the DO resources since the quantity of oxygen needed to satisfy sediment oxygen demand (SOD) is directly related to the detention time and inversely related to depth, as shown by Butts et al. (1974). Depths behind navigation dams at intermediate to low-flow fluctuations change at a lower rate than do corresponding detention times because flat pool elevations need to be maintained for navigational interests. Essentially, a fixed volume of water is preserved, allowing more time for benthic organisms to deoxygenate the water as flow rates decrease.

The reduction in oxygen levels behind the dams can be partially compensated for by aeration at the dam site. This localized aeration cannot make up for the overall damage rendered in the pools, but it can establish or control conditions in the next succeeding downstream reach. Unfortunately, dam aeration theory dictates that head loss structures deaerate water with supersaturated levels of DO at the same rate at which they would aerate water at equivalent subsaturated levels.

For example, water with a DO level 2 mg/l above saturation is deoxygenated at the same rate as it would be reaerated at 2 mg/l below saturation with all other physical conditions remaining unchanged.

Butts and Evans (1978) found that for highly productive streams such as the Fox River in Illinois, any DO above 200 percent saturation is lost instantaneously to the air as the flow makes contact with a weir or spillway crest. Dams in essence "blow out" supersaturated oxygen which may be needed as a reserve for algal respiration at some future time downstream.

Illinois Waterway Background Information

The Illinois Waterway (figure 1) 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. The waterway is not a free-flowing stream; it consists of eight navigational pools extending over 327 miles between the Mississippi River and Lake Michigan (figure 2). Locks and dams are located at Lockport (Mile 291.1), Brandon Road (286.0), Dresden Island (271.5), Marseilles (247.0), Starved Rock (231.0), Peoria (157.7), and LaGrange (80.2). Flow control at Brandon Road, Dresden Island, Marseilles, and Starved Rock is exercised using Tainter gates. Ten gates are used at Starved Rock (figure 3). A cross-sectional view of a Tainter gate installation at the Starved Rock dam is also shown on figure 3. The face of the gate pivots on an arc facing upstream. As the gate pivots upward flow is released through the opening created between the bottom of the gate face and the concrete sill.

The Peoria and LaGrange dams are unique in that bottom hinged rectangular plates, known as Chanoine wickets, are lowered to lie flat on the bottom during high flows for river traffic to pass. During low flows, desired upstream head is achieved by raising the wickets and inserting timbers called needles between each wicket, thereby creating a sharp-crested, low-head channel dam or spillway.

All the flow at Lockport is passed through penstocks for power. Water passed through a hydropower plant is aerated very little.

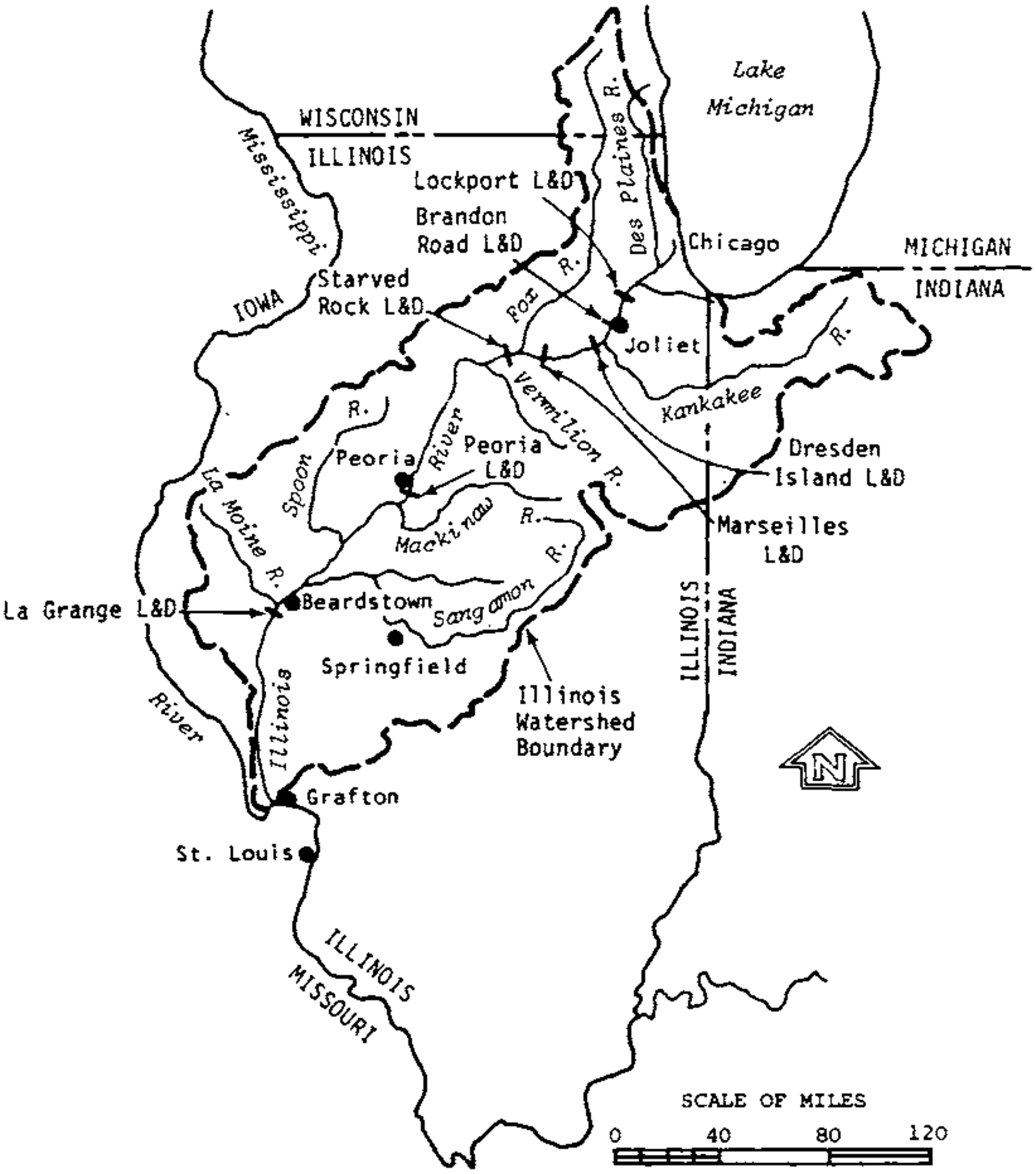

Figure 1. Illinois Waterway

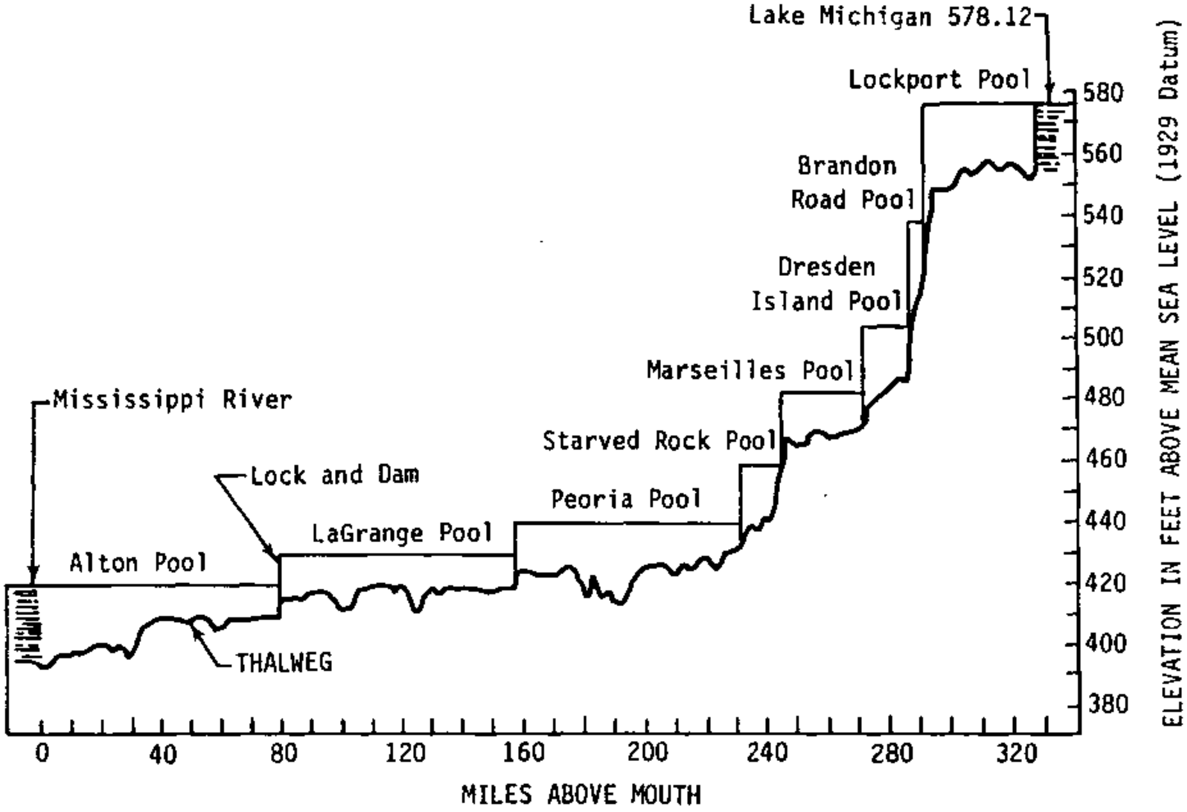

Figure 2. Illinois Waterway profile

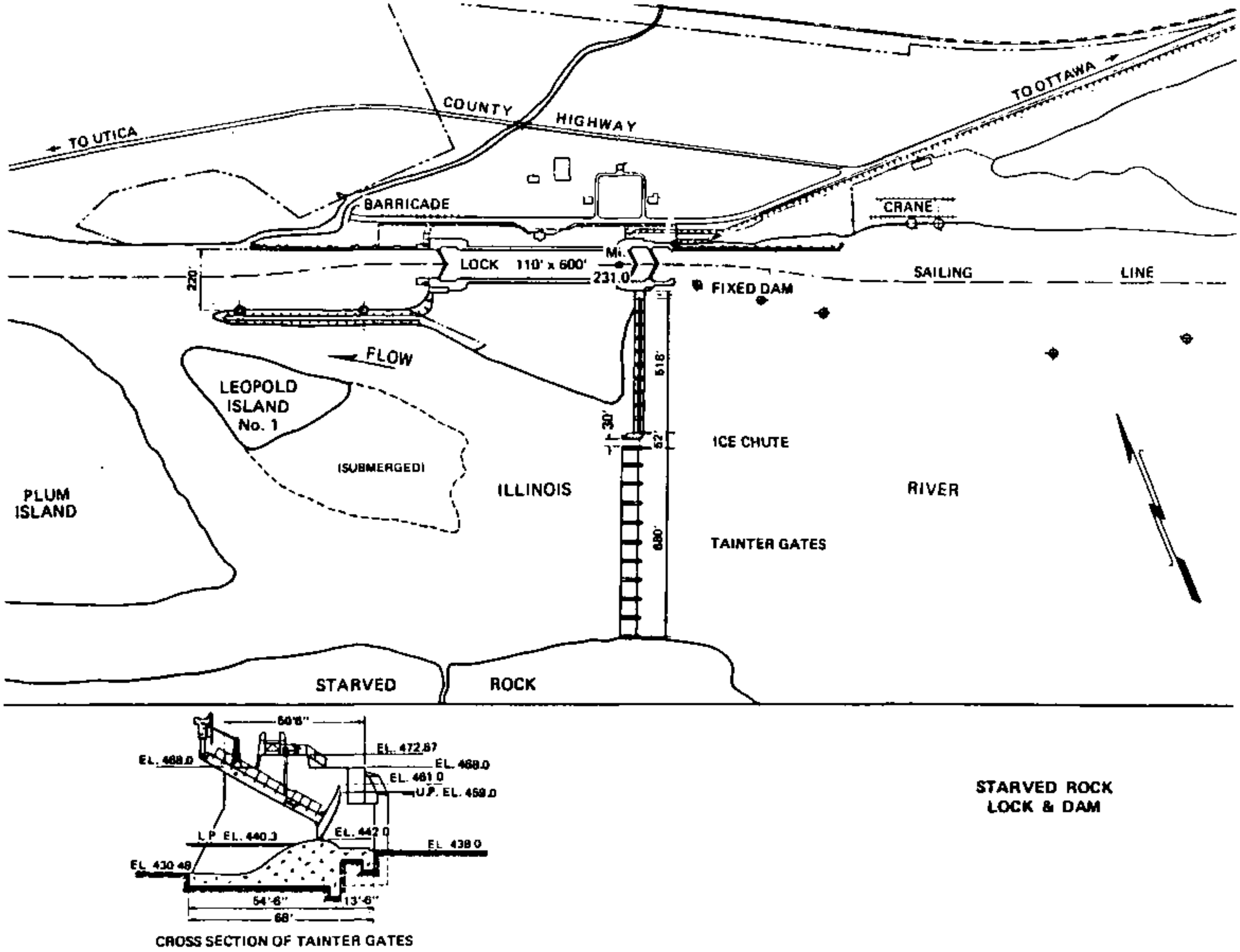

Figure 3. Plan and section views of Starved Rock dam

Although the dams are principally responsible for the overall reduction in the ability of the waterway to assimilate wastes, some of the natural aeration capacity lost through pooling can be partially made up at the dam. As water is passed either under or over flow release control structures at the dams, it is instantaneously reaerated due to the great turbulence and head loss factors associated with these releases. Historically, these flow release structures have been operated only to meet flow needs. No consideration has been given to optimizing and coordinating flow control adjustments with downstream water quality needs.

If slightly more than one part per million of DO could be added by reaeration at the Starved Rock dam by better management relative to reaeration, the DO standards could probably be achieved in the Peoria pool when or if improvements are made to the Calumet treatment plant. The purpose of this study was to define the aeration characteristics of the Starved Rock flow release control structures so that a practical operating scheme could be developed and employed to enhance the dissolved oxygen resources in the Peoria pool below the dam.

DAM AERATION THEORY

As previously noted, water flowing over weirs and spillways or through head-loss control structures such as Tainter and sluice gates can be aerated or deaerated depending upon the ambient upstream DO concentration. This relatively instantaneous DO change at a dam site may be dramatic and may have a more lasting effect on water quality and overall aquatic biology than any other single physical factor. This is especially true where deep pools are created behind navigation dams which limit the natural physical reaeration capacity of a stream. The effects of these structures on water quality cannot be ignored; any water quality model dealing with DO as a parameter must take into consideration the influence of all types of dams, and this must be done with accuracy and confidence.

Unfortunately, however, little work has been done to develop universally applicable techniques for predicting DO changes at dams. The lack of information and methodologies applicable to navigation dams where flow releases are usually gate-controlled is especially noticeable when searching for information. Most of the limited work on developing a dam reaeration model has been done by studying channel dams, weirs, and head loss structures on small streams and rivers. Usually when dam aeration is incorporated into a water quality model, it is handled with a simplistic "black box" approach whereby the change in DO concentration is correlated to a single factor, the water fall height.

Typical examples of this approach are the simple models developed by Crevensten and Stoddard (1974) and by Foree C1976). From field observations, Crevensten and Stoddard derived an empirical expression in which dam aeration is expressed as a direct function of the water fall and a variable numerical coefficient. Foree derived an empirical expression from field data, in which dam aeration is a direct function of the natural logarithm base, e, raised to the power of 0.16 times the water fall. The specificity of these equations limits their usage to the streams or stream reaches for which they were developed.

Only two references were found related to evaluating the aeration capacity of flow-controlling works at navigation dams. One was the work reported by Susag et al. (1967) for the Hastings Dam on the Mississippi River below Minneapolis, Minnesota, and the other was the work reported by Preul and Holler (1969) for two dams in the vicinity of Cincinnati on the Ohio River. Of particular note is the fact that both these published papers were void of references to previous works on the subject, indicating an historical lack of interest in the subject. In addition to studying the two Ohio River Dams in situ, Preul and Holler evaluated a laboratory scale model of a Tainter gate of one of the dams.

Both the Mississippi and Ohio River dam studies were interesting and informative, and management techniques were developed to increase aeration efficiencies in a manner compatible with navigation interests. However, these management techniques were basically site specific and not directly transferable to other locations, although an attempt was made by Preul and Holler (1969) to develop a more universally applicable mathematical model using dimensional analysis. Aeration efficiencies were equated to the Froude number. A good relationship was found to occur within the range of conditions encountered during sampling of the two Ohio River dams. However, this relationship, along with the operational procedures proposed, is dependent upon an intimate knowledge of hydraulic parameters relative to energy dissipation and to the discharge characteristics of the gates and attendant receiving basins. Essentially, the application of this approach requires discharge rating information on flow releases through gates.

The Hastings Dam study was designed to evaluate the aeration efficiencies of navigational dam flow releases for three conditions: 1) Tainter gates unsubmerged in the downstream direction (tailwater area), 2) Tainter gates submerged by tailwater, and 3) replacement of Tainter gates with bulkheads (fixed walls) which create sharp-crested weir overflows. Unsubmerged Tainter gate discharges were found to be three times more efficient than submerged discharges relative to reaeration when the upstream DO was 0 mg/l. Under similar DO and head conditions, the bulkhead overflow-weirs exhibited aeration efficiencies 2.5 times as great as the submerged Tainter gate discharges.

Preul and Holler also explored the possibility of increasing the aeration by overflow rather than underflow. Instead of using bulkheads in the gate openings, the gates were fully closed, letting water spill over the top. This operational procedure was found to be the least efficient method; both submerged and unsubmerged tailwater releases exhibited higher efficiencies.

In addition to differential water levels around which simplistic statistical formulations have been developed, other factors such as water film thickness, water quality, structural design and/or configuration, and flow rate all influence aeration to some degree.

Gameson (1957) has shown experimentally that the largest percentage of DO changes occurs at the foot or on the aprons of spillways or flow release structures; consequently, the physical design of a structure is important. Water spilling onto a concrete apron or a rocky scarp and water forming a hydraulic jump at the base of a dam have reaeration potentials different from those of water falling into a deep, quiet pool. Preul and Holler (1969) showed that the size of the hydraulic jump created in Tainter gate stilling basins was the most important factor regulating reaeration at the two Ohio River dams studied. Their conclusion was that submerged hydraulic jumps are inefficient aerators. For optimum oxygen absorption, the supercritical flow under a gate must break the surface for gates that discharge into protected pools (stilling basins).

Velz (1947) and many others have shown experimentally that aeration is a direct function of water temperature, i.e., warm water reaerates at a faster rate than cold water. This fact should be accounted for in the development of a dam aeration model.

Another criterion which should be directly accounted for in an aeration formulation is water quality. On the basis of a literature review on the effects of contaminants on reaeration rates, Kothandaraman (1971) reported that most contaminants retard oxygen uptake although a few appear to enhance it. Aeration rates have been reduced up to 60 percent by adding large portions of sewage to tap water, whereas suspended sediments, depending on the type, either increase or decrease the aeration rate to a slight degree.

Preul and Holler (1969) recognized the existence of this phenomenon in their work, but they made no attempt to ascertain its effect on their DO observations which were made year-round. In the laboratory scale model study of a Tainter gate, they assume that alpha, the oxygen transfer ratio of polluted to unpolluted water, is unity. While this assumption may be correct, it is open to question because the chemical contaminants sodium sulfite and cobalt chloride had to be added to deoxygenate the experimental water. Susag et al. (1967) used alpha values ranging from 0.9 to 1.0.

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

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

where C_S 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 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 $C_S \pm 10$ mg/l. However, data collected by Barrett et al. (1960) indicate that this independence may be reduced to $C_S \pm 4$ 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):

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

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 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) by definition is a sharp-crested weir with the flow free-falling into a receiving pool having a depth equal to or greater than 0.16 h. 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.

Equation 2 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 equation. In addition, close examination of the equation reveals that the factor (1 - 0.11 h) mathematically restrains the use of the equation to heights slightly less than 9.1 meters.

The water quality factor, a, has to be evaluated experimentally in the field or estimated from published criteria. The following generalized values have been used in the absence of direct determinations.

Polluted state	a
Gross	0.65
Moderate	1.0
Slight	1.6
Clean	1.8

These values are based on a minimal amount of field and laboratory data and are refinements of those originally published by Gameson (1957). The direct applications of these values are subjective, and since considerable latitude exists numerically between values, significant errors can result. With this in mind, measures were taken to design into this study a means of indirectly determining the water quality factor at the dam sites during each field trip.

The objective of this study was achieved by determining a rational weir or gate aeration coefficient by directly measuring differential water levels, above and below dam DOs, and water temperatures, and by indirectly measuring the water quality of the waterway coincident with direct measurements.

METHODS AND PROCEDURES

The methods and procedures used are presented under "laboratory" and "field" subheadings. The laboratory work was done in conjunction with developing a methodology and procedure for determining the water quality factor in the field.

Laboratory Weir Box Experiments

A portable weir system as devised and developed by Butts and Evans (1980) was used to estimate the water quality factor in the field. A weir box and receptacle trough were constructed of Plexiglas as detailed in figures 4 and 5. The weir box setup is shown operating in the laboratory in figures 6 and 7. Experimental laboratory data were collected to verify that the product "ab" in equation 2 equals 1.8 for a sharp-crested weir (b = 1.0) discharging clean water (a = 1.8). A verification that the standard weir has a coefficient of unity would enable the water quality to be computed with the weir box in conjunction with river water at the dam sites.

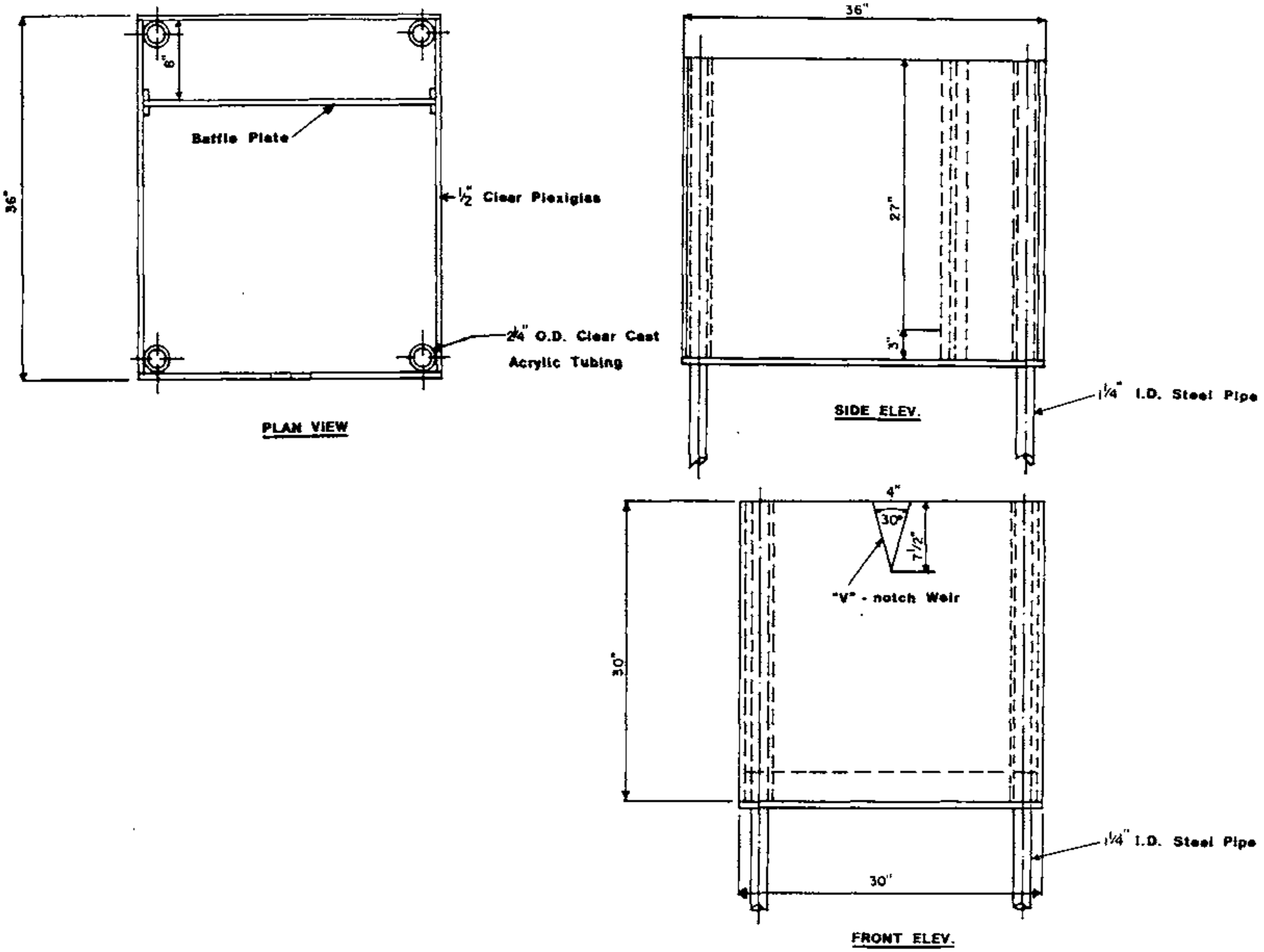

Figure 4. Weir box

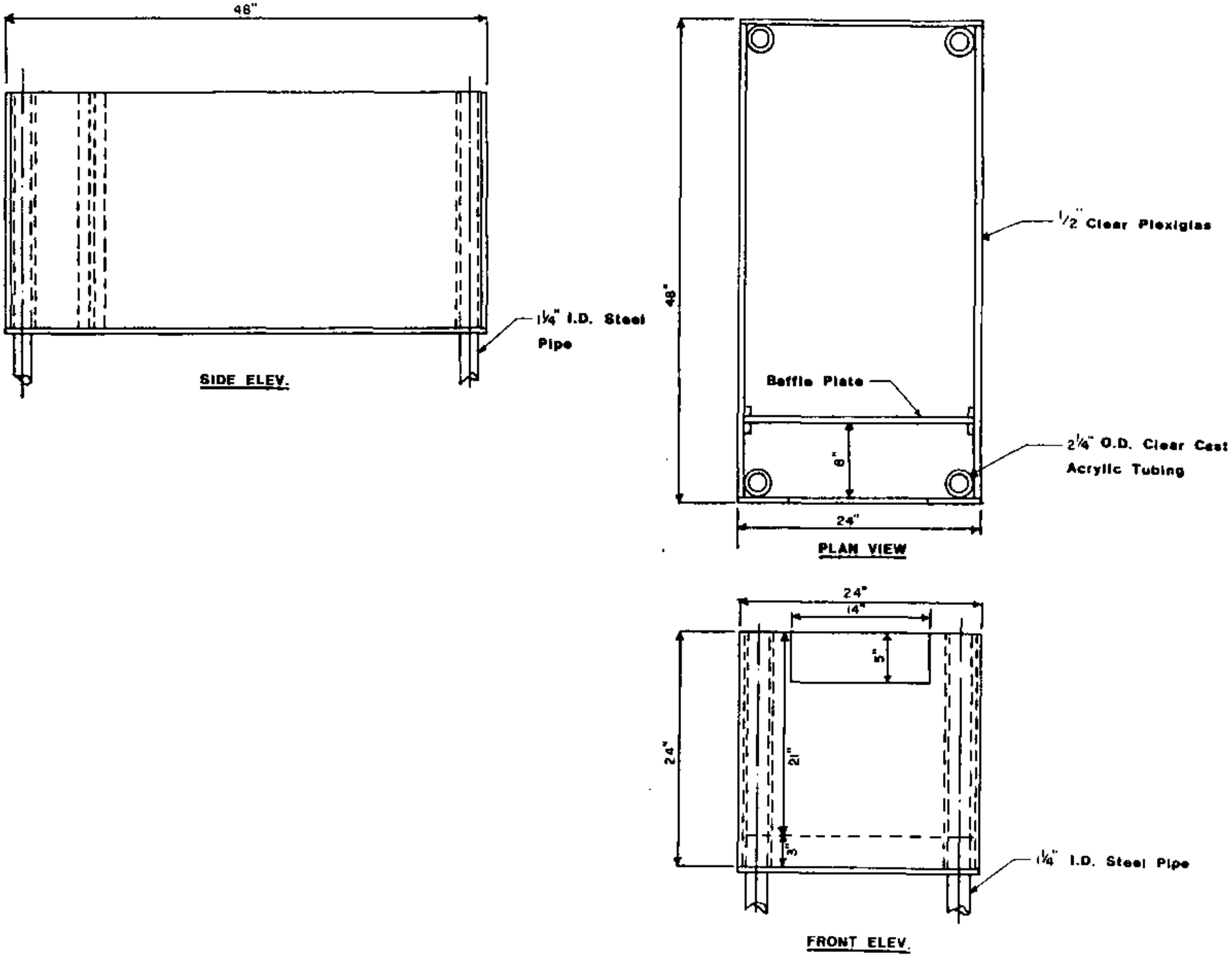

Figure 5. Weir receptacle box

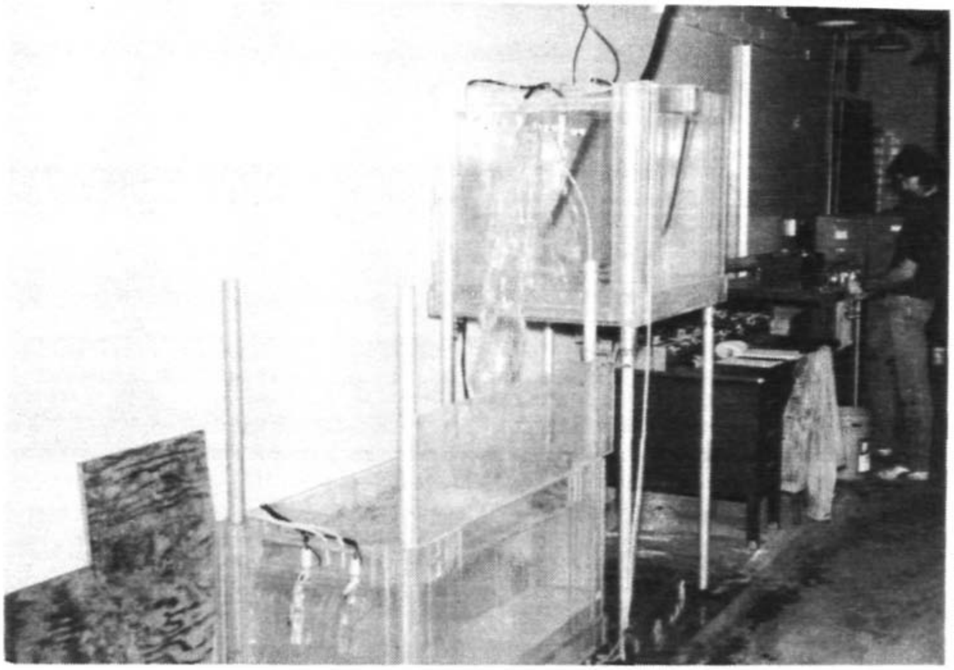

Figure 6. Weir box run in the laboratory - front view

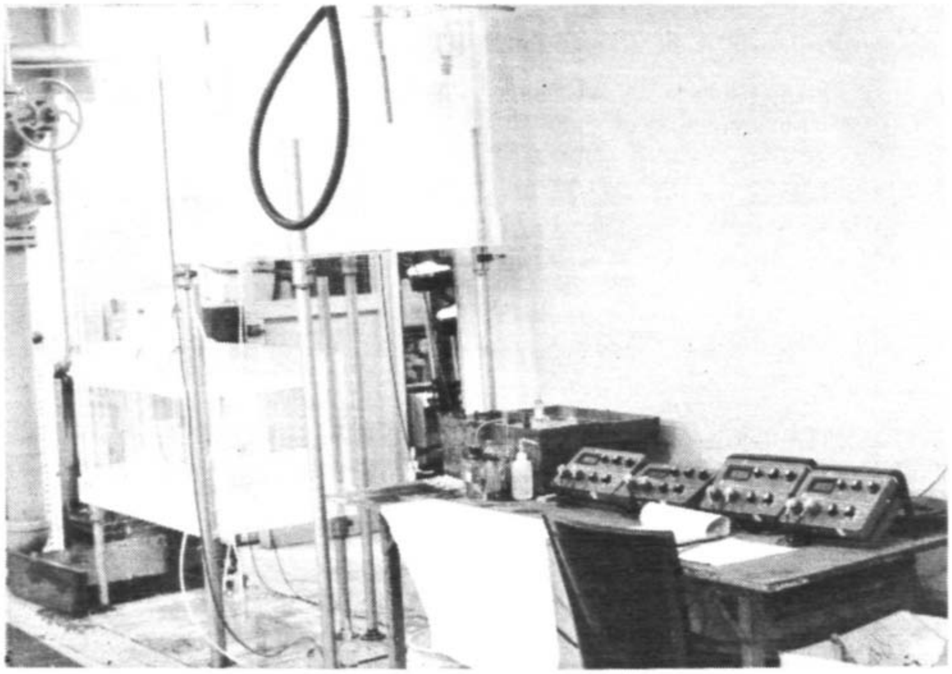

Figure 7. Weir box run in laboratory - rear view, showing DO - temperature meters

The experimental design was developed around analysis of variance (ANOVA) statistical concepts. This was done to gain some insight into what factors might cause "b" to deviate from unity if, by chance, it did so. Four parametric inputs were monitored and varied. They are: 1) flow, 2) weir box DO, 3D water level differential, and 4) receptacle box depth h'. Four different ranges of flow, DO, receptacle box depth, and water level differential were investigated. The values of ranges used during the experimental runs are given in table 1. Each parameter was set at a particular value, within the stated range, while all the others were varied. This resulted in a total of 256 data sets or runs.

Table 1. Weir Box Parameter Setting for Laboratory Experiment

	Settings or setting ranges of variables			
Parameter	1	2	3	4
Flow, Q (liters/sec)	0.18	0.46	0.97	1.77
Dissolved oxygen, DO (mg/l)	<2.32	3.0-3.4	3.5-6.0	7.5-8.0
Receptacle depth, h' (m)	0.00	0.16	0.32	0.48
Water fall height, h (m)	0.39-0.52	0.75-0.86	1.09-1.22	1.41-1.52

Tap water was used during the experiment. Tap water has several qualities which make it ideal for use in an aeration experiment. The Peoria Water Company supplies the SWS Peoria laboratory with shallow well water which has a relatively constant temperature throughout the year and a DO content generally less than 1.5 mg/l. The latter is significant in that no chemical additions are needed for deoxygenation. Also, the water receives no treatment before distribution except for chlorination.

Dissolved oxygen levels were controlled reasonably well within a setting (within 0.5 mg/l) and over the overall range of all settings by using an aspirator working on the Venturi principle (figure 8). Air intake, and therefore oxygen concentration, was controlled by a pinch clamp attached to the rubber section tubing.

Flow was controlled using a common garden hose ball valve installed above the "Venturi" section (figure 8). Discharge depths were controlled by adjusting a false bottom fitted for movement within the receptacle box (figure 9). Water fall heights were varied by moving the receptacle box up or down on extended legs. The legs were fitted with rubber lined compression couplings for use as leveling stops (figures 6 and 7). Baffles were installed at the inlet end of the weir box and the outlet end of the receptacle box to dissipate energy and to facilitate the dissolution of air bubbles to minimize their interference with DO readings (figures 4, 5, and 8).

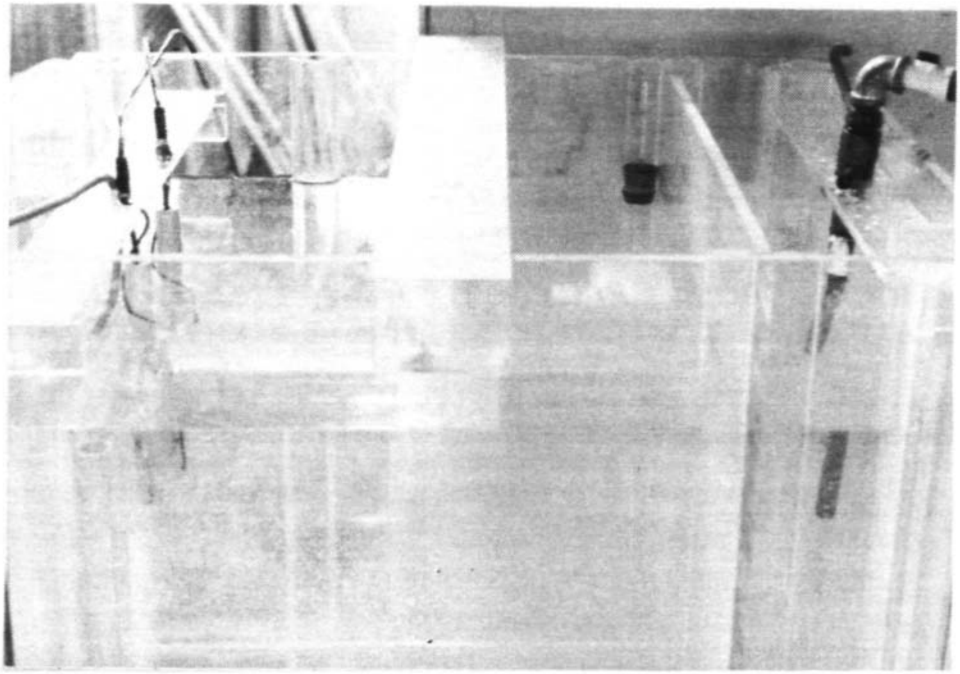

Figure 8. Weir box run in laboratory - top view, showing Venturi control

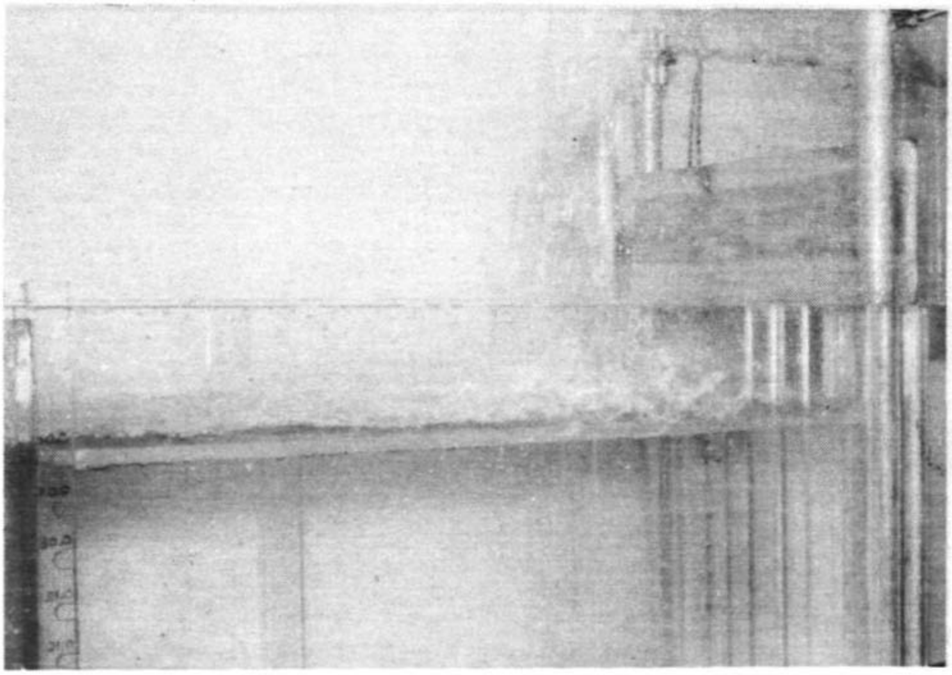

Figure 9. Receptacle box, showing false bottom set at zero receiving depth

All DO and temperature measurements were made using 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: two in the weir box and two in the receptacle box (figures 6, 7, and 8). This provided duplicate readings for both the unaerated and aerated water. The 00 probes were calibrated before the beginning of each run and checked periodically using the standard Winkler method. 00 saturation determinations were made concurrent with each weir box run. This was done to verify or check textbook values. Approximately 4 liters of tap water was aerated using compressed air and a diffuser stone over the length of the run. Periodically, samples were drawn off and the DO and temperatures were recorded.

Flow rates were measured by timing the filling of a 20.33-liter bucket. The four basic flow rates were established, and the heads required to produce these rates were permanently marked on the weir box for routine reference.

Water depths and water surface elevations were measured using a carpenter's rule. Stilting wells, consisting of half sections of 2-1/4-inch-diameter clear plastic tubing, were established along the side walls of both tanks to facilitate making these measurements (figure 8). Receiving depths were adjusted by placing the false bottom in notches spaced at 0.04 meters in four 0.48-meter-high stilted legs.

Field Studies

The field work at a given location consisted of two distinct operations. One was setting up and operating the weir box for gathering data pertinent to the determination of the water quality factor. The other was instream DO and temperature sampling by boat above and below each dam. The weir box data collection was made prior to the instream boat run.

Upon arrival at the dam, immediate contact was made with the lockmaster or one of his assistants to make arrangements for obtaining the desired gate setting, to record pool elevations, and to obtain a bucket of well water for use in calibrating the DO meters. The weir box and appurtenances were then set up on a mooring pier above the upstream lock gates (figures 10 and 11).

A 4-liter sample of river water was obtained and poured back and forth between two 5-gallon buckets four or five times and then placed in an 8-liter plastic jug for further aeration (or deaeration in the case of supersaturated conditions). Jug aeration was accomplished by attaching a fine bubble aeration stone to a portable air compressor equipped with a cigarette lighter electrical attachment. At the end of the weir box run (1-1/2 to 2 hours) two samples were drawn off for DO and

Figure 10. Weir box run in the field at the Starved Rock dam

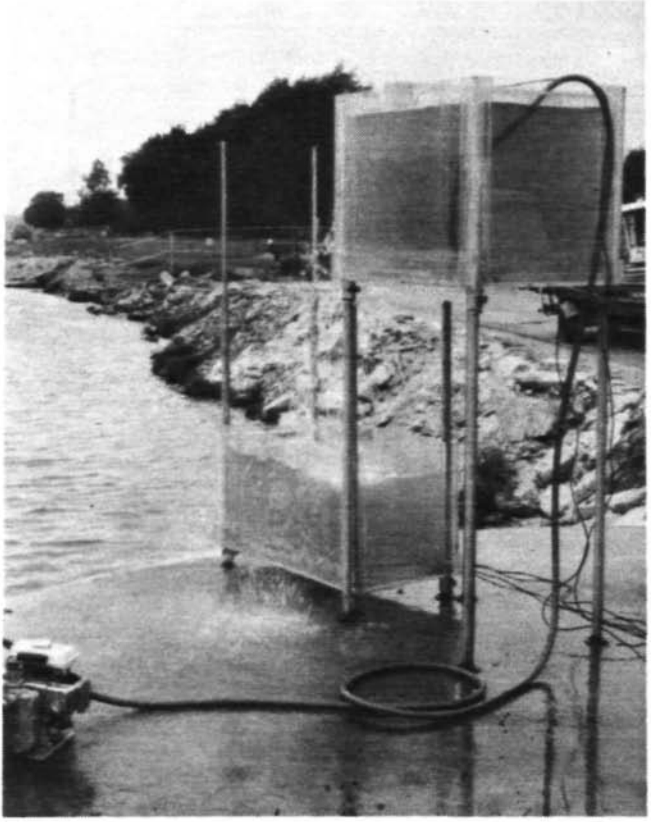

Figure 11. Weir box run in the field at the Starved Rock dam, showing inlet pumping

temperature measurements. If the DO differences exceeded 0.1 mg/l, a third sample was drawn and measured.

The four DO probes were calibrated in the field using tap water from a well located at the lock control house. River water does not suffice for calibrating because algal activity can cause river water DOs to fluctuate widely over the 20 minutes needed for calibration. The cloudy nature of the water in the boxes shown in figures 10 and 11 is due primarily to suspended algal cells and to some degree to suspended organic sediments and debris. The well-water DO is stable but needed to be vigorously aerated since it is naturally low in DO. This was done by passing the water back and forth at least 10 times between two 5-gallon buckets.

The weir and receptacle boxes were set up to attain maximum head loss (h) and receiving depth (h') values, and pumping was started. After the boxes filled, 30 minutes were allowed to elapse before DO and temperature measurements were made. Pumping was accomplished using a lightweight portable gasoline-powered Honda model WB15 1-1/2-inch centrifugal pump (figures 11 and 12). Pumping rates of around 1.5 1/sec were maintained through all the runs.

Special precautions had to be taken to prevent the wind from disrupting the weir box operation. Note the wind-blown overflows shown in figures 10 and 11. Wind gusts actually prevented the weir discharge from reaching the receiving box at times as shown by figure 11. To prevent this, a tarp was strung around the receptacle box to act as a wind shield as shown in figures 12 and 13.

The general layout of the dam is shown on figure 3; figures 14 and 15 show upstream and downstream photographic views of the dam. Flow is normally controlled and released through one or more of ten Tainter gates located along the east end of the dam. The head gates are used only during special situations such as during excessive flooding or possibly during Tainter gate repairs.

The gates were set at uniform openings during a sampling run. If a total of 8 feet of openings were needed by the Corps of Engineers at the time of sampling, either 8 gates open at 1 foot, 4 gates at 2 feet, or 2 gates at 4 feet were used. Upstream DO and temperature readings were taken at 2-foot depth intervals in line with the center of each open gate and about 400 feet upstream from it using a boat. Downstream readings were taken at one location, the centerline of all the open gates.

The water downstream was always very turbulent and shallow, and the river bottom is very rocky. This made movement and anchoring difficult and dangerous. In any event, only one sampling location was really necessary since the turbulence always created well mixed conditions. The downstream sampling

Figure 12. Closeup of weir box in the field, using tarp as a windbreak

Figure 13. General view of weir box setup on pier at the Starved Rock dam

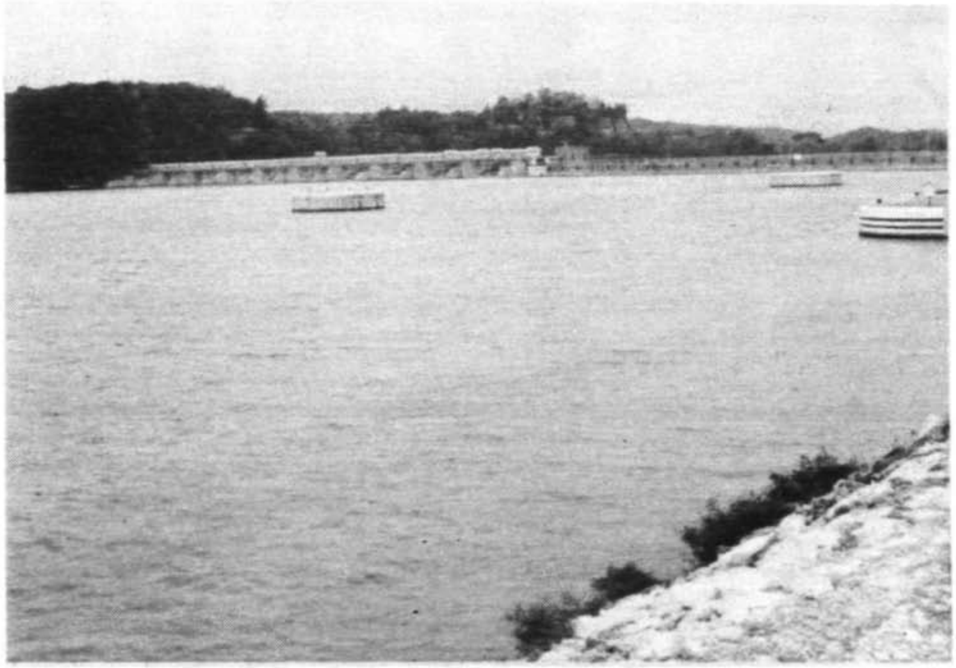

Figure 14. Upstream view of Starved Rock dam

Figure 15. Downstream view of Starved Rock dam
as viewed from sampling boat

boat was normally anchored approximately 1000 feet below the gates (figure 15). Downstream DO and temperature readings were taken in concert with the upstream readings, with an additional downstream reading taken five to ten minutes after termination of the upstream measurements to allow for the downstream results to match up with the last upstream reading. The DO-temperature probe was maintained at mid-depth since the water was only 2 to 3 feet deep.

The sampling depths were accurately and easily controlled by attaching the stirrer-probe to a heavily weighted fishing downrigger (figure 15). Algae samples were collected both upstream and downstream. Secchi disk readings were taken upstream during day runs. The upstream algae samples were collected as integrated samples over the depth of the Secchi disk reading using a small battery operated Pony pump with the intake line attached to the downrigger. During night runs, the previous daylight Secchi disk reading was used to gage upstream algae sampling depth. A 2-liter water quality sample was obtained downstream for analysis in the laboratory for suspended solids, chemical oxygen demand, and methylene blue active substances (MBAS) in terms of linear alkylate sulfonate (LAS). The latter chemical parameter is a measure of the surface active agent (detergent) content of the water. These parameters, along with algal enumeration, are easily measured variables considered (on an intuitive and subjective basis) to have a significant influence on reaeration.

Runs were made once a week (during June through October 1985) and were alternated between day and night periods during the warm summer months. Night runs are essential because significant diurnal fluctuations in the DO above the dam can occur due to algal activity. Algal blooms regularly crop up in the Starved Rock pool, producing supersaturated DO concentrations. Theoretically, deaeration of supersaturated water is supposed to occur at the same rate as aeration of equally under-saturated waters. However, some information has been published which indicates that this may not always be valid. On the basis of studies of several head loss structures in Ontario, Gowda (1984) concludes that, counter to theory, separate aeration coefficients should be developed for aeration and deaeration conditions. Although algal activity may not always raise the DO levels to supersaturated levels, the increase may be great enough that saturation is closely approached, which, as Butts and Evans (1984) point out, makes data interpretation difficult and often impossible. By performing night sampling, the chances of avoiding this predicament are enhanced.

Prior to starting the routine field work, an evaluation was made regarding the time required for a slug of water 400 feet above the dam to travel to a point 1000 feet below it. A small quantity of fluorescent tracer dye, Rhodamine WT, was injected upstream. The results are presented in table 2. At the time of the experiment, 7 gates were open at 1 foot, resulting in a

Table 2. Time of Travel - 400 Feet Above to 1000 Feet Below the Starved Rock Dam for: 7 gates set at 1'; Lower Pool Elevation = 439.8, Flow = 10.640 cfs

Elapsed time after dye injection (min)	Dye concentration (μg/l)	Comments
0	0.0	Injection time 11:30
4	0.0	
8	0.0	Dye Visible at Dam
11	25.3	Dye Visible at Boat
12	26.9	Peak Concentration
12.5	48.5	
13	34.1	
13.5	21.3	
14	135.6	
14.5	38.1	
15	23.7	Dye No Longer Visible
15.5	8.5	
16	4.5	
16.5	2.9	
17	0.6	
17.5	0.4	

Table 3. Two-way ANOVA Table Development Required for Four-Way ANOVA Investigation

Evaluation number	Parameter desianation for		
	Columns	Rows	Cell summation
1	DO	h	Q-h'
2	h'	DO	0-h
3	h'	0	DO-h
4	h'	h	DO-Q
5	h	0	DO-h'
6	DO	0	h-h'

discharge of approximately 10,640 cfs; the downstream pool elevation was 439.8 feet. Less than 15 minutes was required for the slug to move 1400 feet through the dam.

Data Reduction

Laboratory Weir Box Data

Butts and Evans (1980) verified that, under limited conditions, the "ab" factor in equation 2 can equal 1.8; i.e., the product of the theoretical sharp-crested weir factor (b = 1.0) times the clean water factor (a = 1.8). Their work was done with a plywood weir box system. The wood construction had several major drawbacks, and consequently for this study the boxes were constructed of Plexiglas plastic. The primary purpose of the laboratory weir box study was to see if the plastic construction produced the same results as that reported by Butts and Evans (1980). If it did not, the system would then have to be calibrated for field use. A secondary consideration was to thoroughly investigate the factors or variables which could significantly affect reaeration at a weir or dam location.

Analysis of variance (ANOVA) statistical techniques were used to isolate the physical factors which could influence the deficit ratio as defined by equation 1. Because four independent variables (as listed in table 1) were investigated, a four-way ANOVA technique had to be developed. Such a development is procedural as opposed to theoretical or basic. The methodology outlined by Crow et al. (1960) for performing a three-way ANOVA was used as a guide. Basically, the data had to be broken down and regrouped into a number of independent two-way tables. A four-way ANOVA for the parameters investigated in this work required the development of six two-way ANOVA tables formulated according to the criteria presented in table 3. A 95 percent confidence level was used in the analysis to determine the significance of each variable relative to weir aeration.

Stepwise regression techniques were used to determine the order of importance of water fall height, water receiving depth, flow rate, DO, and temperature on deficit ratio (r) values. Regression equations were developed for each step analysis.

Field Data

The field weir box data were used to calculate the water quality factor of the river water for use in calculating Tainter gate aeration coefficients. Weir box deficit ratios were calculated by using equation 1 and setting these ratios equal to equation 2, using in equation 2 the value of "b" derived from the laboratory experiments. The r-values were computed on the basis of field-determined DO saturation values and not on book values. Book saturations were used only for comparative purposes. These were computed using the American Society of Civil Engineers (1960) formula:

$$C_s = 14.652 - 0.41022T + 0.00791T^2 - 0.000077774T^3 \qquad (3)$$

where C_S = DO saturation in mg/l and T = temperature in degrees Celsius.

Instream deficit ratios were computed and equated to equation 2, using in equation 2 the value of "a" derived from the on-bank weir box run. On certain runs, however, the computed instream dam deficit ratios produced anomalous b-values when equated to equation 2. Sometimes negative values resulted for the expression (r-1) which was created by the rearrangement of terms in equation 2. Butts and Evans (1980) point out the following situations which can account for these negatives:

Case I $C_B < C_A < C_s$

Case II $C_B > C_S > C_A$

Case III $C_B > C_A > C_S$

Case IV $C_A > C_S > C_B$

The negative values that resulted from the reduction of field data collected during this study were Case II situations. The downstream DOs were "pushed" above saturation although the upstream DOs were at less than saturation levels. Theoretically, this is not possible, but this anomaly has occurred to some degree in the other two dam aeration studies undertaken by the Water Quality Section -- Butts and Evans C1978) and Butts and Evans (1980). Communication with other researchers in this field indicates that they have observed this phenomenon also. To create useable results for Case II situations encountered during this study, most of the C_B values were reduced by nominal amounts ranging from 1 to 7 percent. In one case, a better relationship between C_B and C_S was obtained by increasing C_S slightly instead of reducing C_B . These corrections reduced C_B to values less than C_S, thus producing positive realistic r-values.

The r-values and b-values derived from the dam data collections were subjected to several statistical tests. A one-way ANOVA test for unequal sample sizes was used to determine if different gate opening heights produced significantly different aeration rates. Also, the data were grouped into day and night results and statistically analyzed using the Student's t-test to see if the mean of the day runs differed from the mean of the night runs. Similarly, the t-test was used to ascertain if values derived for undersaturated DO conditions differed from those derived for supersaturated DO conditions. A 95 percent confidence level was used in all the statistical evaluations.

Stepwise regression techniques were used to equate the computed dam deficit ratio (the independent variable) to 13 dependent variables: (1) number of gates open, (2) gate opening height, (3) head loss over the dam, (4) gate sill submergence, (5) river flow, (6) the water quality factor derived from the weir box setup, (7) above-dam DO, (8) below-darn algae counts, (9) chemical oxygen demand CCOD), (10) suspended solids (SS), (11) methylene blue active substances (MBAS), (12) temperature, and (13) Secchi disk readings.

RESULTS

The results of this study were good. The laboratory weir box experiment produced interesting, informative results. It provided both calibration data specific for use in the field work at the Starved Rock dam site and general information that contributes to a better understanding of the underlying principles governing reaeration at weir and/or dam sites. Aeration coefficients were established for the Tainter gate flow control and release structures at the dam. The information generated will greatly aid in developing an optimum reaeration management program at the dam. The establishment of such a program appears almost an absolute necessity since the Corps of Engineers has given official notice that hydropower development at Starved Rock is economically feasible (see Appendix A). Such a development is presently being actively pursued, and if completed it could have a profound effect on downstream dissolved oxygen resources.

Laboratory Weir Box Experiments

A total of 1024 DO and temperature measurements were made during the 256 runs conducted during the weir box calibration process. The DO-temperature information generated, the data for the controlled variables, the resultant computed deficit ratio (r), and the products of the water quality factors times the weir coefficients (ab-values) are summarized in Appendix B.

The ANOVA tests were conducted on the r-values given in Appendix B. The data, grouped to describe the ANOVA modes given in table 3, are presented in tables 4 through 9. A close examination of these tables reveals that two factors, water fall height and receptacle depth, stand out as being the major influences on weir box aeration. This visual observation is verified statistically as shown by the results of the four-way ANOVA summarized by the data presented in table 10. These results are similar to the results reported by Butts and Evans (1980) for the data generated during the calibration of the wooden weir box system. Also, as found during the previous study, DO variability appears to have a small but significant influence on the. deficit ratio. However, the results of this

Table 4. Weir Box Aeration Table for Deficit Ratio Cr), Two-Way ANOVA Classification; DO Versus h' with Q-h Cell Summations

DO	Recentacle depth h' (m)				Row values	
(mg/l)	0.00	0.16	0.32	0.48	r-sum	r-Avg
1.6-2.3	27.11	33.54	33.71	33.34	127.70	2.00
3.0-3.4	27.36	33.08	34.32	33.50	128.26	2.00
3.5-6.0	27.14	36.76	37.23	38.19	139.32	2.18
7.5-8.0	28.53	35.07	41.98	36.51	142.09	2.22
Column r-sum	110.14	138.45	147.24	141.54	537.37	
Column r-avg	1.72	2.16	2.30	2.21		2.10

Table 5. Weir Box Aeration Table for Deficit Ratio Cr), Two-Way ANOVA Classification; Q Versus h' with DO-h Cell Summations

Q	Receptacle death, h' (m)				Row values	
(1/sec)	0.00	0.16	0.32	0.48	r-sum	r-Avg
0.18	25.81	36.99	37.81	37.69	138.30	2.16
0.46	27.36	36.14	40.48	36.90	140.88	2.20
0.97	28.80	35.04	35.98	33.73	133.55	2.09
1.77	28.17	30.29	32.97	33.23	124.66	1.95
Column r-sum	110.14	138.46	147.24	141.55	537.39	
Column r-avg	1.72	2.16	2.30	2.21		2.10

Table 6. Weir Box Aeration Table for Deficit Ratio Cr), Two-Way ANOVA Classification; h Versus h' with DO-Q Cell Summations

h	Receptacle deDth. h' (m)				Row values	
(m)	0.00	0.16	0.32	0.48	r-Sum	r-Avg
0.39-0.51	22.19	26.47	26.45	26.90	102.01	1.59
0.75-0.86	24.34	31.55	33.67	31.90	121.46	1.90
1.09-1.22	29.13	36.61	40.60	41.07	147.41	2.30
1.41-1.52	34.48	48.83	46.53	41.67	166.51	2.60
Column r-sum	110.14	138.46	147.25	141.54	537.39	
Column r-avg	1.72	2.16	2.30	2.21		2.10

Table 7. Weir Box Aeration Table for Deficit Ratio (r), Two-Way ANOVA Classification; 0 Versus h with DO-h' Summations

Q	Water fall height. h(m)				Row values,	
(l/sec)	0.39-0.52	0.75-0.86	1.09-1.22	1.41-1.52	r-Sum	r-Avg
0.18	25.91	31.29	39.11	41.99	138.30	2.16
0.46	25.97	31.57	38.72	44.63	140.89	2.20
0.97	26.73	30.91	36.65	40.26	133.55	2.09
1.77	24.40	27.68	32.95	39.63	124.66	1.95
Column r-sum	102.01	121.45	147.43	166.51	537.40	
Column r-avg	1.59	1.90	2.30	2.60		2.10

Table 8. Weir Box Aeration Table for Deficit Ratio (r), Two-Way ANOVA Classification; Q Versus DO with h-h' Summations

Q	Dissolved oxygen concentrations. DO (mg/l)				Row values	
(1/sec)	1.6-2.3	3.0-3.4	3.5-6.0	7.5-8.0	r-Sum	r-Avg
0.18	32.91	32.83	37.89	34.68	138.31	2.16
0.46	33.08	32.74	37.34	37.70	140.86	2.20
0.97	32.09	32.48	33.30	35.67	133.54	2.09
1.77	29.62	30.20	30.79	34.04	124.65	1.95
Column r-sum	127.70	128.25	139.32	142.09	537.36	
Column r-avg	2.00	2.00	2.18	2.22		2.10

Table 9. Weir Box Aeration Table for Deficit Ratio (r), Two-Way ANOVA Classification; DO Versus h with Q-h' Summations

h	Dissolved oxygen concentration. DO (mg/l)				Row values	
(m)	1.6-2.3	3.0-3.4	5.5-6.0	7.5-8.0	r-Sum	r-Avg
0.39-0.52	24.67	24.53	25.01	27.80	102.01	1.59
0.75-0.86	29.54	29.33	30.59	32.00	121.46	1.90
1.09-1.22	35.10	35.79	37.68	38.86	147.43	2.30
1.41-1.52	38.40	38.62	46.05	43.44	166.51	2.60
Column r-sum	127.71	128.27	139.38	142.10	537.41	
Column r-avg	2.00	2.00	2.18	2.22		2.10

Table 10. Statistical Summary and Results of Four-Way ANOVA Performed on Deficit Ratios Generated with Sharp-Crested Weir

Factor number	Source of variation	Sum of square	Degrees of freedom	Mean squares	F-ratios		Significant	
					Computed	F.05	Yes	No
1	h'	12.82767	3	4.27589	53.99	2.60	X	
2	DO	2.59311	3	0.86437	10.91	2.60	X	
3	Q	2.38800	3	0.79600	10.05	2.60	X	
4	h	37.77017	3	12.59006	158.98	2.60	X	
5	h' × DO	1.73635	3	0.19293	2.44	1.88	X	
6	h' × Q	2.41009	9	0.26779	3.38	1.88	X	
7	h' × h	1.99773	9	0.22197	2.80	1.88	X	
8	DO × Q	1.00816	9	0.11202	1.41	1.88		X
9	DO × h	1.33603	9	0.14845	1.87	1.88		X
10	Q × h	0.75617	9	0.08402	1.06	1.88		X
11	Residual	14.96754	189	0.07919				

study show that flow variability influences reaeration significantly, whereas it did not appear to do so previously. This apparent contradiction appears to be due to the fact that the earlier experiment was conducted over only a twofold range of flows while the present experiment was conducted over a tenfold range of flows (table 1).

Examination of table 6 shows that reaeration is significantly reduced when the overflow merely splashes onto a receiving plate (figure 8) rather than spilling into a deep stilling basin (figures 16,17,18). This verifies what was observed during the 1980 study.

Examination of the DO means (rows) in table 4 and the flow rate means (rows) in table 5 shows that the variability of these two parameters influences reaeration much less than h or h', albeit the influence is statistically significant as demonstrated by the statistical summary outlined in table 10.

The deficit ratio average for all 256 runs was 2.10 compared to a value of 1.57 for the 192 runs conducted during the 1980 study. This large increase was due partly to the fact that a fourth box height run was added and was 150 percent greater than the maximum height set during the 1980 study. Also contributing significantly to this difference is the fact that the three 1980 height settings were considerably less than the lower three settings used during this study. The data in table 11 and figure 19 demonstrate the effects of water level differentials on aeration during both studies. The 1980 values fall slightly below the 1986 values, with the 1986 data having a line slope of approximately 45 degrees while both regression lines intercept the Y-axis close to the theoretical value of unity. That is, when $h = o$, no aeration occurs and C_A and C_B in equation 1 are equal, resulting in $r = 1$.

Table 12 summarizes the interrelationships between the water fall height (h) and the receiving depth (h') relative to the "ab" factor in equation 2. The optimum depth criteria are those contained in the discussion in the publication of the Water Research Centre (1973) on the effects of receiving depths on aeration. A "rule of thumb" was devised which stated that to effect maximum aeration, the receiving depths should be at least 6 cm greater than one-tenth the water fall height (h). In other words, the bubble jets should not be allowed to penetrate the whole depth as shown in figure 16, but the bubbles should be controlled to impact as shown in figures 17 and 18. The experimental results of this laboratory study support this criterion. Note that for each water fall height significant increases in aeration occurred at about the "rule of thumb" value.

The results of the stepwise regression analysis are presented in table 13. Surprisingly, flow rate was found to be the most important independent variable. Water fall height was

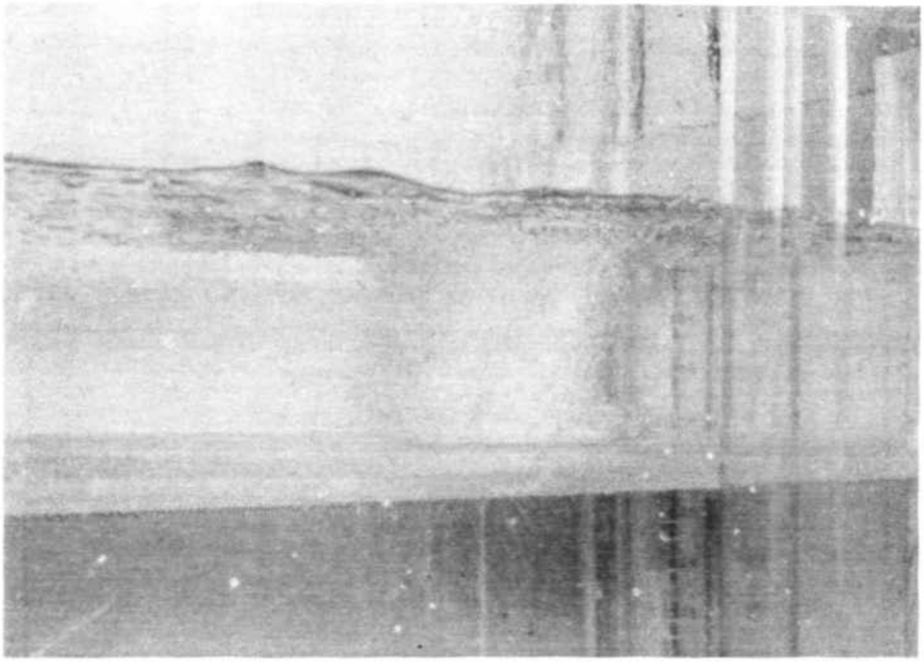

Figure 16. Weir box run, showing shallow depth setting in receptacle box

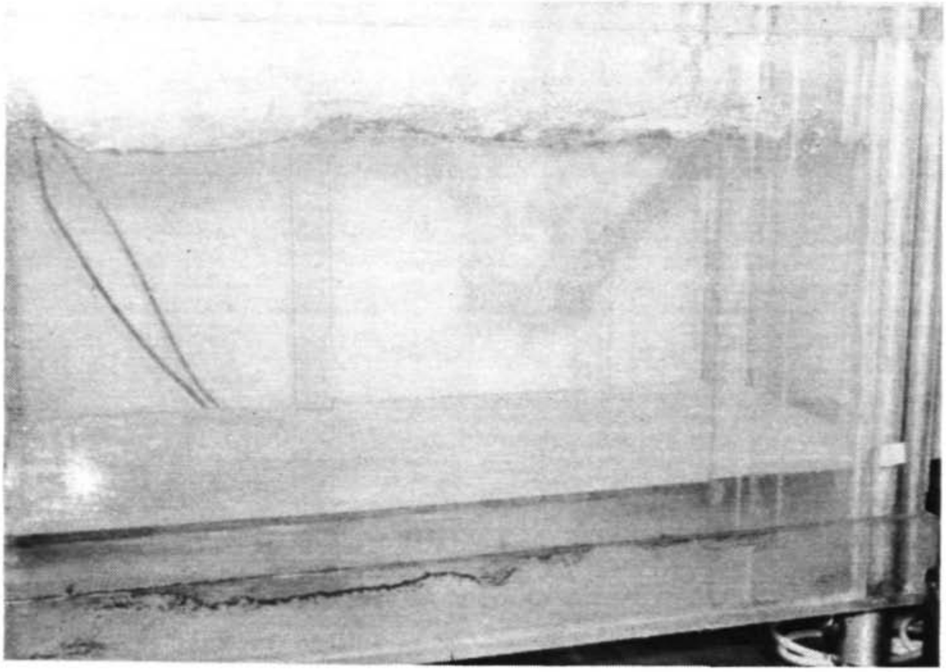

Figure 17. Weir box run, showing deep depth setting in receptacle box for high flow

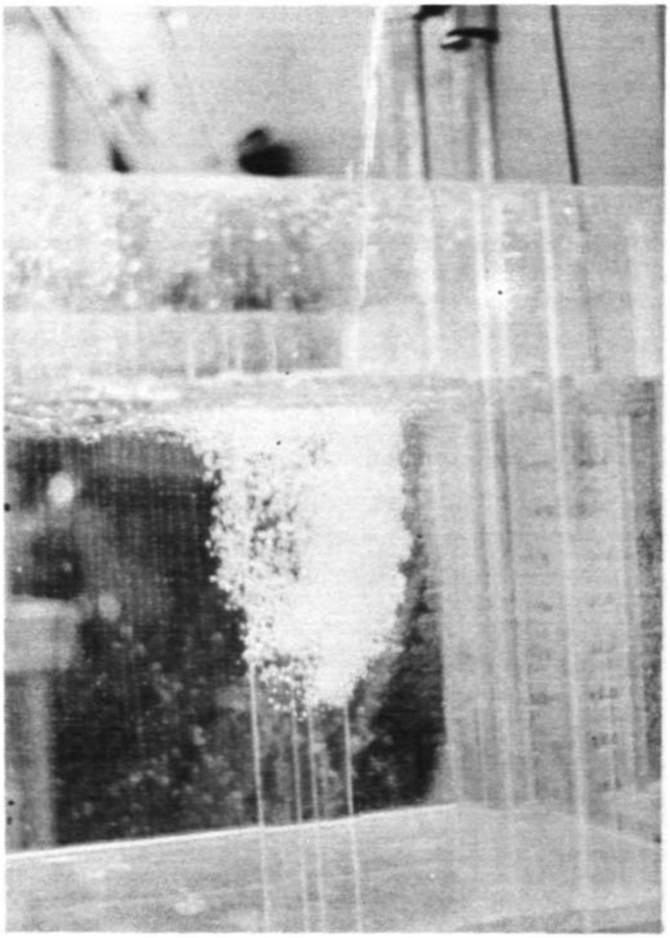

Figure 18. Weir box run, showing deep depth setting in receptacle box for low flow

Table 11. Comparison of Deficit Ratios (r) Derived for Various Head Loss Settings (h) for the 1980 and Present Weir Box Experiments

Avg h (m)	Average r-values 1980	 Present
0.32	1.31	-
0.46	-	1.59
0.64	1.57	-
0.81	-	1.90
0.98	1.83	-
1.16	-	2.30
1.47	-	2.60

Table 12. h × h' Matrix of ab Values Computed for Laboratory Weir Box Experimental Data

h	Receptacie death h' (m)				Row	Optimum h' (m)
(m)	0.00	0.16	0.32	0.48	avg	(.1h + 0.6)*
0.39-0.52	1.44	2.47	2.50	2.58	2.25	0.10-0.11
0.75-0.86	1.14	2.24	2.41	2.16	1.99	0.14-0.15
1.09-1.22	1.30	2.06	2.49	2.54	2.10	0.17-0.18
1.41-1.52	1.49	2.22	2.41	2.14	2.07	0.20-0.21
Column avg.	1.32	2.25	2.45	2.36	2.10	

* Water Research Centre C1973)

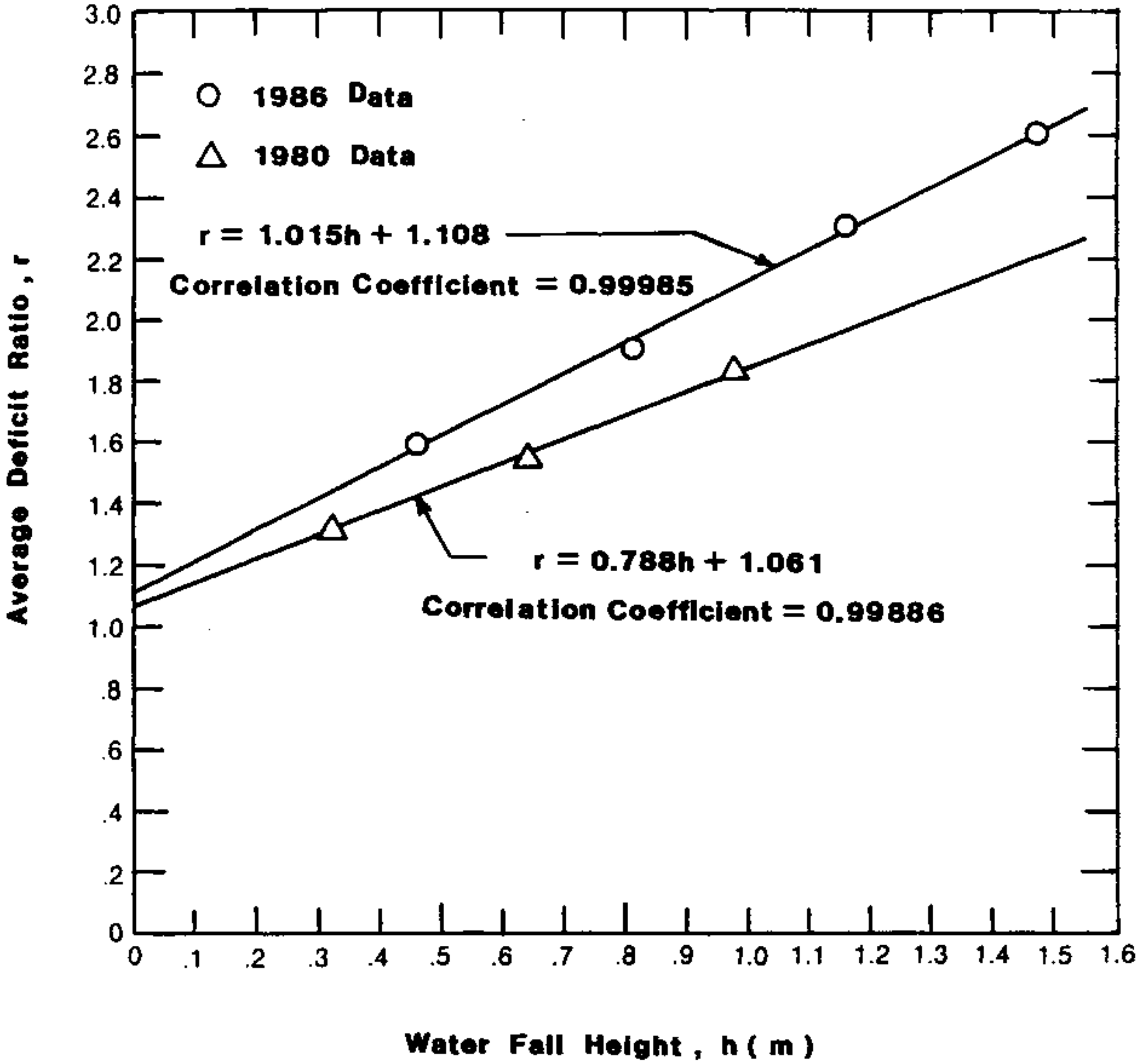

Figure 19. Water fall height (head loss) versus observed deficit ratios for 1980 and 1986 weir box studies

Table 13. Stepwise Regression Equation Relating the Deficit Ratio (r) to the Five Parameters Measured for the Laboratory Weir Box Experiment

	Regression coefficients for							
Stop No.	Flow Q (1/sec)	Water fall h (m)	Receiving depth, h (m)	Dissolved oxygen, DO (mg/l)	Temperature T (°c)	Intercept	Correlation coefficient	Standard Error of estimate
1	0.985					0.309	0.9826	0.927
2	1.002	0.055				0.028	0.9839	0.892
3	0.992	0.044	-0.025			0.209	0.9842	0.887
4	0.996	0.040	-0.141	0.112		0.244	0.9843	0.886
5	0.996	0.065	-0.143	0.113	-0.025	0.242	0.9843	0.888

Table 14. Selected Data Used to Calibrate the Weir Box for Field Use in Determining the Water Quality Factor (a):
0 = 1.77 1/sec

		"ab"-values							
		Range of h(m) 1.41-1.52		Range of h (m) 1.09-1.22		Range of hCm) 0.75-0.86		Range of h(m) 0.39-0.52	
Range of DOs (mg/l)	h'(m) =	0.48	0,32	0.48	0.32	0.48	0.32	0.48	0.32
1.71-2.29		1.55	1.52	1.74	1.45	1.71	1.74	1.87	1.90
3.01-3.41		1.63	1.59	1.88	1.88	1.64	1.70	1.63	2.04
5.53-5.91		2.16	1.70	1.78	1.85	1.82	1.91	1.94	2.13
7.67-7.91		3.36	2.97	2.23	2.24	1.94	2.42	2.14	2.34
Column avg		1.78*	1.60**	1.91	1.86	1.78	1.94	1.90	2.02

Depth avg.
0.48* = 1.844
0.32** = 1.894
Overall avg = 1.869

* average excludes 3.36
** average excludes 2.97

second, but it increased the correlation coefficient very little, which is not surprising since the Q-r correlation coefficient already exceeded 0.98. Adding the variable h did, however, improve the standard error of estimate somewhat. Temperature was not expected to show any effect since only about a 4.5 C temperature differential occurred. This proved to be true, and it was desirable since temperature was not a controlled variable.

The findings of this experiment are contrary to the conclusion expressed by Barrett et al. (1960) that the omission of a flow rate factor in equation 2 does not appear to affect its validity. In the publication of the Water Research Centre C1973), the fact was noted that no significant change in "r" was observed over a 3-1/2-fold change in flow for an experimental step weir. Over such a small flow range this is probably true. During the 1980 study no significant differences were observed over only a twofold range. However, over a much greater flow range, such as the tenfold range used during this study, flow variability became very important, and it must be considered in analyzing and calibrating a weir or spillway. This contention is supported by field studies conducted by Butts and Evans (1978) and Mastropietro (1968). The latter considered it to be the most important variable, which tends to be supported to some degree by the results of this study (at least by the stepwise regression analysis results).

At this point, consideration must be given to the selection of the weir box coefficient appropriate for use in analyzing the field data generated at the Starved Rock dam site. On the basis of the information obtained from this study (which essentially verifies the results of the 1980 study), the weir aeration coefficient (b) cannot be considered constant under all conditions. Consequently, if water quality is considered to have a bearing on dam aeration, careful selection must be made of the conditions under which a weir box coefficient (b) is calculated or derived. For this study, only the data generated for the maximum flow rate of 1.77 1/sec and for receiving water depth greater than 0.32 m were used to calibrate the weir. Also, two extreme values (outliers) were eliminated from the analyses. Table 14 presents the data used and summarizes the average results. Assuming that a = 1.8 for clean water, then for the results shown in table 14, b = 1.869/1.8 = 1.038. This is close to the defined value of unity as proposed by the original developers of equation 2 and essentially verifies the results of the 1980 study which produced a b = 0.981 for a similar data grouping. Consequently, a b-value of 1.038 will be used to assess the river data collected during each dam site run.

Field Studies

Nineteen sampling runs were completed at the dam site. The dates and the physical conditions under which the collections were made are presented in table 15. The unreduced data

Table 15. River Conditions Encountered During Each Sampling Date at the Starved Rock Dam

	Gate operation			Pool elevations (feet above MSL)		Discharge (cfs)		
1985 Date	No. open	Opening (ft/gate)	Total Feet Open	Upper	Lower	Per gate	Total	Flow duration (%)
6/13	2	2	4	458.81	442.27	3138	6276	94.3
6/18.19	3	2	6	458.89	442.67	3145	9435	41.5
6/25	3	2	6	458.87	442.04	3144	9432	41.5
7/02,03	2	2	4	458.70	441.96	3128	6256	94.0
7/09	3	1	3	458.66	441.57	1567	4701	99.8
7/16,17	4	1	4	458.80	442.12	1574	6296	93.5
7/24	4	1	4	458.96	440.98	1581	6324	93.2
7/29,30	3	1	3	458.63	441.52	1566	4698	99.8
8/06	3	3	9	458.94	442.57	4680	14040	17.0
8/13,14	1	3	3	458.84	441.50	4666	4666	99.8
8/19	2	3	6	458.87	443.03	4670	9340	41.5
8/26,27	1	3	3	458.90	441.19	4674	4674	99.8
9/04	4	1	4	458.87	441.68	1577	6308	93.5
9/09,10	1	4	4	458.80	442.03	6073	6073	96.5
9/16	1	4	4	458.83	441.27	6078	6078	96.5
9/23,24	3	2	6	458.77	442.94	3135	9405	41.6
9/30	1	4	4	458.88	441.93	6087	6087	96.5
10/14,15	1	4	4	458.83	441.71	6078	6078	96.5
10/24	3	2	6	458.76	444.13	3114	9342	41.5

Note: Double dates indicate night sampling runs; duration percents based on the Henry gaging station flow duration curve.

collected for the on-bank weir box runs and for the in-stream dam runs are given in Appendixes C and D, respectively. The raw data are summarized in basic terms in table 16 for the weir box and in table 17 for the dam.

General Results

Overall, the above-dam dissolved oxygen concentrations were not ideal during the study. Ideally, the values should fall well below or well above saturation limits to minimize the effects of experimental errors when reducing the data to meaningful terms. The deficit ratio Cr) is the basic parameter around which dam aeration efficiency is measured and evaluated. Note that r, as defined by equation 1, changes significantly with small incremental changes in either C_A or C_B when either of these two values approaches C_S in magnitude. On 13 of the 19 sampling dates, C_A fell witnin + 20 percent of C_S. This made data analysis difficult but not impossible. By effecting a small percentage change in some selected below-darn DOs, negative and unreasonably high r-values could be avoided and the data could be used without jeopardizing the integrity of the results.

For example, on the September 9-10, 1985 sampling date (double dates indicate night sampling), the average C_B value was 7.735 compared to an observed C_S value of 7.740, a difference of only 0.005 mg/l, an undetectable value in the field. This resulted in an unreasonably high r-value of 78.4. However, by reducing C_B by 1 percent (a mere 0.077 mg/l) a realistic, useable r-value of 4.780 was obtained. This type of change, when needed for certain dates, is reflected in the notes accompanying tables 16 and 17. The integrity of the results is retained in each case because the reductions of C_B are small in terms of both absolutes and percentages and because the changes produce conservative results, i.e., the adjusted figures produce reaeration rates slightly less than those which appeared to have occurred in nature. Therefore, a small safety factor has been built into the predictive uses of the results of this study.

Dissolved Oxygen Saturation (C_S)

Tables 18 and 19 present a comparison between observed (experimental) and published (American Society of Civil Engineers, Committee on Sanitary Engineering Research, 1960) 00 saturation concentrations. The foresight of making DO saturation evaluations in the field for each run made this study a success. Not doing so would have necessitated culling and discarding a significant amount of data, as had to be done in the past (Butts and Evans, 1980, 1983). Note that the overall average experimental values were higher than the published values. The published values corrected for elevation (pressure) averaged almost 0.5 mg/l less than the experimental values. Theoretically, these values should agree better with the

Table 16. Summary of Results of On-site Weir Box Runs

Date	Average DO(mg/l)		Temperature (°C)		Experimental DO saturation(mg/l)		Deficit ratio	Water quality
	Above*	Below**	Above	Below	Above	Below	r	factor,a
6/13/85	6.92	8.07	20.6	20.4	9.32	9.36	2.190	1.223
6/18,19	10.45	9.53	21.8	21.5	8.74	8.79	2.311	1.291
6/25	10.87	9.66	23.8	23.7	8.89	8.90	2.605	1.522
7/02.03	10.27	8.88	26.4	26.2	8.16	8.19	3.058	1.873
7/09	9.14	8.59	26.7	26.4	8.33	8.37	2.786	1.606
7/16,17	10.12	8.76	28.2	27.9	7.99	8.04	2.958	1.044
7/24	11.63	9.62	26.9	26.7	8.32	8.39	2.691	1.518
7/29,30	11.41	9.44	28.2	27.9	8.17	8.23	2.678	1.483
8/06	8.01	8.31	25.4	25.3	9.00	9.02	1.457	0.377
8/13,14	8.75	8.43	27.3	27.0	7.90	7.96	1.809	0.723
8/19	8.02	8.40	27.7	25.5	8.68	8.71	2.129	1.039
8/26,27	8.15	8.38	24.2	23.9	8.93	8.98	1.500	0.474
9/04	7.41	7.59	25.9	26.0	8.04	8.02	2.281	1.169
9/09, 10	7.05	7.42	27.6	27.3	7.71	7.76	2.379	1.210
9/16	9.52	9.17	20.8	20.6	8.95	8.99	2.360	1.396
9/23,24	7.14	8.03	20.5	20.2	8.75	8.80	2.091	1.126
9/30	8.02	8.82	18.3	18.0	9.31	9.37	2.345	1.460
10/14,15	9.07	9.42	16.7	16.6	9.65	9.67	2.320	1.498
10/24	9.15	9.42	16.9	16.9	9.77	9.77	1.853	0.962

* Above - above weir
** Below = below weir

Note: The DO and temperatures are the average of two measurements; the 8/13,14 DO saturation values were read from the DO meter - the rest were determined using the standard Winkler procedure; Below weir DOs were increased by 3% for 7/09, by 2% for 6/13 and 9/04, by 1% for 8/26,27 and by less than 0.8% for 8/06, 9/09,10, 9/16, and 10/24 to provide realistic r-values.

Table 17. Summary of Results of In-Stream DO-Temperature Data

	Average DO (mg/l)		Temperature (°C)		Experimental DO saturation (mg/l)		Deficit
Date	Above*	Below**	Above	Below	Above	Below	Ratio, r
6/13/85	6.785	8.657	20.0	20.3	9.43	9.38	3.658
6/18.19	10.059	9.871	21.5	21.6	8.79	8.78	2.126
6/25	11.284	10.154	23.6	23.7	8.92	8.90	1.885
7/02.03	10.200	9.081	26.4	26.3	8.16	8.18	2.264
7/09	9.084	9.185	26.4	26.5	8.37	8.36	1.416
7/16,17	11.931	10.179	28.0	28.1	8.02	8.01	1.803
7/24	12.631	10.166	26.4	26.4	8,39	8.39	2.024
7/29,30	14.162	10.539	28.2	28.1	8.18	8.20	2.568
8/06	8.248	9.069	25.2	25.2	9.03	9.03	2.414
8/13,14	10.501	9.095	27.3	27.2	8.72	8.73	4.879
8/19	7.759	8.565	25.0	25.4	8.80	8.72	6.716
8/26,27	9.006	9.042	24.2	24.0	8.93	8.96	2.375
9/04	7.137	8.225	25.8	25.8	8.05	8.05	2.853
9/09,10	7.398	7.735	27.1	27.4	7.79	7.74	4.780
9/16	11.482	9.698	20.6	20.5	8.99	9.01	3.622
9/23,24	7.328	8.720	20.3	20.3	8.79	8.79	2.889
9/30	7.814	8.948	18.4	18.3	9.29	9.31	8.360
10/14.15	8.874	9.610	16.4	16.4	9.71	9.71	8.360
10/24	9.027	10.200	16.7	16.8	9.81	9.79	3.876

* Above = above dam
** Below = below dam

Note: Above dam DO-values are depth integrated averages for verticals located at the centerline of each open gate while Below dam DO-values are time integrated averages; the Below dam DOs were reduced by 1% for 8/26,27 and 9/09,10, by 3% for 7/09, by 4% for 8/06. by 5% for 6/18.19 and 9/23.24, and by 6% for 9/04 and 10/24 to prevent negative r-values from occurring.

Table 18. A Comparison of Experimental and Published Dissolved Oxygen Saturation Concentrations - Above Weir or Dam

	Saturated dissolved oxygen concentrations (mg/l)					
	Weir box data			In-stream dam data		
		Published			Published	
Date	Experimental	@MSL	@S.R. Elev	Experimental	@MSL	@S.R. Elev
6/13/85	9.32	8.91	8.74	9.43	9.02	8.84
6/18,19	8.74	8.70	8.53	8.79	8.75	8.58
6/25	8.89	8.37	8.21	8.92	8.40	8.23
7/02,03	8.16	7.96	7.81	8.16	7.96	7.80
7/09	8.33	7.92	7.77	8.37	7.96	7.80
7/16,17	7.99	7.69	7.54	8.02	7.72	7.57
7/24	8.32	7.89	7.74	8.39	7.96	7.80
7/29,30	8.17	7.69	7.54	8.18	7.69	7.54
8/06	9.00	8.11	7.95	9.03	8.14	7.98
8/13,14	7.90	7.83	7.68	8.72	7.83	7.68
8/19	8.68	8.07	7.92	8.80	8.18	8.02
8/26,27	8.93	8.30	8.14	8.93	8.30	8.14
9/04	8.04	8.04	7.89	8.05	8.05	7.89
9/09,10	7.71	7.78	7.63	7.79	7.86	7.70
9/16	8.95	8.91	8.74	8.99	8.91	8.73
9/23,24	8.75	8.93	8.76	8.79	8.97	8.79
9/30	9.31	9.34	9.16	9.29	9.32	9.14
10/14,15	9.65	9.69	9.50	9.71	9.73	9.54
10/24	9.77	9.63	9.45	9.81	9.67	9.48
Avg.	8.664	8.408	8.247	8.746	8.443	8.276

Note: MSL = Mean Sea Level; S.R. Elev. = 745 feet above MSL at the Starved Rock dam site

Table 19. A Comparison of Experimental and Published Dissolved Oxygen Saturation Concentrations - Below Weir or Dam

	Saturated dissolved oxygen concentrations (mg/l)					
	Weir box data			In-stream dam data		
		Published			Published	
Date	Experimental	@MSL	@S.R. Elev	Experimental	@MSL	@S.R. Elev
6/13/85	9.36	8.95	8.77	9.38	8.97	8.79
6/18,19	8.79	8.75	8.58	8.78	8.74	8.57
6/25	8.90	8.38	8.22	8.90	8.38	8.21
6/02,03	8.19	7.99	7.84	8.18	7.98	7.82
7/09	8.37	7.96	7.81	8.36	7.95	7.56
7/16,17	8.04	7.74	7.59	8.01	7.71	7.56
7/24	8.39	7.92	7.77	8.39	7.96	7.80
7/29,30	8.23	7.74	7.59	8.20	7.71	7.56
8/06	9.02	8.13	7.97	9.03	8.14	7.98
8/13,14	7.96	7.87	7.72	8.73	7.84	7.68
8/19	8.71	8.10	7.95	8.72	8.11	7.95
8/26,27	8.98	8.35	8.19	8.96	8.33	8.17
9/04	8.02	8.02	7.87	8.05	8.05	7.89
9/09, 10	7.76	7.83	7.68	7.74	7.71	7.56
9/16	8.99	8.88	8.71	9.01	8.93	8.75
9/23,24	8.80	8.98	8.81	8.79	8.97	8.79
9/30	9.37	9.40	9.22	9.31	9.34	9.16
10/14, 15	9.67	9.67	9.43	9.71	9.73	9.54
10/24	9.77	9.63	9.45	9.79	9.65	9.46
Avg.	8.701	8.436	8.272	8.739	8.432	8.264

Note: MSL = Mean Sea Level; S.R. Elev. = 745 feet above MSL at the Starved Rock dam site

experimental values than do the published values for mean sea level. This is an extremely important fact in view of the discussion presented in the previous paragraph demonstrating how significant a difference as small as 0.005 mg/l can be in producing logical, useable information.

Table 20 shows that using the experimental C_S values reduced both the number of case rejections and the C_B correction percentages. Only 4 case rejections, requiring C_B to be reduced by an average of just 4.25 percent, occurred using the experimental C_S data; the MSL and S.R. Elev. data produced, respectively, 6 and 7 rejections with both needing significantly higher percentage corrections of C_B to produce reasonable r-values. Table 21 presents the C_B percentage corrections by dates. Of significance is the fact That the unrealistic r-values could be readily corrected using only a relatively small percentage change in C_B when the experimental C_S-values were used.

Water Quality Factor

The water quality factors presented in table 16 were computed using the experimental dissolved oxygen saturation concentrations. As the note on table 16 indicates, some corrections were made in C_B to eliminate unrealistic deficit ratios. Eight dates required corrections, but the percentage changes required were very small.

The a-values ranged from 0.38 to 1.87 which, according to the criteria of Gameson (1957), indicates that the Illinois River water quality ranged from grossly polluted to clean during the study. Gameson rates grossly polluted water at 0.65, moderately polluted at 1.0, slightly polluted at 1.6, and clean at 1.8. The median study-value was 1.29 while the arithmetic average was 1.25. Only two of the a-values, which were lower than 0.65, appeared unrealistic; however, they were still used in equation 2 to compute the dam aeration coefficient (b).

Essentially an even split between under-saturated and supersaturated DO conditions occurred during the weir box runs. Supersaturation occurred 9 times while subsaturation occurred 10 times. This provided an ideal situation for applying the Student's t-test to determine if a statistically significant difference existed between the means of the two data groupings. The supersaturated conditions produced a mean a-value equal to 1.457 while the subsaturated conditions produced a value equal to 1.054. At a 95 percent confidence level, one can conclude that the means are different and that supersaturated conditions are indicative of better water quality. The t-test produced a computed t-value of 2.513 compared to a theoretical t-curve value of 2.110 at the 95 percent confidence level. Computed values exceeding 2.110 indicate that a 95 percent chance exists that the true means of the two data groupings are different.

Table 20. Comparison of In-stream DO Percent Saturations (C_S) and r-value Rejection Rate Cases Using Three DO Saturation Values

	Experimental				@ MSL				@ S.R. Elev.			
	% Saturation		%	Reject.	% Saturation		%	Reject.	% Saturation		%	Reject.
Date	Above	Below	Change	class	Above	Below	Chanae	class	Above	Below	Chanae	class
6/13/85	72	92	+20	-	75	98	+23	-	77	98	+22	-
6/18,19	113	112	-1	-	115	104	-11	-	117	115	-2	-
6/25	127	114	-13	-	134	121	-13	-	137	123	-14	-
6/02.03	125	111	-14	-	128	114	-14	-	131	116	-15	-
7/09	109	110	+1	III	114	115	+1	III	116	118	+2	III
7/16,17	149	127	-22	-	155	132	-23	-	158	134	-24	-
7/24	151	121	-30	-	164	132	-32	-	162	130	-28	-
7/29,30	173	129	-44	-	184	137	-47	-	188	140	-48	-
8/06	91	100	0	-	101	114	+13	III	103	114	+11	III
8/13,14	120	104	-16	-	134	116	-18	-	137	118	-19	-
8/19	88	98	+10	-	95	104	+9	II	97	107	+10	II
8/26,27	101	101	0	-	109	109	0	-	111	111	0	-
9/04	89	102	+13	II	89	102	+13	II	90	104	+14	II
9/09,10	95	100	-20	-	94	101	7	II	96	101	+5	II
9/16	128	108	-20	-	129	109	-20	-	132	111	-21	-
9/23,24	83	101	+18	II	82	97	+15	-	83	99	+16	-
9/30	84	96	+12	-	84	96	+12	-	85	98	+14	-
10/14,15	91	99	+8	-	91	99	+8	-	93	101	+8	II
10/24	92	104	+12	II	93	106	+13	II	95	108	+13	II
Number of Rejections				4				6				7
Avg. C_b Percentage Correction				4.25				5.15				5.43

Note: MSL = Mean Sea Level; S.R. Elev. = 745 feet above MSL at the Starved Rock dam site

Table 21. Comparison of Percent Corrections Needed in C_B To Obtain the r-values Listed in Table 17

	C_B Percentage Corrections Using		
Date	Exp.-C_S	MSL-C_S	S.R. Elev. -C_S
6/18,19/85	5.00	5.22	6.13
7/09	3.49	4.03	5.32
8/06	4.10	9.75	10.78
8/19	-	6.04	7.63
8/26,27	0.55	4.59	5.61
9/04	2.50	2.50	1.24
9/09,10	1.00	1.57	3.08
9/23,24	5.00	4.29	2.98
10/14,15	-	0.18	1.55
10/24	6.00	7.02	8.40
Avg. - Total	3.45	4.52	5.27
- negative r	4.25	5.15	5.43
- unrealistic r	2.66	3.57	4.94

Note: underlined values indicate C_B corrected to eliminate negative r-values; others are corrected to eliminate unrealistically high r-values. Exp. = experimental; MSL = Mean Sea Level; S.R. Elev. = 745 feet above MSL at the Starved Rock dam site

Dam Aeration Coefficients

The dam or weir aeration coefficients derived on the basis of observed and computed input data contained in tables 15, 16, and 17 are summarized in table 22. These b-values and the r-values listed in table 17 have been rearranged and segregated according to gate opening and values obtained during day and night runs as shown in tables 23a and 23b. Both the deficit ratio and the dam aeration coefficients tend to increase as the gate opening height increases. Both parameters exhibit considerable variability within each grouping. However, the average values for both parameters exhibit good linear relationships as shown by figures 20 and 21. The deficit ratio curve intercepts the Y-axis at 1.03 very near the theoretical intercept point of unity when no aeration occurs (zero gate opening), and both the slope of the line and the correlation coefficient are near the theoretical limit of 1.0.

The association between the dam aeration coefficients and the gate openings is nearly perfect when only the 1-, 2-, and 4-foot openings are considered. The coefficient associated with the 3-foot opening appears anomalous and out of line (figure 21). The 1-, 2-, and 4-foot coefficients are essentially even multiples of each other, and the line through these three points goes through the origin. For gate management relative to reaeration and downstream 00 considerations, the linear fit shown on figure 21 will be used. This will probably provide for conservative estimates when considering 3-foot openings in an evaluation or management scheme. Although the data show that a 4-foot gate opening has a reaeration coefficient twice that of a 2-foot opening and four times that of a 1-foot opening, this does not mean that a 4-foot gate will produce twice the aeration of a 2-foot opening or four times that of a 1-foot opening. This will be discussed in more detail later.

No statistical difference appeared to exist between the means of the daylight and night data for either the r-values or the b-values given in table 23. Using the Student's t-test, t-values of 0.328 and 0.178 were computed for the r-values and the b-values, respectively. These values were much smaller than the theoretical curve value of 2.110 for 17 degrees of freedom and a 95 percent confidence level. Therefore, a hypothesis that the means are equal could be accepted with a high degree of reliability. This was not the case, however, when the data were grouped according to subsaturated and supersaturated conditions as presented in table 24. The deficit ratio and dam aeration averages, even in the absence of statistical analysis, were obviously different. The supersaturated aeration coefficient average was over twice as great as that for subsaturated conditions. Gowda (1984) in his critical review of Butts and Evans' (1984) paper on dam aeration pointed out the possibility of this occurring although it runs counter to aeration-deaeration theory. Gowda recommended developing two sets of coefficients,

Table 22. Dam Aeration Coefficients

Date	Opening (ft)	Coefficient, b
6/13/85	2	1.322
6/18,19	2	0.511
6/25	2	0.328
7/02.03	2	0.359
7/09	1	0.139
7/16,17	1	0.243
7/24	1	0.499
7/29,30	1	0.542
8/06	3	2.065
8/13,14	3	2.832
8/19	3	2.962
8/26,27	3	1.651
9/04	1	0.859
9/09,10	4	1.631
9/16	4	1.154
9/23,24	2	1.009
9/30	4	1.341
10/14,15	4	3.315
10/24	2	1.956

Table 23. r and b-values Segregated According to Gate Opening and Time of Day

a. r-values

Daily Period	Gate opening (ft.)				Average
	1	2	3	4	
Daylight	2.042	3.658	6.716	3.622	
	1.416	1.885	2.414	4.077	
	2.853	3.876			3.256
Night	1.803	2.264	4.879	8.360	
	2.568	2.889	2.375	4.780	
		2.216			3.570
Average	2.136	2.798	4.096	5.210	

b. b-values

Daylight	0.499	1.322	2.962	1.154	
	0.139	0.328	2.065	1.341	
	0.859	1.956			1.263
Night	0.243	0.359	2.832	3.315	
	0.542	1.009	1.651	1.631	
		0.511			1.344
Average	0.456	0.914	2.378	1.860	

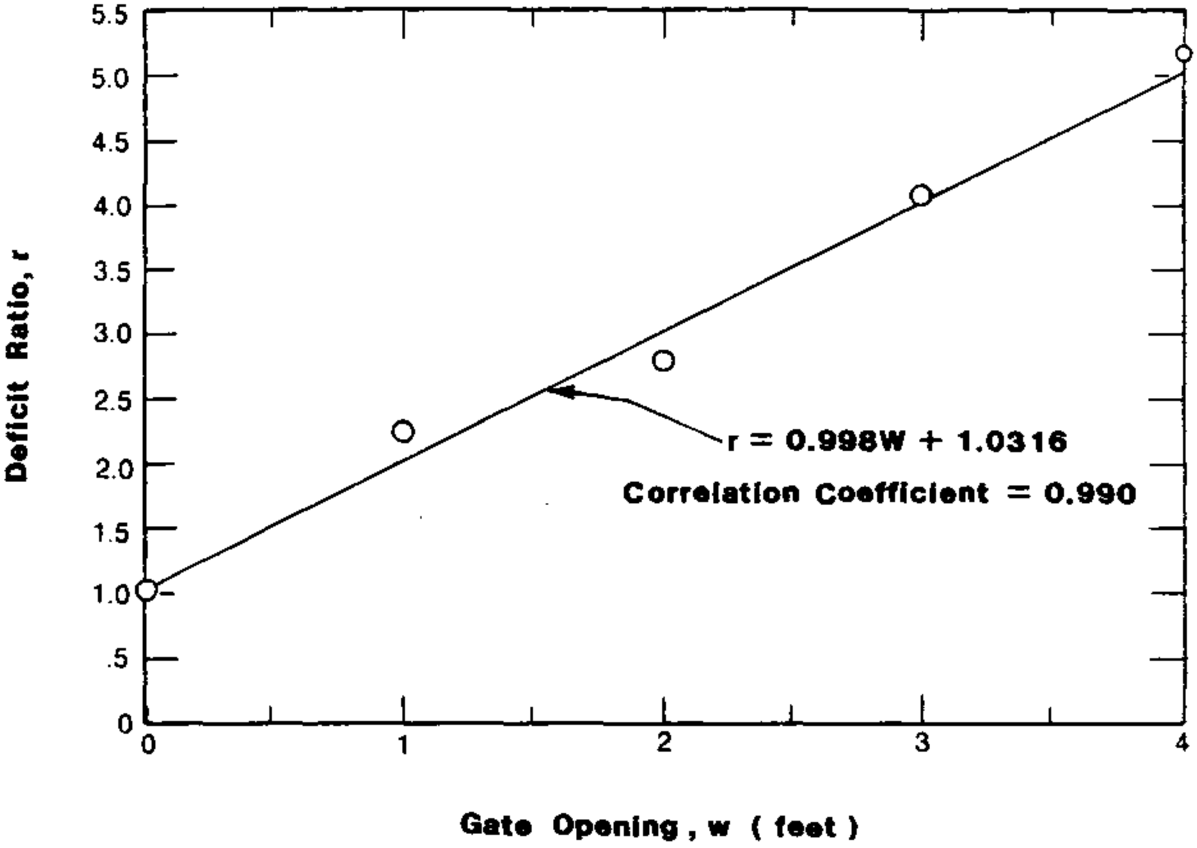

Figure 20. Relationship between gate openings and deficit ratios

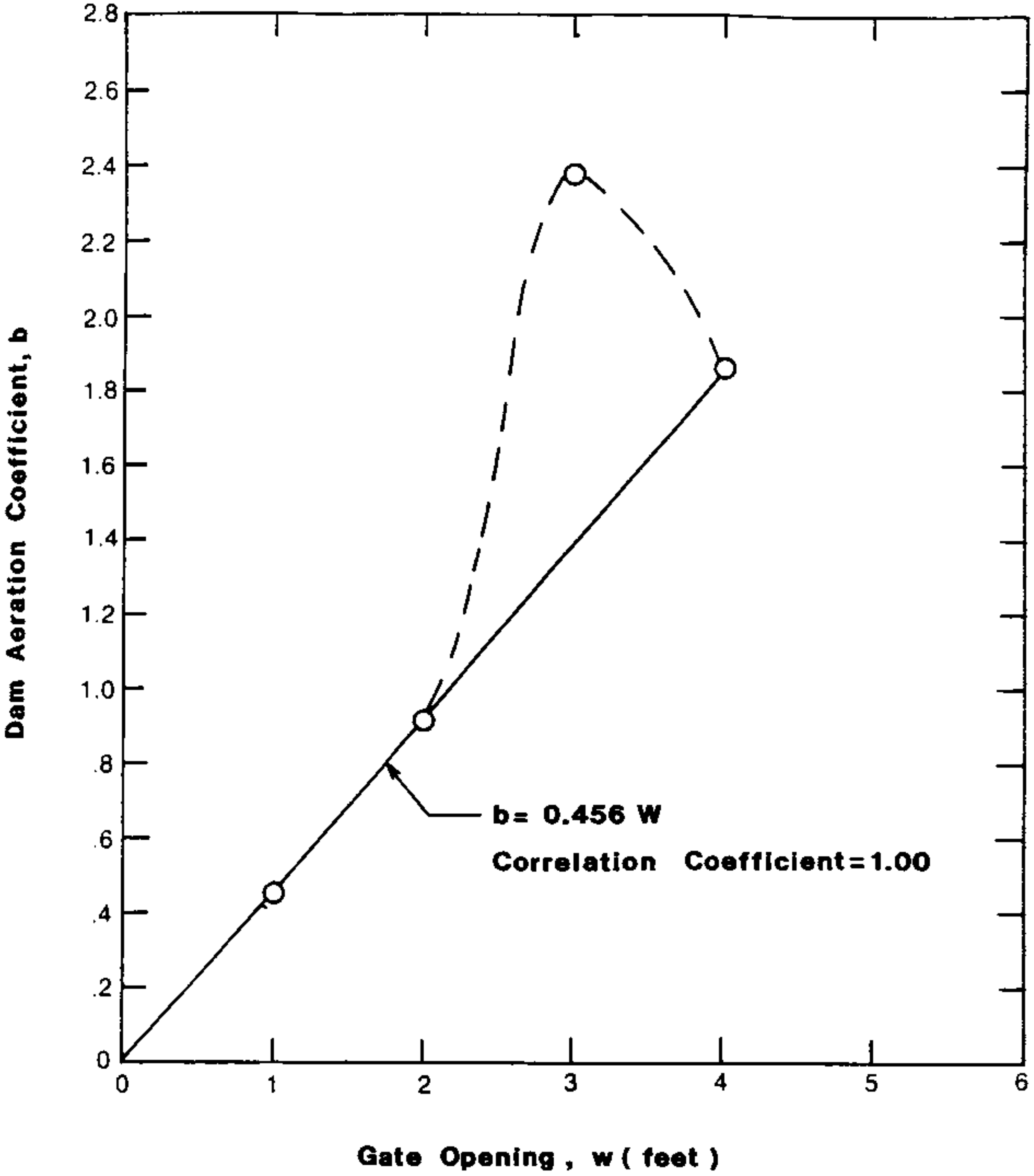

Figure 21. Relationship between gate openings and dam aeration coefficients

Table 24. r and b-values Segregated According to Subsaturated and Supersaturated DO Conditions

	r-values		b-values	
	Subsaturation	Supersaturation	Subsaturation	Supersaturation
	2.126	3.658	0.511	1.322
	1.885	2.414	0.328	2.065
	2.264	6.716	0.359	2.962
	1.416	2.375	0.139	1.651
	1.803	2.853	0.243	0.859
	2.042	4.780	0.499	1.631
	2.568	2.889	0.542	1.009
	4.879	4.077	2.832	1.341
	3.622	8.360	1.154	3.315
		3.876		1.956
Avg	2.512	4.200	0.734	1.811

Table 25. Summary of Results of Stepwise Regression Analyses Relating the Deficit Ratio to Appendix E Data

Step No.	Parameter addition	Standard error of estimate	Multiple correlation coafficient.R	Explained variation.R^2
1	Gate Opening (ft/gate)	1.383	0.6582	0.4332
2	Surfactants, MBAS (mg/l)	1.211	0.7689	0.5912
3	Suspended Solids (mg/l)	1.193	0.7924	0.6279
4	Algae Counts (No./ml)	1.096	0.8407	0.7068
5	Gate Submergence (ft.)	1.025	0.8728	0.7618
6	Total Flow (cfs)	0.950	0.9006	0.8111
7	No. Gates Open	0.853	0.9275	0.8603
8	Seechi Disk	0.777	0.9459	0.8947
9	Temperature (°C)	0.708	0.9599	0.9214
10	COD (mg/l)	0.582	0.9761	0.9528
11	Head Loss (ft.)	0.594	0.9782	0.9567
12	Above Dam DO (mg/l)	0.635	0.9786	0.9577
13	Water Quality Factor, a	0.687	0.9792	0.9588

one for use during subsaturated conditions and the other for use during supersaturated conditions.

An effort was made to determine, in the order of importance, the factors which significantly control and influence reaeration at a Tainter gate flow release structure at a navigation lock and dam. A stepwise statistical regression analysis was used to equate the deficit ratio (the independent variable) to 13 dependent variables. The data used as input to this analysis are tabulated in Appendix E; the results are summarized in table 25.

The step number indicates the order of importance of a dependent variable; the standard error indicates the probable range the <u>true</u> mean of the 13 r-values will fall within. That is, a 67 percent chance exists that the <u>true</u> mean will fall between the sample mean (4.966) plus or minus one standard error of estimate (4.966 ± 1.383 at step 1 or 4.966 + 0.582 at step 10).

The square of the multiple correlation coefficient indicates the fraction (or percentage) of the variability explained by the combination of factors; i.e., the gate opening height alone explains only about 43 percent (0.6582) of the observed variability in the reaeration as measured by the deficit ratio, whereas the explained variability is increased to over 95 percent by including the first 10 variables. Inclusion of the last three variables increases the explained variability by only 0.6 percent while actually decreasing the accuracy by increasing the standard error of estimate slightly from 0.582 to 0.687.

Gate Discharge Ratings

The Starved Rock Tainter gate rating table, as developed by Mades (1981), has been expanded for use in this study. The expanded tables are presented in Appendix F. The original tables were developed for an upstream pool elevation of 458.5 in conjunction with 2-foot downstream pool elevation increments. For obtaining flows for upstream pool elevations other than 458.5, the values in Appendix F should be multiplied by the factor (X - 441.5) /4.123 where X equals the upper pool elevation. For example, during the July 24, 1985 run the upstream and downstream pool elevations were 458.96 and 440.98 feet, respectively, and four gates were open 1 foot (table 15). Using a 1-foot opening and the 442.0 column in Appendix F (column 442.0 is applicable to all downstream elevations 442.0 or less), the flow per gate equals (1560) $(458.96-441.5)^{1/2}$ /4.123 or 1581 cfs.

DISCUSSION

The principal objective of this study was to develop Tainter gate reaeration rates for use in devising an operating scheme(s) to optimize reaeration without interfering with commercial navigation interests. This objective has been fulfilled. The information contained in table 23b and in figure 21 has made this possible in that the data clearly show that the manipulation of gate opening heights can significantly affect downstream DO levels. From the straight line relationship between gate opening height and the dam aeration coefficient shown in figure 21, nine gate management schemes or operational methods have been developed to cover almost all possible gate combinations needed to handle a wide range of flows. These methods are presented in Appendix G.

The weighted (Wtd) average (Avg) b-values were computed on the basis of the percentage of the total flow released through a given gate opening. As an example, 4 gates at 1.0 foot and 6 gates at 1.5 feet are needed to handle the flow not exceeded 14 percent of the time using management method 1 CAppendix G); the flow through 4 gates at 1 foot is 4584 cfs while that through 6 gates at 1.5 feet is 10,830 cfs; b = 0.456 and 0.684 for the 1.0 and 1.5 foot openings, respectively; therefore, the weighted average b-value equals (4584/15,414) 0.456 + (10,830/15 ,414) (0.684) or 0.617 as given in method 1 of Appendix G.

Theoretically, only one management scheme is needed to effect maximum aeration -- the one employing the least number of gates for a given flow. The fewer gates that are open for a given flow, the larger the openings and the greater the aeration. For the 99.8 percent flow duration, method 1 requires four open gates at one-half foot each, resulting in a low b-value of 0.228; whereas, for about the same flow, method 9 requires only one open gate at 2.5 feet, resulting in a relatively high b-vatue of 1.145. Considering only aeration needs, method 9 produces optimal results.

However, two other factors have to be considered hydraulic conditions and safety around the dam. The dam operators do not like to funnel all the flow required at a given time through one gate. This causes scouring around the gate sills and creates dangerous suction velocities above the dam and violent turbulence below it. To minimize these occurrences, the operators prefer to route the flow through several gates. Consequently, a compromise is needed to achieve good aeration without unduly sacrificing hydraulic and safety considerations. For very low flows this could be difficult. As an example, for the 99.8 percent flow, method 5, employing one gate at 2.0 feet and one at 0.5, still probably produces nearly the same hydraulic and safety shortcomings as method 9 with the added drawback of reducing the aeration coefficient by one-third. In this case, the best compromise appears to be method 4, which specifies two gates open one-half foot and one gate open 1.5 foot.

For the higher flows, multiple gates have to be opened to relatively great heights to accommodate the discharge. To accommodate an 8 percent flow duration, four gates can be opened at 4.0 feet and one at 1.0 feet, thereby producing a maximum dam aeration coefficient of 1.730 (Appendix G - method 9). Five open gates would probably be sufficient to minimize hydraulic and safety hazards. Using more gates, such as the 9 specified in method 5 for the 8 percent flow duration, does not appear necessary.

The increase in aeration as predicted by equation 2 is not directly proportional to the increase in "b", i.e., a 100 percent increase in b, such as changing a gate setting from 1.0 to 2.0 feet at Starved Rock, will not produce a commensurate percentage change in the downstream dissolved oxygen. A decreasing rate of increase is achieved, as shown by plots for four different temperature conditions shown on figure 22 ("h" and "a" are assumed to be constant). A gate set at 4.0 feet produces an aeration rate 202 percent greater than a 1.0 foot setting at 0 C. This percentage drops to just 153 at 30 C. Consequently, depending upon temperature, a 4.0-foot setting is about 150 to 200 percent more efficient than a 1.0-foot setting at Starved Rock. It is not 400 percent more efficient.

This study has produced results and evidence that indicate that the British weir equation (equation 2 of this report) is not a particularly good dam aeration model. The laboratory weir box calibration results showed that flow is an important, if not the most important, variable which has to be considered when evaluating the aeration characteristics of overflow weirs and spillways. The model (equation 2) fails to incorporate flow into its formulation. Also, equation 2 is built on the premise that the aeration or weir coefficient remains constant over a wide range of physical conditions.

This study, and the one conducted earlier by Butts and Evans (1978) have produced evidence in the laboratory showing that the theoretical b-value for a sharp-crested overflow weir can be verified only under limited conditions. Only 12.5 percent of the data (table 14) could be used to show that the aeration coefficient for a sharp-crested weir could under some circumstances equal unity if the water quality factor is assumed to be 1.8.

The information and data produced from the field portion of this study also direct attention to the fact that equation 2 is somewhat inadequate as a universal model even when used within the constraints of its development. The information gleaned from the stepwise regression analysis was particularly revealing. The fact that the water quality factor (a) ranked last among the 13 independent variables considered (table 25) casts serious doubt on the need to include "a" in equation 2 in its present form. Obviously water quality is an important factor and must be considered, as evidenced by the fact that MBAS, suspended solids,

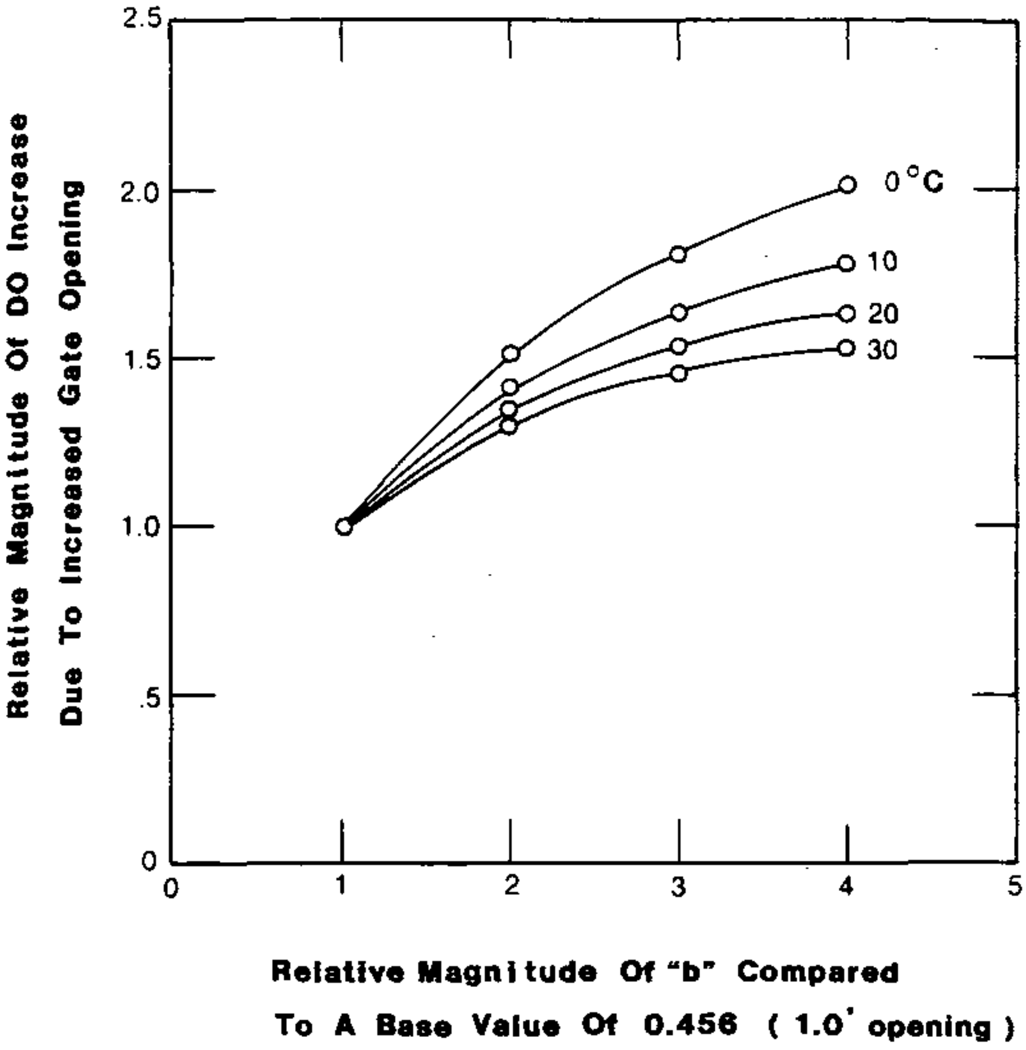

Figure 22. Relationship between relative gate opening and aeration efficiency for four temperatures

and algal counts ranked 2, 3, and 4, respectively, in the regression analysis. However, for Illinois River water, an all-inclusive factor, such as "a", appears inappropriate and unwarranted.

Other noteworthy information was derived from the stepwise regression analysis. Some facts surfaced that verified rational concepts, while others, such as the low ranking of the water quality factor a, did not. The fact that the gate opening height appears to be the number one factor influencing aeration was a welcome revelation since it is a controllable variable. Also, it justifies the development of the management methods outlined in Appendix G.

The fact that the next three most influential parameters were related to water quality was not so welcome in that these factors are basically uncontrollable. Rationally, however, these variables should rank high; the fact that they were included in the analyses indicates that during the planning and designing of the study they were suspected of being influential.

The second-place ranking of MBAS is appropriate since MBAS stands for methylene blue active substances and measures the concentration of surfactants or detergents. Detergents act as surface active agents (surfactants) to break up surface tension, and this renders water more susceptible to air entrainment and/or reaeration. What is surprising is that Illinois River water still contains sufficient levels of detergent to do this in view of the fact that all manufactured detergents are now biologically degradable and are reduced to low levels in most wastewater treatment plants. Evidently, these low detergent levels plus natural surfactants are sufficient to enhance reaeration at flow release gates and weirs. Some low-level foaming was observed below the dam during several runs. On one occasion it was so widespread that several observers queried SWS sampling personnel about the possibility of a return to the recent past when mountainous frothing occurred along the river.

Three dam-related parameters -- gate submergence, total flow, and the number of gates open -- placed 5, 6, and 7, respectively. Ranking 8 and 9 were the physical measurements Secchi disk readings and temperature, while the chemical parameter, chemical oxygen demand (COO), placed tenth and appeared to be the least significant parameter. These ten factors appeared to explain 95.28 percent of the Tainter gate aeration variability. Head loss, above-dam DO, and the water quality factor (a) explained only an additional 0.60 percent of the variability (table 25).

The fact that head loss was not significant probably results from the fact that it generally fluctuated within a narrow range during the study. The head loss ranged between 14.63 and 17.98 feet, but 15 of the 19 values fell between just 15.8 and 17.4 feet (Appendix E). During intermediate to low flow conditions pool elevation differential appears to be unimportant. However, the downstream (Peoria) pool elevation appears to be important in itself, since the Tainter gate opening begins to flood when the water level raises above 442.0, and this appears to influence the aeration rate somewhat.

The preceding discussion and revelations help explain why significant variability occurs in the r-values and b-values within the gate opening groupings presented in tables 23a and 23b. The gate opening height alone accounts for only 43.32 percent of the explained variability in the deficit ratio (table 25) whereas the rather intangible water quality related factors -- MBAS, suspended solids, and algae density -- account for 27.36 percent of the variability.

As an alternative to using equation 2 for modeling DO pickup across a dam, a statistical, "black box" reaeration formulation was developed for Starved Rock. Statistical, stepwise regression curve fitting was used to equate the deficit ratio to the dam-related physical parameters: gate opening height, number of gates open, head loss across the gates, gate opening submergence, and total flow. The results are summarized in table 26. Only the gate opening height, gate submergence, and total flow are significant and are included in the predictive equation given below:

$$r = 1.17W + 1.16\ (P-442) - 0.0003Q + 2.7 \qquad (4)$$

where W = the gate opening height in feet, P = the lower (Peoria) pool elevation in feet above MSL, and Q = the total flow in cfs.

The actual predictive reliability of equation 4 is probably no better than that of equation 2. The three included parameters account for only about 56 percent of the observed variability in "r"; approximately 40 percent of the observed variability is attributable to measured water quality factors (table 25). Equation 2 includes the water quality factor "a", but "a" was shown to be an irrelevant inclusion in the equation.

The results of the field-run DO saturation tests and their influence on the aeration-deaeration data evaluations and results need to be discussed briefly. DO saturation concentrations were determined with the thought in mind that some Class I, II, III, and IV data rejections could be avoided by doing this. Many such rejections occurred in past studies by Butts and Evans (1978, 1980). These rejections were suspected to stem, at least in part, from the "clean water" textbook saturation values. The results summarized in tables 18 and 19 support this contention. The information presented in table 20 shows that class rejections were significantly reduced but not entirely eliminated by using field run saturation values.

Since some class rejection situations still appeared in the results of this study, the suspicion was raised that, under

Table 26. Summary of Results of Stepwise Regression Analysis Equating Five Dam-related Parameters to the Deficit Ratio

Step No.	Parameter Addition	Standard error of estimate	Multiple correlation coefficient. R	Explained variation. R^2
1	Gate Opening (ft/gate)	1.383	0.6582	0.4332
2	Gate Submergence (ft)	1.388	0.6800	0.4624
3	Total Flow (cfs)	1.308	0.7434	0.5526
4	No. Gates Open	1.3415	0.7488	0.5607
5	Head Loss (ft)	1.3911	0.7493	0.5615

certain circumstances, DO concentrations can actually be physically pushed across the saturation threshold. This contradicts theory; however, past and present experience, and private communication with other researchers, indicate that this really happens. In other words, some subsaturated DO waters can be physically disturbed to such a degree that slight supersaturation results. Similarly, some supersaturated DO waters appear to be capable of being deaerated to a point below saturation.

These facts demonstrate the need for determining saturation concentrations when conducting scientific reaeration/deaeration field studies. For general modeling and engineering investigations, the use of textbook saturation values cannot be avoided and will have to remain acceptable. Textbook values will generally produce conservative results when DO concentrations approach saturation levels since DO models are usually programmed according to theory, and theoretically, physical aeration cannot produce supersaturated DO concentrations. Only photosynthetic oxygen production can produce supersaturated conditions.

The Corps of Engineers has shown that hydropower can be economically developed at Starved Rock (Appendix A). The subject of whether such a development will adversely affect downstream water quality, particularly dissolved oxygen levels, has not been addressed. A modeling study is now being conducted by the Water Quality Section of the State Water Survey to fully investigate what implications hydropower development at Starved Rock will have on downstream DO resources. The results of the Starved Rock dam aeration study have made the model study possible.

The aeration study has established the fact that proper gate manipulation can enhance downstream DO resources. This is important because very little aeration is achieved in the water routed through a hydropower plant; therefore, that which is not should be subjected to the greatest aeration possible. The significance of using the maximum gate opening to produce aeration is shown in table 27 for the maximum expected river temperature of 28 C. The results indicate that even in the absence of hydropower development, minimum downstream DOs will fall below the IEPA minimum standard of 5.0 mg/l. However, by using the maximum gate opening, significant increases in downstream DO can be achieved, especially during extremely low flows.

At flow durations greater than 75 percent (low flows), below-darn DO can be increased up to 1.32 mg/l by using 3-foot settings in place of 1-foot ones. Minimum levels are increased commensurately by about 0.77 mg/l. The effect is not so pronounced for higher flows (lower duration percent*). For example, at 10 percent duration the below-darn and minimum pool differentials are, respectively, only 0.06 mg/l and 0.03 mg/l. The principal reason the higher flow increases are minimal is

Table 27. Predicted Below-Dam and Minimum Peoria Pool DOs For Various Gate Opening Heights: T = 28 C, h = 5m, a = 1.25

Flow duration	Observed above-dam	Predicted below-dam DO (mg/l) for gate openings of				Predicted minimum pool DO (mg/l) for gate openings of			
%	DO(mg/l	1'	2'	3'	4'	1'	2'	3'	4'
99.8	3.28	5.62	6.34	-	-	3.48	3.92	-	-
99	3.49	5.72	6.41	-	-	3.56	3.98	-	-
98	2.49	5.24	6.10	6.52	-	3.17	3.68	3.93	-
97	2.58	5.29	6.13	6.54	-	3.09	3.58	3.82	-
96	2.26	5.14	6.03	6.46	-	2.99	3.51	3.76	-
95	2.90	5.44	6.23	6.61	-	3.07	3.51	3.73	-
90	3.36	5.66	6.37	6.72	-	3.03	3.41	3.59	-
85	4.00	5.96	6.57	6.86	-	3.47	3.83	4.00	-
80	4.21	6.06	6.53	6.91	7.08	3.25	3.51	3.71	3.80
75	4.49	6.19	6.72	6.98	7.13	3.36	3.64	3.78	3.86
70	4.79	6.33	6.71	7.04	7.18	3.53	3.74	3.92	4.00
65	4.88	6.38	6.74	7.07	7.20	3.62	3.82	4.01	4.08
60	4.64	6.27	6.67	7.01	7.16	3.61	3.84	4.04	4.12
55	5.42	6.63	6.91	7.19	7.30	3.81	3.97	4.13	4.19
50	5.47	6.66	6.92	7.20	7.31	3.86	4.01	4.17	4.23
45	5.64	6.74	6.98	7.24	7.34	4.05	4.19	4.35	4.41
40	5.20	6.53	6.84	7.14	7.26	3.87	4.11	4.29	4.36
35	6.43	7.11	7.22	7.42	7.84	4.55	4.62	4.75	4.79
30	6.11	6.96	7.12	7.35	7.43	4.33	4.43	4.57	4.62
25	6.49	7.14	7.24	7.44	7.49	4.46	4.53	4.65	4.69
20	7.02	7.39	7.41	7.56	7.59	4.59	4.60	4.70	4.72
17	6.92	7.34	7.37	7.53	7.57	4.32	4.34	4.43.	4.45
15	7.24	7.49	7.47	7.61	7.63	4.34	4.34	4.42	4.44
14	7.09	7.42	7.43	7.58	7.61	4.20	4.20	4.28	4.30
13	7.17	7.48	7.45	7.59	7.62	4.27	4.25	4.33	4.35
12	7.21	7.48	7.46	7.60	7.63	4.23	4.22	4.30	4.31
11	7.25	7.50	7.48	7.61	7.63	4.23	4.22	4.30	4.31
10	7.51	7.62	7.56	7.67	7.68	4.25	4.21	4.28	4.28
9	7.10	7.43	7.58	7.61	4.27	4.27	4.36	4.36	4.37
8	7.34	7.54	7.60	7.63	7.65	4.24	4.27	4.29	4.30

that the above-dam DOs are near saturation and this leaves little room for improvement.

The DO predictions in table 27 are based strictly on physical reaeration at the dams and within the pools. In reality, photosynthetic oxygen production, due to primary productivity, plays an important part in balancing oxygen production and usage in the river. The values presented in table 27 are for "worst case" situations. In situations where supersaturated DO concentrations occur above the Starved Rock dam, a wise management procedure would be to route the flow through minimum gate openings, or, in the case of hydropower development, to route as much of it as possible through the power plant. This would prevent "blowing out" the excess DO (deaeration) and would make it available for downstream biological use.

Table 28 illustrates the advisability of limiting deaeration by gate manipulation. Note that supersaturated dissolved oxygen levels are needed to some degree at almost all flow conditions during very warm water conditions to maintain a minimum downstream DO of 5.0 mg/l. The magnitude required can be drastically reduced, however, by passing the flow through a hydropower plant (0' gate column in table 28) and/or through 1-foot gate openings. The range of saturation percentages required for the 0-, 1-, 2-, 3-, and 4-foot openings are, respectively, 101-121, 103-145, 104-168, 106-192, and 107-212.

Supersaturation appears to be a common phenomenon in the pool above the Starved Rock dam during the summer as evidenced by the data summary in table 17. Sampling runs were made on 16 dates on which the river water temperature was 20 C or greater. On 11 of these dates, the upstream DO concentration was 8.25 mg/l or greater. This value would guarantee a minimum Peoria pool DO of 5.0 mg/l minus or plus a few tenths of a mg/l for most flow conditions. Of major significance is the fact that during the July 16-17, 1985, run the water temperature was 28 C and the upstream depth integrated average DO concentration was 11.93 mg/l (table 17). This value is sufficiently high to maintain well over a 5.0 mg/l minimum downstream DO if all the water were to be released through 1-foot gate openings.

A plan will be developed to continuously monitor temperature and dissolved oxygen conditions above the dam. A battery operated, submersible DO-temperature monitor and recorder has been purchased and will be installed above the dam on a trial basis, at a position not yet selected. The point will be statistically selected to represent the average DO concentration in the area immediately upstream of the Tainter gate section of the dam (figure 3). The DO-temperature monitor can be programmed to record values at any desired time interval. One-hour recording intervals probably will be used. The unit will be retrieved once a week and returned to the Peoria laboratory where

Table 28. Above-Dam DOs Needed to Insure the Minimum Downstream Standard of 5.0 mg/l Is Met at 28 C.

Flow duration	Above-dam DO needed to produce a minimum Pool DO=5 mg/l for gate settings of					Below-darn DO needed to produce a
(%)	0'	1'	2'	3'	4'	minimum pool DO = 5 mo/I
99.8	8.08	8.48	8.88	-	-	8.08
99	8.05	8.42	8.79	-	-	8.05
98	8.28	8.90	9.53	10.15	-	8.28
97	8.55	9.37	10.40	11.33	-	8.55
96	8.60	9.58	10.56	11.54	-	8.60
95	8.87	10.00	11.43	12.72	-	8.87
90	9.35	11.17	12.98	14.80	-	9.35
85	8.58	9.54	10.50	11.46	-	8.58
80	9.31	11.08	12.86	14.63	16.40	9.31
75	9.22	10.89	12.57	14.24	15.91	9.22
70	8.98	10.39	11.79	13.19	14.60	8.98
65	8.82	10.05	11.27	12.50	13.73	8.82
60	8.68	9.75	10.82	11.89	12.96	8.68
55	8.70	9.79	10.89	11.98	13.07	8.70
50	8.63	9.64	10.66	11.67	12.69	8.63
45	8.32	8.99	9.66	10.33	11.00	8.32
40	8.44	9.24	10.05	10.85	11.65	8.44
35	7.82	7.93	8.04	8.15	8.27	7.82
30	8.04	8.40	8.75	9.11	9.47	8.04
25	7.99	8.29	8.59	8.89	9.19	7.99
20	8.05	8.42	8.79	9.15	9.52	8.05
17	8.50	9.37	10.24	11.11	11.98	8.50
15	8.60	9.58	10.56	11.54	12.52	8.60
14	8.84	10.09	11.34	12.59	13.84	8.84
13	8.76	9.92	11.08	12.34	13.40	8.76
12	8.84	10.09	11.34	12.59	13.84	8.84
11	8.86	10.13	11.40	12.67	13.94	8.86
10	8.97	10.36	11.76	13.15	14.55	8.97
9	8.70	9.79	11.11	11.98	13.07	8.70
8	8.90	10.22	11.53	12.85	14.16	8.90

Note: DO saturation at 28°C = 7.72 mg/l

it will be interfaced with a computer to catalog and analyze the data.

The data generated during the monitoring will provide insight into whether gate manipulation by the Corps of Engineers, designed to improve downstream water quality, is practical over the long run. Discussions with Rock Island District Corps of Engineers officials indicate that they would be amenable to using gate settings to improve downstream DO levels as long as these settings would be compatible with navigation interests and would not create potential structural problems at the dam site. For instance, this study has shown that a 4-foot gate opening produces significantly greater dissolved oxygen transfer than does a 1-foot opening. However, the Corps of Engineers would be unwilling to use a single gate setting of 4 feet. For example, only 4 feet or less of total gate opening is needed during low flows; but Corps of Engineer officials would not allow just a single gate to be opened at 3 or 4 feet. This would concentrate the flow in one area and promote channel scour and possible undermining of the dam structure. The preferred setting, for a total opening requirement of 4 feet, would be 4 gates open 1 foot; however, two gates set at 2 feet would be acceptable. One gate set at 1 foot and one set at 3 feet would not be acceptable. Continuous monitoring would be a necessity because upstream supersatured conditions would dictate using minimum gate openings to minimize deaeration or "blowing out" of excess DO. Consequently, in the case of the occurrence of supersaturation during a period when 4 total feet of gate opening is needed, downstream water quality interests would be better served by using 4 1-foot gate openings.

CONCLUSIONS

The general conclusions reached as a result of this study are:

1. Increased aeration can be achieved at the Starved Rock dam by gate manipulation and management. The dam aeration coefficient increased linearly with gate opening height; a 4-foot opening produced an aeration coefficient four times as great as that for a 1-foot opening.

2. Routine Illinois River water Quality dictates, to a great extent, the reaeration capacity of the Starved Rock flow release gate structures. Thirteen physical, chemical, and biological parameters were measured and equated to the deficit ratio, a measure of reaeration. Statistically, these 13 parameters accounted for 96 percent of the explained variations. Physical parameters accounted for 56 percent, whereas water quality related parameters accounted for 40 percent of the explained variation.

3. The British weir equation, a general model used to describe the aeration capacity of a weir, dam, or spillway, was found to be inadequate in several respects. Laboratory weir box experiments showed that flow rate is the single most important parameter governing reaeration rates for a simple, sharp-crested weir. The British weir equation does not take flow rate into account. Also, as noted in conclusion 2, water quality dictates the aeration rate to a large degree. The British weir equation has a water quality indexing factor incorporated into it, but this was found to be inadequate for describing the water quality effects of llinois River water on dam aeration.

4. A statistical regression equation was developed to relate five physical dam or river parameters to the deficit ratio, but the resultant model proved to be no better a predictive "tool" than the British weir equation. This was because water quality is so significant and a strictly physical model alone cannot adequately describe reaeration.

5. Hydropower can be developed at Starved Rock without detrimental effects on water quality if certain controls are exercised. A good management plan has to be developed and adhered to in order to prevent violations of downstream DO standards. During periods of sustained supersaturated above-dam DOs, hydropower development could enhance downstream DO.

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Appendix A

October 17, 1985 Corps of Engineers Public Information Fact Sheet On The Economic Feasibility Of Developing Hydropower At Starved Rock Dam

US Army Corps
of Engineers
Rock Island District

Public Information Fact Sheet

Planning Division October 17, 1985

PROJECT: Final Feasibility Report
for Hydropower at
Starved Rock Lock and Dam
Illinois Waterway

In June 1983, a Final Feasibility Report evaluating Federal development of hydropower at the Starved Rock Lock and Dam on the Illinois Waterway was completed by the Rock Island District of the U.S. Army Corps of Engineers.

On the basis of the Administration's present policy, the Acting Assistant Secretary of the Army (Civil Works) recently returned the report without action. The Administration's current policy is to encourage non-Federal hydropower development and to only pursue Federal development where it is economically feasible and where such non-Federal activity is impractical. It was concluded that non-Federal implementation appears practical at this site.

AUTHORITY

Starved Rock Lock and Dam is one of the navigation project sites that the National Hydropower Study, completed in 1982, identified as having economically feasible generating potential. This feasibility study was initiated to more fully evaluate the hydropower potential. The study was conducted under authority of Section 216 of the River and Harbor Flood Control Act of 1970, P.L. 91-611, dated December 31, 1970.

BACKGROUND

The study resulted in a Feasibility Report evaluating the engineering, environmental, and economic feasibility of adding hydroelectric generating capabilities to the Starved Rock Lock and Dam. The final report presents the results of this study.

ALTERNATIVES CONSIDERED

Starved Rock Lock and Dam is located at river mile 231, approximately 8 miles west of Ottawa, Illinois, on the Illinois River, and is part of an eight-lock navigation waterway connecting Lake Michigan to the Mississippi River. Constructed in the 1930's, the dam and spillway structure was provided with a headgate section so that a future powerplant could be built immediately downstream of the dam. The recommended plan location and layout is shown on Plate 2 (enclosed). The powerhouse would tie into the existing headgate section constructed with the lock and dam. The powerhouse would use gate sections 21 through 30. The switchyard would be located on the right bank adjacent to the powerhouse as shown on Plate 2. The plant would be tied into an existing substation located about 3 miles from the project site.

Hydropower development at the site would consist of adding a 15.0-megawatt powerplant to the existing project. Within a 50-mile radius of the study site, there are portions of five investor-owned utility service areas. The service areas within this radius include Illinois Power Company, Commonwealth Edison Company, Central Illinois Light Company, Central Illinois Public Service Company, and Cedar Point Light and Water Company.

The existing headgate structures limited the location and ultimate size of the turbines. To construct anywhere but at the existing headgates would have decreased the net benefits because of a large increase in costs. The dependable flow of the river limited the ultimate installed capacity of the proposed project.

Only run-of-the-river alternatives were investigated at Starved Rock. Starved Rock Lock and Dam was not designed for higher pool operating levels. Raising the pool level allows water to run around the gates and into the lock gate machinery, causing the replacement or modification of lock gate operating equipment. Also, there now exists limited flowage and flooding easements upstream of Starved Rock Dam. Fluctuating the pool upward for electrical generation would require purchasing additional easements.

Three different turbine/generator configurations were considered as a means of obtaining the power required. The three turbines were selected because it was found to be less expensive to use the existing headgate sections than to construct additional civil works, because the study limited itself to predesigned turbine units, and because of the particular characteristics of the study site.

PROJECT FEASIBILITY

Based on present power values provided by the Federal Energy Regulatory Commission (FERC), conventional hydropower development at the Starved Rock Lock and Dam appears to be economically feasible. A total of 24 different installations were evaluated. The plan that produces the greatest economic net benefits is a powerplant with a 15.0 MW installed capacity installation. The plant would use five 3.0-meter tubular turbines in a powerhouse that is 173 feet long and 120 feet wide, and have an average annual energy production of 58,187,000 kWh. It would produce net annual economic benefits of $1,979,580 and have a benefit-to-cost ratio of 1.78 to 1.0, based on a 50-year economic life. A 15.0-megawatt conventional powerplant would cost about $26,090,000.

RECOMMENDATIONS

The Administration's policy is to encourage non-Federal hydropower development and to only pursue Federal development where it is economically feasible and where such non-Federal activity is impractical. Although economically feasible, non-Federal implementation appears practical. Federal development at this site is, therefore, not recommended at this time. The Federal Energy Regulatory Commission remains responsible for review and approval of non-Federal proposals. The Corps of Engineers will still be involved with review of any non-Federal hydropower proposals at the Lock and Dam, both from a permit or general regulatory standpoint and from the standpoint of determining whether a non-Federal proposal is compatible with the existing navigation project and related project purposes.

ADDITIONAL INFORMATION

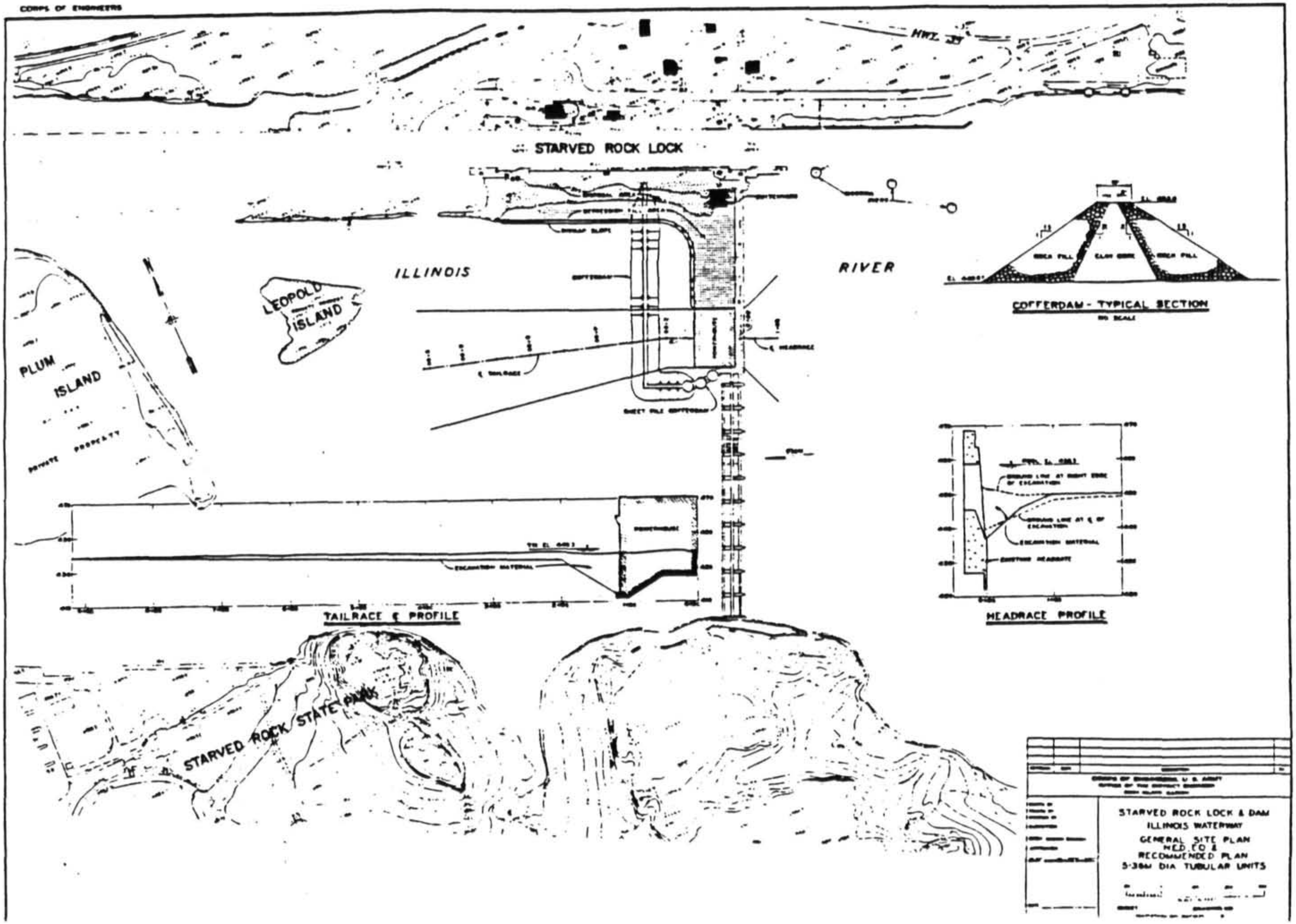
Non-Federal hydropower developed and other interested parties can request additional information regarding the Final Feasibility Report by contacting the District Engineer at the following address:

District Engineer
U.S. Army Engineer District, Rock Island
ATTN: NCRPD-P
Clock Tower Building - P.O. Box 2004
Rock Island, Illinois 61204-2004

Thank you for your continued interest in our activities.

William C. Burns
Colonel, Corps of Engineers
District Engineer

Enclosure


CORPS OF ENGINEERS
U. S. ARMY
HWY. 71
STARVED ROCK LOCK
ILLINOIS
RIVER
LEOPOLD ISLAND
PLUM ISLAND
PRIVATE PROPERTY
N
COFFERDAM
SHEET PILE COFFERDAM
℄ TAILRACE
℄ HEADRACE
POWERHOUSE
ROCK FILL
CLAY CORE
ROCK FILL
COFFERDAM - TYPICAL SECTION
NO SCALE
EXCAVATION MATERIAL
TAILRACE ℄ PROFILE
GROUND LINE AT RIGHT EDGE OF EXCAVATION
GROUND LINE AT ℄ OF EXCAVATION
EXCAVATION MATERIAL
EXISTING HEADGATE
HEADRACE PROFILE
STARVED ROCK STATE PARK
STARVED ROCK LOCK & DAM
ILLINOIS WATERWAY
GENERAL SITE PLAN
NED.CO &
RECOMMENDED PLAN
5-3.0M DIA TUBULAR UNITS

Appendix B

Unreduced Laboratory Weir Box Data Generated During Calibration Runs

Above = above weir
Below = below weir

Laboratory Weir Box Data, Unreduced

			Temperature, T, (C)				DO (mg/l)					
h	h'	Flow	Above T		Below T		Above DO		Below DO			
m	m	1/sec	1	2	1	2	1	2	1	2	r	ab
1.410	0.48	0.18	10.8	10.7	11.0	11.0	1.60	1.60	7.30	7.30	2.5571	2.29
1.429	0.48	0.46	10.8	10.7	11.0	11.1	1.68	1.69	7.26	7.26	2.5159	2.21
1.448	0.48	0.97	10.7	10.6	10.8	10.9	1.84	1.84	7.06	7.03	2.3153	1.90
1.467	0.48	1.77	10.8	10.8	10.9	10.9	1.95	1.95	6.68	6.66	2.0888	1.55
1.410	0.48	0.18	11.5	11.5	11.7	11.8	3.18	3.18	7.67	7.66	2.4469	2.08
1.429	0.48	0.46	11.4	11.4	11.6	11.7	3.11	3.10	7.52	7.49	2.3408	1.91
1.448	0.48	0.97	11.5	11.5	11.6	11.7	3.40	3.37	7.25	7.22	2.0803	1.52
1.467	0.48	1.77	13.1	13.0	13.1	13.1	3.40	3.41	7.28	7.30	2.2237	1.63
1.410	0.48	0.18	16.4	16.4	16.4	16.5	5.76	5.78	8.66	8.67	3.7539	3.47
1.429	0.48	0.46	16.3	16.3	16.4	16.4	5.55	5.58	8.53	8.54	3.5018	3.12
1.448	0.48	0.97	16.2	16.2	16.3	16.3	5.71	5.75	8.36	8.38	2.9260	2.38
1.467	0.48	1.77	16.2	16.3	16.3	16.4	5.90	5.92	8.35	8.35	2.7692	2.16
1.410	0.48	0.18	13.0	13.0	13.2	13.2	7.85	7.79	9.20	9.21	2.1506	1.59
1.429	0.48	0.46	13.0	12.9	13.1	13.2	7.54	7.49	9.07	9.10	2.1747	1.60
1.448	0.48	0.97	12.9	12.9	13.0	13.1	7.50	7.45	8.98	9.01	2.0433	1.41
1.467	0.48	1.77	16.7	16.8	16.8	16.9	7.93	7.89	9.17	9.18	3.7858	3.36
1.467	0.32	0.18	16.3	16.4	16.3	16.3	1.78	1.79	6.62	6.63	2.5446	1.89
1.486	0.32	0.46	16.5	16.4	16.5	16.5	1.62	1.63	6.73	6.77	2.7532	2.09
1.505	0.32	0.97	16.4	16.4	16.5	16.5	1.73	1.76	6.67	6.60	2.5973	1.91
1.524	0.32	1.77	15.4	15.4	15.4	15.5	1.78	1.78	6.30	6.32	2.2528	1.52
1.410	0.32	0.18	16.4	16.5	16.5	16.5	3.23	3.24	7.15	7.15	2.5337	1.93
1.429	0.32	0.46	12.6	12.6	12.6	12.6	3.14	3.13	7.43	7.40	2.3454	1.86
1.448	0.32	0.97	15.7	15.7	15.7	15.8	3.38	3.44	7.46	7.43	2.6688	2.09
1.524	0.32	1.77	15.0	15.1	15.1	15.2	3.02	3.00	6.93	6.97	2.2987	1.59
1.410	0.32	0.18	15.9	16.0	16.0	16.1	5.59	5.60	8.66	8.65	3.6797	3.41
1.429	0.32	0.46	15.8	15.8	15.9	15.9	5.%	5.64	8.80	8.78	3.7329	3.45
1.448	0.32	0.97	12.5	12.5	12.6	12.5	5.49	5.51	8.34	8.34	2.2573	1.72
1.467	0.32	1.77	12.2	12.1	12.1	12.2	5.52	5.53	8.39	8.40	2.2408	1.70
1.410	0.32	0.18	13.0	12.9	13.3	13.3	7.91	7.85	9.21	9.23	2.1803	1.63
1.429	0.32	0.46	16.3	16.4	16.4	16.5	7.63	7.73	9.30	9.32	5.0264	5.02
1.467	0.32	1.77	16.2	16.3	16.3	16.3	7.75	7.79	9.16	9.18	3.4249	2.97
1.467	0.16	0.18	14.9	15.0	15.1	15.5	1.71	1.71	6.77	6.81	2.5871	2.01
1.486	0.16	0.46	15.2	15.2	15.3	15.3	1.76	1.77	6.94	6.94	2.7165	2.14

Laboratory Weir Box Data, Unreduced

			Temperature, T, (C)				DO (mg/l)					
h	h'	Flow	Above T		Below T		Above DO		Below DO			
m	m	1/sec	1	2	1	2	1	2	1	2	r	ab
1.505	0.16	0.97	14.7	14.8	14.8	14.8	1.78	1.78	6.86	6.80	2.5578	1.94
1.524	0.16	1.77	14.8	14.8	14.8	14.9	1.65	1.66	6.64	6.63	2.4540	1.79
1.467	0.16	0.18	14.7	14.8	14.8	14.8	3.11	3.10	7.71	7.74	2.9674	2.51
1.486	0.16	0.46	14.7	14.8	14.7	14.8	3.12	3.08	7.68	7.68	2.9002	2.40
1.505	0.16	0.97	15.9	15.9	16.0	16.0	3.13	3.11	7.42	7.44	2.8157	2.19
1.524	0.16	1.77	14.3	14.4	14.4	14.5	3.20	3.14	7.06	7.07	2.2666	1.58
1.410	0.16	0.18	15.9	15.9	16.1	16.1	5.59	5.58	8.63	8.63	3.6523	3.38
1.429	0.16	0.46	15.6	15.7	15.8	15.8	5.81	5.83	8.75	8.75	3.6722	3.39
1.448	0.16	0.97	15.5	15.6	15.6	15.7	5.85	5.90	8.61	8.58	3.1154	2.66
1.467	0.16	1.77	16.2	16.3	16.2	16.3	5.82	5.83	8.31	8.30	2.7018	2.08
1.410	0.16	0.18	13.7	13.7	13.7	13.8	7.55	7.55	9.26	9.26	2.6241	2.20
1.429	0.16	0.46	12.6	12.5	12.6	12.6	7.86	7.86	9.50	9.50	2.5072	2.09
1.448	0.16	0.97	12.7	12.6	12.6	12.7	7.55	7.54	9.18	9.20	2.1800	1.61
1.467	0.16	1.77	12.9	13.0	13.0	12.9	7.63	7.63	9.14	9.15	2.1092	1.49
1.467	0.00	0.18	14.4	14.4	14.5	14.5	1.68	1.69	5.93	5.93	2.0121	1.30
1.486	0.00	0.46	14.4	14.4	14.5	14.5	1.66	1.68	6.06	6.06	2.0798	1.37
1.505	0.00	0.97	15.6	15.6	15.6	15.7	1.69	1.70	6.24	6.24	2.2478	1.52
1.524	0.00	1.77	14.6	14.6	14.6	14.7	1.68	1.69	6.17	6.16	2.1377	1.41
1.410	0.00	0.18	15.8	15.9	16.2	16.3	3.18	3.14	6.51	6.50	2.0532	1.34
1.429	0.00	0.46	15.7	15.8	16.0	16.1	3.18	3.16	6.57	6.59	2.0774	1.36
1.448	0.00	0.97	15.7	15.7	15.8	15.9	3.24	3.25	6.81	6.78	2.1735	1.47
1.467	0.00	1.77	15.9	16.0	15.9	16.0	3.30	3.31	7.14	7.14	2.4276	1.76
1.410	0.00	0.18	12.3	12.2	12.6	12.7	5.56	5.56	7.65	7.65	1.7461	1.05
1.429	0.00	0.46	12.6	12.7	12.8	12.8	5.71	5.70	8.06	8.02	1.9459	1.30
1.448	0.00	0.97	13.6	13.6	13.7	13.7	5.81	5.82	8.06	8.03	1.9854	1.31
1.467	0.00	1.77	13.9	13.8	13.9	13.9	5.76	5.76	8.38	8.36	2.3690	1.79
1.410	0.00	0.18	15.6	15.7	15.9	15.9	7.71	7.68	8.96	8.96	2.5039	1.93
1.429	0.00	0.46	14.0	14.0	14.1	14.1	7.54	7.55	9.10	9.07	2.3551	1.80
1.448	0.00	0.97	13.9	14.0	14.0	14.1	7.74	7.69	9.15	9.11	2.2840	1.69
1.467	0.00	1.77	13.9	13.9	14.0	14.0	7.80	7.83	9.09	9.06	2.0813	1.41
1.162	0.48	0.18	14.5	14.5	14.6	14.6	1.75	1.77	6.79	6.81	2.5230	2.37
1.181	0.48	0.46	14.4	14.5	14.5	14.6	1.78	1.80	6.78	6.78	2.4939	2.29
1.130	0.48	0.97	12.8	12.9	12.8	12.9	1.57	1.58	6.60	6.60	2.2770	2.13
1.219	0.48	1.77	14.4	14.5	14.5	14.5	2.30	2.27	6.50	6.52	2.1649	1.74

Laboratory Weir Box Data, Unreduced

			Temperature, T, (C)				DO (mg/l)					
h	h'	Flow	Above T		Below T		Above DO		Below DO			
m	m	1/sec	1	2	1	2	1	2	1	2	r	ab
1.092	0.48	0.18	13.9	14.0	14.1	14.1	3.16	3.17	7.74	7.74	2.8450	3.07
1.111	0.48	0.46	13.9	14.0	14.1	14.1	3.31	3.33	7.78	7.71	2.7885	2.93
1.130	0.48	0.97	14.0	14.1	14.2	14.1	3.16	3.17	7.46	7.43	2.5468	2.49
1.149	0.48	1.77	13.9	14.0	13.9	13.8	3.33	3.32	7.13	7.08	2.1770	1.88
1.092	0.48	0.18	13.8	13.7	13.9	14.0	5.68	5.67	8.70	8.70	2.9523	3.27
1.111	0.48	0.46	13.8	13.7	13.9	14.0	5.58	5.61	8.79	8.78	3.1747	3.58
1.130	0.48	0.97	13.6	13.6	13.7	13.6	5.70	5.73	8.38	8.43	2.3937	2.28
1.149	0.48	1.77	13.7	13.8	13.8	13.7	5.77	5.77	8.17	8.15	2.1064	1.78
1.092	0.48	0.18	14.0	14.1	14.2	14.2	7.51	7.52	9.25	9.28	2.8776	3.12
1.111	0.48	0.46	13.9	14.0	14.1	14.1	7.97	7.97	9.39	9.39	2.7144	2.81
1.130	0.48	0.97	14.1	14.0	14.0	14.1	7.54	7.58	9.20	9.24	2.6411	2.65
1.149	0.48	1.77	13.9	14.0	14.0	14.1	7.75	7.76	9.20	9.20	2.3981	2.23
1.162	0.32	0.18	14.2	14.2	14.2	14.2	1.73	1.73	6.62	6.66	2.3732	2.16
1.181	0.32	0.46	14.1	14.2	14.2	14.2	1.78	1.78	6.87	6.85	2.5174	2.35
1.130	0.32	0.97	13.2	13.3	13.3	13.2	1.64	1.63	6.56	6.56	2.2698	2.10
1.219	0.32	1.77	14.2	14.3	14.3	14.3	2.06	2.04	6.06	6.01	1.9613	1.45
1.092	0.32	0.18	14.0	14.1	14.2	14.3	3.13	3.14	7.65	7.64	2.7805	2.95
1.111	0.32	0.46	14.1	14.1	14.2	14.2	3.18	3.19	7.53	7.53	2.6265	2.66
1.130	0.32	0.97	14.0	14.0	14.2	14.2	3.30	3.36	7.24	7.30	2.3402	2.16
1.146	0.32	1.77	14.0	13.9	13.9	13.9	3.38	3.42	7.13	7.12	2.1757	1.88
1.092	0.32	0.18	14.1	14.0	14.2	14.3	5.38	5.35	8.53	8.56	2.9447	3.23
1.111	0.32	0.46	14.0	14.1	14.1	14.2	5.68	5.68	8.57	8.55	2.7415	2.85
1.130	0.32	0.97	13.9	14.0	14.0	14.1	5.69	5.73	8.38	8.43	2.4732	2.38
1.149	0.32	1.77	14.0	14.0	14.0	14.1	5.88	5.88	8.23	8.21	2.1583	1.85
1.092	0.32	0.18	13.6	13.7	13.7	13.7	7.25	7.24	9.34	9.35	3.1399	3.60
1.111	0.32	0.46	13.4	13.4	13.4	13.4	7.58	7.59	9.49	9.47	3.0536	3.43
1.130	0.32	0.97	14.3	14.2	14.3	14.3	7.70	7.72	9.20	9.29	2.6322	2.62
1.149	0.32	1.77	14.2	14.1	14.2	14.2	7.67	7.67	9.14	9.17	2.4112	2.24
1.092	0.16	0.18	14.2	14.2	14.4	14.4	1.93	1.93	6.94	6.93	2.5615	2.58
1.111	0.16	0.46	14.3	14.2	14.4	14.4	1.87	1.86	6.76	6.76	2.4457	2.35
1.130	0.16	0.97	14.6	14.7	14.7	14.8	1.67	1.69	6.52	6.54	2.3686	2.17
1.219	0.16	1.77	13.9	13.9	14.0	14.1	2.02	2.01	6.00	6.04	1.9550	1.45
1.162	0.16	0.18	13.9	13.9	14.1	14.0	3.20	3.20	6.91	6.95	2.1339	1.79
1.181	0.16	0.46	13.9	13.9	14.0	14.1	3.19	3.19	6.86	6.87	2.0959	1.71

Laboratory Weir Box Data, Unreduced

			Temperature, T, (C)				DO (mg/l)					
h	h'	Flow	Above T		Below T		Above DO		Below DO			
m	m	1/sec	1	2	1	2	1	2	1	2	r	ab
1.130	0.16	0.97	14.4	14.5	14.4	14.4	3.28	3.30	7.09	7.08	2.2266	1.96
1.149	0.16	1.77	13.8	13.9	13.9	14.0	3.26	3.28	6.67	6.67	1.9500	1.52
1.092	0.16	0.18	15.0	15.0	15.1	15.2	5.78	5.79	8.31	8.34	2.5356	2.48
1.111	0.16	0.46	15.0	15.1	15.1	15.2	5.86	5.82	8.28	8.30	2.4450	2.30
1.130	0.16	0.97	15.0	15.1	15.1	15.2	5.88	5.85	8.17	8.23	2.3089	2.05
1.149	0.16	1.77	15.0	15.1	15.1	15.1	5.97	5.93	8.01	8.02	2.0397	1.61
1.092	0.16	0.18	13.5	13.6	13.9	13.9	7.76	7.76	9.34	9.33	2.7444	2.93
1.111	0.16	0.46	14.9	15.0	15.0	15.0	7.73	7.74	9.07	9.11	2.4469	2.31
1.130	0.16	0.97	14.8	14.9	14.9	14.9	7.72	7.74	8.97	9.01	2.1919	1.88
1.149	0.16	1.77	14.1	14.1	14.1	14.1	7.65	7.66	9.05	9.04	2.1646	1.85
1.149	0.00	0.18	14.7	14.8	15.0	14.9	2.18	2.19	5.71	5.75	1.8319	1.30
1.181	0.00	0.46	13.7	13.7	13.9	13.9	2.14	2.14	5.44	5.36	1.6769	1.06
1.130	0.00	0.97	14.7	14.7	14.8	14.8	1.74	1.76	5.67	5.62	1.8835	1.40
1.149	0.00	1.77	13.7	13.7	13.8	13.8	2.32	2.30	5.81	5.86	1.7932	1.27
1.092	0.00	0.18	14.9	15.0	15.0	15.1	3.13	3.16	6.08	6.05	1.7434	1.20
1.181	0.00	0.46	13.7	13.8	13.9	13.9	3.36	3.37	6.06	6.07	1.6481	1.01
1.130	0.00	0.97	14.7	14.7	14.8	14.9	3.31	3.33	6.45	6.47	1.8789	1.39
1.149	0.00	1.77	14.6	14.7	14.6	14.6	3.39	3.40	6.46	6.44	1.8284	1.30
1.092	0.00	0.18	14.9	14.8	15.0	15.1	5.85	5.82	7.63	7.68	1.7874	1.28
1.111	0.00	0.46	14.8	14.8	14.9	15.0	5.77	5.76	7.68	7.69	1.8277	1.33
1.130	0.00	0.97	14.8	14.8	14.9	14.9	5.71	5.71	7.82	7.81	1.9491	1.50
1.149	0.00	1.77	14.5	14.6	14.7	14.7	5.82	5.82	7.74	7.77	1.8391	1.31
1.092	0.00	0.18	13.8	13.8	13.9	13.9	7.62	7.61	8.24	8.29	1.3333	0.56
1.111	0.00	0.46	15.0	14.9	14.9	14.9	7.71	7.73	8.89	8.92	2.0194	1.63
1.130	0.00	0.97	14.1	14.2	14.1	14.1	7.65	7.65	9.10	9.10	2.2634	2.04
1.149	0.00	1.77	14.7	14.7	14.7	14.8	7.78	7.79	8.82	8.82	1.8237	1.29
0.806	0.48	0.18	13.9	14.0	14.0	14.0	1.86	1.90	6.34	6.34	2.1402	2.49
0.826	0.48	0.46	13.7	13.7	13.7	13.8	1.73	1.73	6.30	6.26	2.1291	2.43
0.845	0.48	0.97	14.3	14.3	14.5	14.5	1.58	1.58	5.66	5.65	1.9174	1.90
0.864	0.48	1.77	13.7	13.8	13.8	13.8	1.80	1.79	5.62	5.67	1.8281	1.71
0.749	0.48	0.18	14.8	14.8	14.9	15.0	3.42	3.41	6.60	6.62	1.9398	2.14
0.826	0.48	0.46	13.8	13.8	13.9	13.9	3.30	3.31	7.01	7.01	2.1384	2.44
0.787	0.48	0.97	14.9	14.9	15.0	15.0	3.30	3.30	6.53	6.53	1.9281	2.01
0.806	0.48	1.77	15.0	15.0	15.0	15.0	3.34	3.34	6.25	6.25	1.7765	1.64

Laboratory Weir Box Data, Unreduced

			Temperature, T, (c)				DO (mg/l)					
h	h'	Flow	Above T		Below T		Above DO		Below DO			
m	m	1/sec	1	2	1	2	1	2	1	2	r	ab
0.749	0.48	0.18	14.5	14.6	14.8	14.8	5.76	5.75	8.14	8.14	2.2592	2.88
0.768	0.48	0.46	14.9	15.0	15.1	15.1	5.70	5.71	7.84	7.85	2.0030	2.22
0.787	0.48	0.97	14.8	14.9	15.0	15.1	5.80	5.78	7.77	7.79	1.9071	1.97
0.806	0.48	1.77	14.7	14.7	14.7	14.6	5.73	5.69	7.73	7.75	1.8508	1.82
0.749	0.48	0.18	15.0	15.1	15.2	15.2	7.57	7.58	8.82	8.80	2.0750	2.43
0.768	0.48	0.46	14.9	14.9	14.9	14.9	7.77	7.78	8.98	8.98	2.1193	2.48
0.787	0.48	0.97	14.6	14.6	14.6	14.6	7.67	7.70	8.89	8.85	1.9714	2.12
0.806	0.48	1.77	15.0	14.9	15.0	14.9	7.84	7.79	8.87	8.89	1.9139	1.94
0.806	0.32	0.18	13.7	13.8	13.9	13.9	1.86	1.86	6.22	6.20	2.0761	2.36
0.826	0.32	0.46	13.9	14.0	14.0	14.1	1.63	1.63	6.22	6.21	2.1420	2.44
0.845	0.32	0.97	13.8	13.8	13.8	13.9	1.66	1.66	5.96	5.94	1.9897	2.08
0.864	0.32	1.77	13.4	13.4	13.5	13.5	1.70	1.72	5.64	5.66	1.8382	1.74
0.806	0.32	0.18	13.7	13.7	13.7	13.8	3.27	3.24	6.91	6.94	2.0844	2.38
0.826	0.32	0.46	13.7	13.7	13.7	13.7	3.19	3.20	6.93	6.94	2.1010	2.37
0.787	0.32	0.97	14.7	14.7	14.8	14.8	3.21	3.22	6.67	6.68	2.0231	2.23
0.864	0.32	1.77	13.6	13.6	13.6	13.7	3.19	3.18	6.41	6.40	1.8205	1.70
0.749	0.32	0.18	14.9	15.0	15.1	15.1	5.92	5.92	5.25	8.25	2.3414	3.04
0.768	0.32	0.46	14.8	14.8	15.0	15.0	5.84	5.84	8.08	8.09	2.1747	2.61
0.787	0.32	0.97	14.8	14.9	14.9	15.0	5.73	5.79	7.90	7.93	2.0221	2.22
0.806	0.32	1.77	14.8	14.8	14.9	14.9	5.82	5.84	7.81	7.83	1.8998	1.91
0.749	0.32	0.18	14.7	14.7	14.7	14.8	7.77	7.78	9.11	9.11	2.3734	3.13
0.768	0.32	0.46	14.6	14.6	14.6	14.6	7.57	7.58	9.10	9.10	2.4891	3.33
0.787	0.32	0.97	14.6	14.7	14.8	14.8	7.77	7.77	8.98	9.01	2.1613	2.53
0.806	0.32	1.77	14.6	14.6	14.7	14.7	7.91	7.90	9.05	9.07	2.1307	2.42
0.806	0.16	0.18	13.5	13.5	13.6	13.6	1.70	1.67	6.10	6.11	2.0455	2.31
0.826	0.16	0.46	13.3	13.3	13.3	13.3	1.61	1.64	5.72	5.73	1.8720	1.90
0.845	0.16	0.97	13.4	13.5	13.5	13.6	1.76	1.76	5.94	5.93	1.9473	2.01
0.864	0.16	1.77	13.1	13.2	13.2	13.2	1.66	1.67	5.26	5.26	1.6949	1.46
0.749	0.16	0.18	13.0	13.1	13.1	13.1	3.17	3.17	6.46	6.46	1.8225	1.97
0.768	0.16	0.46	14.2	14.3	14.2	14.3	3.38	3.36	6.62	6.63	1.9095	2.06
0.787	0.16	0.97	14.8	14.9	14.9	14.9	3.17	3.16	6.65	6.68	2.0353	2.25
0.864	0.16	1.77	12.9	13.0	13.0	13.0	3.16	3.14	6.01	6.02	1.6417	1.35
0.749	0.16	0.18	14.7	14.8	14.9	14.9	5.56	5.55	8.21	8.20	2.4494	3.30
0.768	0.16	0.46	14.6	14.7	14.7	14.8	5.79	5.79	8.13	8.12	2.19%	2.68

Laboratory Weir Box Data, Unreduced

			Temperature, T, (C)				DO (mg/l)					
h	h'	Flow	Above T		Below T		Above DO		Below DO			
m	m	l/sec	1	2	1	2	1	2	1	2	r	ab
0.787	0.16	0.97	14.5	14.6	14.7	14.7	5.67	5.67	8.02	8.02	2.1453	2.51
0.806	0.16	1.77	14.8	14.9	14.9	15.0	5.78	5.72	7.79	7.78	1.1902	1.93
0.749	0.16	0.18	15.1	15.2	15.4	15.4	7.80	7.83	8.91	8.91	2.1105	2.50
0.168	0.16	0.46	14.6	14.7	14.7	14.7	7.85	7.84	9.17	9.16	2.4216	3.18
0.787	0.16	0.97	14.4	14.5	14.6	14.6	7.76	7.73	9.12	9.11	2.3914	3.05
0.806	0.16	1.77	15.3	15.3	15.3	15.4	7.88	7.84	8.70	8.69	1.6705	1.41
0.806	0.00	0.18	13.0	13.1	13.2	13.2	1.78	1.79	4.25	4.25	1.4034	0.90
0.826	0.00	0.46	13.1	13.2	13.3	13.3	1.76	1.78	4.71	4.70	1.5192	1.13
0.845	0.00	0.97	13.1	13.1	13.1	13.2	1.71	1.72	4.76	4.79	1.5401	1.16
0.864	0.00	1.77	12.9	12.9	13.0	13.0	2.32	2.26	4.84	4.85	1.4562	0.%
0.806	0.00	0.18	13.0	13.1	13.1	13.1	3.20	3.21	5.15	5.15	1.3675	0.82
0.826	0.00	0.46	12.8	12.8	12.9	12.9	3.29	3.31	5.52	5.52	1.4486	0.99
0.787	0.00	0.97	14.8	14.8	14.9	15.0	3.39	3.40	5.83	5.82	1.5837	1.27
0.806	0.00	1.77	15.2	15.2	15.2	15.3	3.18	3.22	5.99	6.01	1.7065	1.49
0.749	0.00	0.18	14.8	14.9	15.0	15.0	5.71	5.72	6.96	6.97	1.4182	0.95
0.768	0.00	0.46	14.7	14.8	14.9	14.9	5.74	5.74	7.23	7.21	1.5336	1.19
0.787	0.00	0.97	14.6	14.7	14.8	14.8	5.74	5.72	7.37	7.37	1.6179	1.35
0.806	0.00	1.77	14.5	14.6	14.7	14.7	5.88	5.89	7.39	7.41	1.5734	1.23
0.749	0.00	0.18	14.7	14.7	14.8	14.8	7.68	7.67	8.34	8.32	1.3874	0.88
0.768	0.00	0.46	14.6	14.7	14.8	14.9	7.75	7.77	8.34	8.35	1.3657	0.82
0.787	0.00	0.97	14.7	14.8	14.7	14.8	7.78	7.76	8.74	8.76	1.7312	1.59
0.806	0.00	1.77	15.1	15.1	15.1	15.1	7.77	7.75	8.65	8.70	1.6844	1.45
0.464	0.48	0.18	12.0	12.1	12.1	12.1	1.66	1.67	5.30	5.32	1.6760	2.60
0.483	0.48	0.46	12.2	12.2	12.2	12.3	1.76	1.77	5.07	5.08	1.5925	2.18
0.502	0.48	0.97	12.8	12.9	13.0	13.0	1.73	1.73	4.92	4.92	1.5783	2.01
0.521	0.48	1.77	12.2	12.2	12.3	12.3	1.74	1.77	4.88	4.90	1.5467	1.81
0.464	0.48	0.18	12.6	12.6	12.7	12.7	3.22	3.20	5.94	5.94	1.5467	1.87
0.483	0.48	0.46	12.7	12.7	12.8	12.8	3.26	3.29	6.03	6.03	1.6153	2.23
0.432	0.48	0.97	14.9	15.0	15.0	15.0	3.03	3.03	5.60	5.60	1.5821	2.21
0.521	0.48	1.77	12.5	12.5	12.5	12.6	3.25	3.25	5.63	5.63	1.4805	1.63
0.394	0.48	0.18	15.2	15.2	15.3	15.3	5.53	5.52	7.45	7.40	1.7559	3.10
0.413	0.48	0.46	15.0	15.1	15.2	15.1	5.72	5.68	7.45	7.41	1.6816	2.69
0.432	0.48	0.97	15.0	15.1	15.1	15.2	5.78	5.76	7.39	7.35	1.6166	2.33
0.451	0.48	1.77	14.9	15.0	15.0	15.1	5.75	5.75	7.26	7.19	1.5351	1.94

Laboratory Weir Box Data, Unreduced

			Temperature, T, (C)				DO (mg/l)					
h	h'	Flow	Above T		Below T		Above DO		Below DO			
m	m	1/sec	1	2	1	2	1	2	1	2	r	ab
0.394	0.48	0.18	14.9	15.0	15.0	15.1	7.66	7.68	8.91	8.92	2.1437	4.73
0.413	0.48	0.46	14.9	15.0	15.0	15.1	7.64	7.67	8.77	8.78	1.9153	3.62
0.432	0.48	0.97	14.7	14.6	14.7	14.8	7.65	7.65	8.86	8.86	2.0019	3.82
0.451	0.48	1.77	14.8	14.9	14.9	14.9	7.78	7.75	8.63	8.58	1.5864	2.14
0.464	0.32	0.18	12.0	12.0	12.0	12.1	1.76	1.76	5.21	5.22	1.6284	2.42
0.483	0.32	0.46	12.0	12.0	12.0	12.0	1.75	1.77	5.25	5.26	1.6365	2.36
0.502	0.32	0.97	11.9	12.0	12.0	12.1	1.79	1.80	5.15	5.15	1.6054	2.17
0.521	0.32	1.77	11.8	11.8	11.8	11.8	1.73	1.75	4.94	4.94	1.5469	1.90
0.394	0.32	0.18	14.9	15.0	15.1	15.1	3.30	3.31	6.01	6.00	1.6822	2.82
0.413	0.32	0.46	14.8	14.8	14.9	15.0	3.27	3.27	5.90	5.91	1.6445	2.56
0.432	0.32	0.97	14.7	14.8	14.8	14.9	3.26	3.29	5.87	5.88	1.6255	2.38
0.451	0.32	1.77	15.2	15.3	15.3	15.3	3.38	3.39	5.77	5.74	4.5652	2.04
0.394	0.32	0.18	14.9	15.0	15.0	15.1	5.60	5.58	7.40	7.41	1.7018	2.90
0.413	0.32	0.46	15.0	15.1	15.1	15.1	5.77	5.78	7.49	7.49	1.6844	2.70
0.432	0.32	0.97	14.9	14.9	14.9	15.0	5.70	5.72	7.32	7.31	1.5919	2.25
0.451	0.32	1.77	15.1	15.2	15.2	15.2	5.90	5.90	7.40	7.42	1.5896	2.13
0.394	0.32	0.18	15.4	15.5	15.6	15.7	7.93	7.93	8.75	8.74	1.7492	3.05
0.413	0.32	0.46	15.3	15.3	15.3	15.4	7.76	7.80	8.75	8.77	1.8281	3.24
0.432	0.32	0.97	15.3	15.4	15.4	15.4	7.77	7.78	8.67	8.68	1.7169	2.69
0.451	0.32	1.77	15.5	15.6	15.5	15.6	7.90	7.90	8.68	8.71	1.6528	2.34
0.464	0.16	0.18	12.1	12.1	12.2	12.2	1.67	1.70	5.11	5.13	1.6206	2.38
0.483	0.16	0.46	12.2	12.2	12.2	12.2	1.71	1.73	5.03	5.03	1.5842	2.16
0.432	0.16	0.97	15.0	15.1	15.0	15.1	1.67	1.68	4.73	4.73	1.5772	2.18
0.521	0.16	1.77	12.0	12.0	12.0	12.0	1.87	1.88	5.01	5.04	1.5506	1.90
0.394	0.16	0.18	15.7	15.7	15.7	15.7	3.37	3.40	5.91	5.92	1.6380	2.59
0.413	0.16	0.46	15.3	15.4	15.4	15.4	3.27	3.31	5.73	5.73	1.5814	2.27
0.432	0.16	0.97	15.4	15.4	15.4	15.5	3.15	3.15	5.64	5.63	1.5805	2.17
0.521	0.16	1.77	12.2	12.3	12.3	12.3	3.15	3.15	5.70	5.71	1.5171	1.77
0.394	0.16	0.18	15.6	15.6	15.7	15.8	5.95	5.97	7.44	7.42	1.6159	2.50
0.413	0.16	0.46	15.4	15.5	15.6	15.6	5.87	5.89	7.33	7.30	1.5674	2.21
0.432	0.16	0.97	15.3	15.4	15.4	15.4	5.88	5.89	7.38	7.44	1.6057	2.27
0.451	0.16	1.77	15.5	15.6	15.6	15.6	5.96	5.97	7.31	7.30	1.5202	1.86
0.394	0.16	0.18	15.9	16.0	16.2	16.2	7.70	7.70	8.65	8.64	1.8852	3.56
0.413	0.16	0.46	15.7	15.7	15.8	15.9	7.77	7.80	8.67	8.66	1.7714	2.99

Laboratory Weir Box Data, Unreduced

			Temperature, T, (C)				DO (mg/l)					
h	h	Flow	Above T		Below T		Above DO		Below DO			
m	m	1/sec	1	2	1	2	1	2	1	2	r	ab
0.432	0.16	0.97	15.9	16.0	16.0	16.1	7.86	7.91	8.83	8.83	1.9913	3.65
0.451	0.16	1.77	15.9	16.0	16.0	16.1	7.60	7.60	8.59	8.63	1.8632	3.05
0.464	0.00	0.18	12.0	12.1	12.1	12.2	1.67	1.70	3.89	3.88	1.3261	1.25
0.483	0.00	0.46	12.1	12.1	12.1	12.2	1.66	1.71	4.37	4.38	1.4276	1.58
0.502	0.00	0.97	11.9	11.9	12.0	12.0	1.64	1.64	4.31	4.30	1.4177	1.50
0.521	0.00	1.77	11.9	12.0	12.0	12.0	1.92	1.91	4.2	4.21	1.3520	1.22
0.464	0.00	0.18	11.9	11.9	12.0	12.0	3.40	3.40	4.61	4.60	1.2003	0.77
0.483	0.00	0.46	12.0	12.0	12.1	12.1	3.23	3.24	5.65	5.66	1.4827	1.79
0.432	0.00	0.97	15.3	15.4	15.4	15.4	3.36	3.37	5.23	5.21	1.3949	1.48
0.521	0.00	1.77	12.1	12.2	12.2	12.2	3.27	3.26	5.16	5.17	1.3458	1.19
0.394	0.00	0.18	15.7	15.7	15.8	15.9	5.83	5.87	6.77	6.70	1.2947	1.19
0.413	0.00	0.46	15.8	15.9	15.9	15.9	5.54	5.52	6.88	6.87	1.4577	1.77
0.432	0.00	0.97	15.7	15.8	15.9	15.9	5.73	5.69	6.83	6.84	1.3855	1.43
0.451	0.00	1.77	15.6	15.7	15.7	15.8	5.74	5.70	6.92	6.89	1.4071	1.45
0.394	0.00	0.18	15.6	15.7	15.8	15.9	7.68	7.69	8.27	8.27	1.3982	1.61
0.413	0.00	0.46	15.9	16.0	16.0	16.1	7.85	7.81	8.48	8.46	1.4955	1.91
0.432	0.00	0.97	15.3	15.3	15.4	15.4	7.65	7.68	8.37	8.37	1.4614	1.73
0.451	0.00	1.77	15.6	15.7	15.7	15.8	7.77	7.71	8.28	8.25	1.3407	1.22

Appendix C

Unreduced Field Weir Box Data
Generated During 19 Runs
At Starved Rock For
Use In Determining
a-Values

Field Weir Box Data, Unreduced
Flow Range: 1.47-1.52 1/sec

	Above weir			Below weir				
Date	DO mg/l	Temp C	Sat %	DO mg/l	Temp C	Sat %	h m	h' m
6/13/85	7.03	20.6	-	8.20	20.3	-	1.524	0.495
	6.91	20.6	-	8.20	20.3	-		
	6.94	20.6	-	7.96	20.3	-		
	6.78	20.6	-	7.93	20.4	-		
6/18,19/85	10.25	21.8	-	9.57	21.5	-	1.556	0.495
	10.65	21.8	-	9.49	21.5	-		
6/25/85	10.86	23.8	-	9.62	23.7	-	1.537	0.495
	10.88	23.8	-	9.69	23.7	-		
7/2,3/85	10.27	26.4	-	8.90	26.1	-	1.511	0.495
	10.27	26.4	-	8.87	26.2	-		
	10.31	26.3	-	8.87	26.2	-		
	10.23	26.4	-	8.87	26.2	-		
7/9/85	9.16	26.7	-	8.54	26.6	-	1.518	0.495
	9.16	26.7		8.52	26.2			
	9.11		-	8.65				
	9.11			8.63		-		
7/16,17/85	10.09	28.2	-	8.73	27.8	-	1.537	0.495
	10.14	28.2	-	8.78	27.9	-		
7/24/85	11.60	26.9	-	9.58	26.7	_	1.518	0.495
	11.65	26.9	-	9.66	26.7	-		
7/29,30/85	11.34	28.2	-	9.42	27.9	_	1.499	0.495
	11.40	28.2	-	9.40	27.9	-		
	11.49	28.1	-	9.51	27.9	-		
8/6/85	8.03	25.4	98.0	8.32	25.3	101.5	1.511	0.495
	7.98	25.3	97.3	8.29	25.3	101.1		

Field Weir Box Data, Unreduced

Flow Range: 1.47-1.52 l/sec

	Above wier			Below weir				
	DO	Temp	Sat	DO	Temp	Sat	h	h'
Date	mg/l	C	%	mg/l	C	%	m	m
8/13,14/85	8.72	27.3	110.7	8.41	27.0	105.9	1.511	0.495
	8.77	27.3	110.8	8.44	27.0	106.0		
8/19/85	8.10	25.7	99.8	8.41	25.5	102.9	1.518	0.495
	7.94	25.7	97.8	8.38	25.5	102.7		
8/26,27/85	8.17	24.2	-	8.41	23.9	_	1.524	0.495
	8.12	24.1	-	8.35	23.9	-		
9/4/85	7.31	25.8	-	7.48	26.0	-	1.521	0.495
	7.51	25.9	-	7.70	26.0	-		
9/9,10/85	7.07	27.6	89.7	7.47	27.3	94.4	1.517	0.459
	7.02	27.5	89.0	7.37	27.2	93.0		
9/16/85	9.54	20.8	-	9.24	20.6	_	1.517	0.495
	9.49	20.7	-	9.09	20.6	-		
	9.49	20.7	-	9.09	20.6	-		
9/23,24/85	7.26	20.5	80.8	8.03	20.1	88.9	1.524	0.622
	7.02	20.4	78.1	8.03	20.2	89.0		
9/30/85	8.03	18.3	-	8.73	18.0	-	1.530	0.495
	8.01	18.3	-	8.41	18.0	-		
10/14,15/85	9.42	16.6	-	9.06	16.7	-	1.517	0.495
	9.41	16.6	-	9.07	16.7	-		
10/24/85	9.16	16.9	-	9.43	16.8	-	1.517	0.495
	9.14	16.9	-	9.40	16.9	-		

Appendix D

Dissolved Oxygen and Temperature Conditions Observed During The 19 Sampling Runs At The Starved Rock Dam

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius above and below the Starved Rock Dam

Above: Pool Elevation 458.81

6/13/85

Gate No.	4		8	
Gate Opening (ft)	2		2	
Depth (ft)	DO	Temp	DO	Temp
0	7.19	20.5	7.51	20.2
2	7.15	20.5	7.45	20.2
4	6.71	20.3	7.30	20.2
6	6.81	20.2	6.85	19.8
8			6.68	19.6
10			6.66	19.6
12			6.27	19.4
14			6.25	19.3
16			6.29	19.3
18			6.34	19.1
20			6.32	19.1

Below: Pool Elevation 442.27

Time	DO	Temp
11:10	8.61	20.3
11:15	8.61	20.3
11:20	8.60	20.4
11:25	8.60	20.4
11:30	8.60	20.3
11:35	8.70	20.3
11:50	8.80	20.2
11:55	8.75	20.1
12:00	8.65	20.0

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius • above and below the Starved Rock Dam

Above: Fool Elevation 458.89

6/18,19/85

Gate No.	4		6		8	
Gate Opening (ft)	2		2		2	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp
0	9.25	21.6	10.39	21.5	10.53	21.5
2	9.21	21.6	10.37	21.6	10.46	21.6
4	9.10	21.5	10.29	21.6	10.43	21.6
6			10.18	21.4	10.40	21.6
8			10.16	21.5	10.35	21.6
10			10.15	21.4	9.93	21.5
12			10.15	21.4	9.86	21.5
14			10.14	21.4	9.89	21.4
16			10.14	21.4	9.93	21.4
18			10.12	21.4	9.97	21.4
20					10.02	21.3

Below: Pool Elevation 442.67

Time	DO	Temp
00:50	9.88	21.6
00:55	9.88	21.6
01:00	9.88	21.6
01:05	9.88	21.6
01:10	9.80	21.6
01:15	9.88	21.6
01:20	9.88	21.6
01:25	9.88	21.6
01:30	9.88	21.6

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius above and below the Starved Rock Dam

Above: Pool Elevation 458.87

6/25/85

Gate No.	4		6		8	
Gate Opening (ft)	2		2		2	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp
0	10.95	23.8	14.90	24.3	14.60	24.4
2	10.90	23.7	15.02	24.2	12.96	23.8
4	10.40	23.6	14.35	23.9	10.53	23.3
6	10.14	23.5	14.08	23.6	9.80	23.2
8			13.34	23.6	9.70	23.2
10			10.24	23.3	9.62	23.2
12			10.18	23.3	9.50	23.1
14					9.28	23.1
16					9.26	23.1
18					9.27	23.2
20					9.23	23.2

Below: Pool Elevation 442.04

Time	DO	Temp
10:30	10.55	23.7
10:35	10.34	23.6
10:40	10.18	23.6
10:45	10.12	23.6
10:50	10.13	23.6
10:55	10.05	23.6
11;00	10.00	23.6
11:05	9.96	23.6
11:10	10.12	23.6
11:15	10.09	23.7

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius
above and below the Starved Rock Dam

Above: Fool Elevation 458.70

7/02,03/85

Gate No.	7		9	
Gate Opening (ft)	2		2	
Depth (ft)	DO	Temp	DO	Temp
0	10.43	26.4	10.31	26.4
2	10.45	26.4	10.30	26.4
4	10.42	26.4	10.27	26.4
6	10.40	26.4	10.26	26.4
8	10.40	26.4	10.26	26.4
10	10.40	26.3	10.14	26.3
12	10.43	26.4	10.12	26.3
14	10.22	26.4	10.10	26.3
16	9.84	26.3	10.09	26.3
18	9.57	26.2	10.10	26.3
20	9.84	26.3	10.05	26.2

Below: Pool Elevation 441.96

Time	DO	Temp
00:45	9.18	26.3
00:50	9.18	26.3
00:55	9.18	26.3
01:00	9.04	26.3
01:05	8.98	26.3
01:10	9.06	26.3
01:15	8.95	26.2

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius above and below the Starved Rock Dam

Above: Fool Elevation 458.66

7/09/85

Gate No.	5		7		9	
Gate Opening (ft)	1		1		1	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp
0	11.95	27.1	12.66	26.9	14.46	27.2
2	8.91	26.5	11.20	26.6	12.52	26.9
4	8.35	26.4	10.58	26.5	8.27	26.3
6	8.30	26.3	8.32	26.3	7.90	26.3
8	8.23	26.3	8.00	26.3	7.63	26.2
10			8.10	26.3	7.84	26.2
12			8.12	26.2	7.94	26.2
14			8.39	26.3	8.20	26.2
16			8.38	26.3	8.01	26.2
18			8.72	26.3	7.76	26.2
20					7.44	26.1

Below: Fool Elevation 441.57

Time	DO	Temp
10:50	9.23	26.5
10:55	9.13	26.5
11:00	9.14	26.5
11:05	9.13	26.5
11:10	9.14	26.5
11:15	9.26	26.5
11:20	9.20	26.5
11:25	9.25	26.5

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius above and below the Starved Rock Dam

Above: Fool Elevation 458.80

7/16,17/85

Gate No.	3		5		7		9	
Gate Opening (ft)	1		1		1		1	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp	DO	Temp
0	9.97	27.8	13.26	28.3	13.01	28.3	12.91	28.2
2	9.98	27.9	13.74	28.2	13.00	28.3	13.01	28.3
4	9.97	27.9	12.45	27.7	13.00	28.3	12.98	28.3
6	9.96	27.9	11.72	27.8	12.90	28.3	12.90	28.3
8					12.63	28.1	12.82	28.3
10					12.31	27.9	12.73	28.1
12					12.18	27.9	12.30	28.0
14					11.88	27.9	12.11	27.9
16					11.47	27.6	11.52	27.9
18					11.56	27.6	9.64	27.7
20					11.64	27.6	8.36	27.4

Below: Pool Elevation 442.12

Time	DO	Temp
00:05	10.30	28.1
00:10	10.20	28.2
00:15	10.16	28.1
00:20	10.20	28.1
00:25	10.20	28.1
00:30	10.20	28.1
00:35	10.15	28.1
00:40	10.16	28.0
00:45	10.04	28.1

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius above and below the Starved Rock Dam

Above: Fool Elevation 458.96

7/24/85

Gate No.	3		5		7		9	
Gate Opening (ft)	1		1		1		1	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp	DO	Temp
0	13.31	26.6	15.66	26.8	16.01	26.9	17.59	27.2
2	11.80	26.4	15.71	26.7	15.59	26.8	13.80	26.4
4	12.65	26.0	15.98	26.7	13.25	26.4	10.84	26.2
6			16.51	26.1	11.35	26.3	10.47	26.2
8					11.38	26.2	10.89	26.2
10					11.88	26.2	10.87	26.2
12					12.33	26.3	10.70	26.1
14					12.27	26.2	10.30	26.1
16					12.41	26.2	10.18	26.1
18					12.12	26.1	9.76	26.0
20					11.62	26.1	9.56	26.0

Below: Pool Elevation 440.99

Time	DO	Temp
10:30	10.36	26.3
10:35	10.20	26.4
10:40	10.18	26.4
10:45	10.15	26.4
10:50	10.12	26.4
10:55	10.21	26.4
11:00	10.12	26.4
11:05	10.12	26.4
11:10	10.20	26.5
11:15	10.08	26.4
11:20	10.09	26.4

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius
above and below the Starved Rock Dam

Above: Fool Elevation 458.63

7/29,30/85

Gate No.	5		7		9	
Gate Opening (ft)	1		1		1	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp
0	14.47	28.2	14.84	28.2	14.60	28.2
2	14.60	28.2	14.82	28.3	14.68	28.3
4	14.55	28.2	14.85	28.3	14.62	28.3
6	13.74	28.0	14.86	28.3	14.59	28.3
8			14.81	28.3	14.58	28.3
10			14.76	28.3	14.38	28.3
12			14.65	28.2	13.80	28.1
14			14.38	28.1	13.64	27.9
16			14.34	28.0	13.50	27.8
18			14.07	27.9	12.95	27.7
20			13.82	29.9	9.26	27.0

Below: Pool Elevation 441.52

Time	DO	Temp
00:25	10.66	28.1
00:30	10.55	28.1
00:35	10.64	28.2
00:40	10.50	28.1
00:45	10.45	28.1
00:50	10.42	28.0
00:55	10.55	28.1

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius
above and below the Starved Rock Dam

Above: Fool Elevation 458.94

8/06/85

Gate No.	6		8		10	
Gate Opening (ft)	3		3		3	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp
0	9.04	25.6	9.27	25.4	9.40	25.4
2	8.75	25.3	8.86	25.3	9.43	25.2
4	9.02	25.3	8.39	25.2	8.04	25.1
6	8.70	25.3	8.14	25.1	8.01	25.1
8	8.54	25.2	8.08	25.1	7.97	25.1
10	8.53	25.2	7.99	25.1	7.80	25.1
12	8.67	25.2	7.91	25.1	7.72	25.1
14			7.83	25.1	7.66	25.1
16			7.89	25.1	7.77	25.1
18			7.85	25.1	7.62	25.1
20			7.73	25.1	7.57	25.1

Below: Pool Elevation 442.57

Time	DO	Temp
10:15	9.19	25.1
10:20	9.03	25.2
10:25	9.06	25.2
10:30	9.06	25.2
10:35	9.06	25.2
10:40	9.04	25.2
10:45	9.04	25.2

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius above and below the Starved Rock Dam

Above: Pool Elevation 458.84

Above: Pool Elevation 458.87

	8/13,14/85		8/19/85			
Gate No.	6		6		8	
Gate Opening (ft)	3		3		3	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp
0	11.21	27.4	8.65	25.6	8.59	25.2
2	11.17	27.4	8.90	25.4	8.40	25.2
4	11.14	27.4	8.78	25.2	8.26	25.2
6	11.14	27.4	7.84	25.0	7.70	25.1
8	11.09	27.4	7.39	24.9	7.20	24.8
10	10.62	27.3	7.42	24.9	7.19	24.8
12	10.25	27.3	7.40	24.9	7.18	24.8
14	10.08	27.2			7.18	24.7
16	9.89	27.2			7.19	24.7
18	9.67	27.2			7.22	24.7
20	9.25	27.1			7.18	24.7

Below: Pool Elevation 441.50

Time	DO	Temp
12:30	9.45	27.2
12:35	8.98	27.2
12:40	8.90	27.2
12:45	9.05	27.2

Below: Pool Elevation 443.03

Time	DO	Temp
Meter One		
10:35	8.65	25.3
10:40	8.60	25.3
10:45	8.59	25.4
10:50	8.52	25.4
10:55	8.50	25.3
11:00	8.53	25.4
Meter Two		
10:40	9.00	25.3
10:45	9.00	25.3
10:50	8.88	25.3
10:55	8.70	25.3
11:00	8.77	25.3

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius
above and below the Starved Rock Dam

Above: Pool Elevation 458.89

8/26,27/85

Gate No.	6
Gate Opening (ft)	3

Depth (ft)	DO	Temp
0	10.06	24.5
2	10.09	24.5
4	10.03	24.5
6	10.04	24.5
8	10.02	24.5
10	9.89	24.4
12	9.32	24.3
14	8.46	24.2
16	7.92	23.9
18	6.82	23.3
20	6.42	23.1

Below: Pool Elevation 441.19

Time	DO	Temp
12:55	9.06	24.0
1:00	9.00	24.0
1:05	9.06	24.0
1:10	9.05	24.0

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius above and below the Starved Rock Dam

Above: Pool Elevation 458.87

9/04/85

Gate No.	3		5		7		9	
Gate Opening (ft)	1		1		1		1	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp	DO	Temp
0	7.41	25.9	7.84	25.9	7.69	26.0	8.28	25.9
2	7.16	25.8	7.66	25.9	7.22	25.8	7.38	25.8
4	9.92	25.8	7.34	25.8	7.02	25.8	7.13	25.8
6	6.89	25.8	7.13	25.8	6.89	25.7	6.84	25.7
8	6.88	25.8	6.90	25.8	6.95	25.7	6.79	25.7
10	6.89	25.8	6.92	25.8	6.99	25.7	6.78	25.7
12			6.95	25.8	7.04	25.7	6.81	25.7
14								
16								
18								
20								

Below: Fool Elevation 441.6 8

Time	DO	Temp
10:55	8.22	25.8
11:00	8.22	25.8
11:05	8.24	25.8
11:10	8.20	25.8
11:15	8.23	25.8
11:20	8.24	25.8

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius above and below the Starved Rock Dam

	Above: Pool Elevation 458.80		Above: Pool Elevation 458.83	
	9/09,10/85		9/16/85	
Gate No.	6		6	
Gate Opening (ft)	4		4	
Depth (ft)	DO	Temp	DO	Temp
0	7.44	27.1	11.33	20.8
2	7.41	27.1	11.29	20.7
4	7.41	27.1	11.34	20.6
6	7.39	27.1	11.68	20.6
8	7.36	27.1	11.57	20.5
10	7.37	27.1	11.68	20.5
12	7.36	27.1	11.57	20.5
14				
16				
18				
20				

Below: Pool Elevation 442.03			Below: Pool Elevation 441.27		
Time	DO	Temp	Time	DO	Temp
11:55	7.77	27.4	11:35	9.67	20.5
12:00	7.65	27.4	11:40	9.60	20.5
12:05	7.71	27.5	11:45	9.72	20.5
12:10	7.81	27.4	11:50	9.75	20.5
			11:55	9.75	20.5

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius above and below the Starved Rock Dam

Above: Pool Elevation 458.77

9/23,24/85

Gate No.	5		7		9	
Gate Opening (ft)	2		2		2	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp
0	7.28	20.3	7.36	20.3	7.42	20.3
2	7.27	20.3	7.36	20.3	7.42	20.3
4	7.26	20.3	7.36	20.4	7.42	20.3
6	7.24	20.3	7.33	20.4	7.40	20.3
8	7.24	20.2	7.31	20.4	7.39	20.3
10	7.25	20.3	7.30	20.4	7.40	20.3
12	7.24	20.2	7.31	20.4	7.39	20.3
14	7.22	20.2	7.29	20.4	7.39	20.3
16	7.22	20.2	7.30	20.3	7.38	20.3
18					7.38	20.3
20						

Below: Pool Elevation 442.94

Time	DO	Temp
11:50	8.74	20.2
11:55	8.71	20.3
12:00	8.72	20.3
12:05	8.71	20.3
12:10	8.74	20.3

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius above and below the Starved Rock Dam

	Above: Fool Elevation 441.93		Above: Pool Elevation 458.83	
	9/30/85		10/14,15/85	
Gate No.	5		6	
Gate Opening (ft)	4		4	
Depth (ft)	DO	Temp	DO	Temp
0	7.91	18.4	9.07	16.4
2	7.84	18.4	8.88	16.5
4	7.81	18.4	8.80	16.4
6	7.79	18.4	8.82	16.4
8	7.72	18.4	8.79	16.4
10			8.77	16.4
12			8.85	16.4
14			8.88	16.4
16			8.93	16.4
18			8.92	16.4
20			8.90	16.4

Below: Pool Elevation 458.88

Time	DO	Temp
10:45	8.96	18.3
10:50	8.93	18.3
10:55	8.93	18.3
11:00	8.97	18.3

Below: Pool Elevation 441.71

Time	DO	Temp
12:40	16.4	9.58
12:45	16.4	9.60
12:50	16.5	9.65

Dissolved Oxygen (DO) in mg/l and Temperature (T) in Celsius
above and below the Starved Rock Dam

Above: Pool Elevation 458.76

10/24/85

Gate No.	4		6		8	
Gate Opening (ft)	2		2		2	
Depth (ft)	DO	Temp	DO	Temp	DO	Temp
0	8.94	16.8	9.29	16.9	9.23	16.9
2	8.87	16.7	9.24	16.8	9.11	16.8
4	8.83	16.7	9.27	16.8	9.05	16.7
6			9.15	16.8	9.00	16.7
8					8.75	16.6
10					8.67	16.5
12						
14						
16						
18						
20						

Below: Pool Elevation 444.13

Time	DO	Temp
2:50	10.2	16.8
2:55	10.2	16.7
3:00	10.2	16.8

Appendix E

Data Used To Develop Stepwise Regression Equation Relating The Dam Deficit Ratios To Various Measured In-Stream Parameters

Data Used to Develop Stepwise Regression Equation Relating the Dam Deficit Ratios to Various Measured In-stream Parameters

		Gate parameters												
Date (1985)	Deficit ratio r	Open ft	No.	h ft	h' ft	Total flow cfs	Water qual. factor a	DO above dam mg/l	Algae below dam #/ml	COD mg/l	SS mg/l	MBAS mg/l	Temp Cel.	Secchi disk inches
6/13	3.658	2	2	16.54	0.27	6276	1.223	6.785	830	23.4	23	0.05	20.0	21
6/18,19	2.126	2	3	16.22	0.67	9435	1.291	10.059	3654	28.2	32	0.05	21.5	19
6/25	1.885	2	3	16.83	0.04	9432	1.522	11.284	4326	29.0	31	0.05	23.6	16
7/02,03	2.264	2	2	16.74	-0.04	6256	1.873	10.200	2058	27.7	28	0.05	26.4	15
7/09	1.416	1	3	17.27	-0.43	4701	1.606	9.084	3350	29.2	27	0.06	26.4	15
7/16,17	1.803	1	4	16.68	0.12	6296	1.697	11.931	3402	25.8	29	0.04	28.0	18
7/24	2.024	1	4	17.98	-0.02	6324	1.518	12.631	6447	31.1	36	0.06	26.4	21
7/29,30	2.568	1	3	17.11	-0.48	4698	1.483	14.162	5534	26.4	31	0.08	28.2	21
8/06	2.414	3	3	16.37	0.57	14040	0.377	8.248	4137	24.7	36	0.05	25.2	21
8/13,14	4.879	3		17.34	-0.50	4666	0.723	10.501	6174	24.1	33	0.07	27.3	19
8/19	6.716	3	2	15.84	1.03	9340	1.039	7.759	8995	22.6	33	0.07	25.0	18
8/26,27	2.375	3		17.71	-0.81	4674	0.474	9.006	319	22.2	26	0.04	24.2	19
9/04	2.853	1		17.19	-0.32	6308	1.169	7.137	143	25.1	23	0.05	25.8	20
9/09,10	4.780	4		16.77	0.03	6073	1.210	7.398	103	20.2	36	0.05	27.1	19
9/16	3.622	4		17.56	-0.73	6078	1.396	11.482	204	22.3	30	0.05	20.6	18
9/23,24	2.889	2	3	15.83	0.94	9405	1.126	7.328	324	21.1	26	0.08	20.3	17
9/30	4.077	4		16.95	-0.07	6087	1.460	7.814	271	21.0	28	0.08	18.4	16
10/14.15	8.360	4		17.12	-0.29	6078	1.498	8.874	61	22.7	19	0.08	16.4	17
10/24	3.876	2	3	14.63	2.13	9342	0.962	9.027	90	21.7	30	0.06	16.7	18

Open = the height one gate is open in feet
No. = total number of gates open at a given height
h = Head Loss; i.e., the difference between the upstream and downstream pool elevations
h' = a minus value indicates a downstream pool elevation below the gate sill elevation of 442.0; a positive value indicates a downstream pool elevation above the gate sill elevation

Appendix F

Stage-Discharge Rating For One Tainter Gate At The Starved Rock Dam At An Upstream Pool Elevation of 458.5 Feet

Stage-discharge Rating for One Tainter Gate at Starved Rock Dam and Upstream Fool Elevation of 458.5 feet

Gate Opening (feet)	Discharge, in cfs, for Downstream Fool Elevations of:									
	442.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	443.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.5	781	776	772	767	762	757	753	748	743	738	734
1.0	1560	1557	1553	1550	1546	1543	1539	1536	1532	1529	1525
1.5	2340	2340	2340	2340	2340	2340	2340	2340	2340	2340	2340
2.0	3110	3110	3110	3110	3110	3110	3110	3110	3110	3110	3110
2.5	3880	3880	3880	3880	3880	3880	3880	3880	3880	3880	3880
3.0	4620	4620	4620	4620	4620	4620	4620	4620	4620	4620	4620
3.5	5340	5340	5340	5340	5340	5340	5340	5340	5340	5340	5340
4.0	6020	6020	6020	6020	6020	6020	6020	6020	6020	6020	6020
	443.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	444.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.5	734	729	724	719	715	710	705	700	696	691	686
1.0	1525	1522	1518	1515	1511	1508	1504	1501	1497	1494	1490
1.5	2340	2340	2340	2340	2340	2340	2340	2340	2340	2340	2340
2.0	3110	3110	3110	3110	3110	3110	3110	3110	3110	3110	3110
2.5	3880	3880	3880	3880	3880	3880	3880	3880	3880	3880	3880
3.0	4620	4620	4620	4620	4620	4620	4620	4620	4620	4620	4620
3.5	5340	5340	5340	5340	5340	5340	5340	5340	5340	5340	5340
4.0	6020	6020	6020	6020	6020	6020	6020	6020	6020	6020	6020
	444.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	445.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.5	686	681	677	672	668	663	658	654	649	645	640
1.0	1490	1480	1470	1460	1450	1440	1430	1420	1410	1400	1390
1.5	2340	2325	2309	2294	2278	2263	2247	2232	2216	2201	2185
2.0	3110	3096	3081	3067	3052	3038	3023	3009	2994	2980	2965
2.5	3880	3868	3855	3843	3830	3818	3805	3793	3780	3768	3755
3.0	4620	4612	4604	4596	4588	4580	4572	4564	4556	4548	4540
3.5	5340	5340	5340	5340	5340	5340	5340	5340	5340	5340	5340
4.0	6020	6020	6020	6020	6020	6020	6020	6020	6020	6020	6020

Stage-discharge Rating for One Tainter Gate at Starved Rock Dam and Upstream Pool Elevation of 458.5 feet

Gate Opening (feet)	Discharge, in cfs, for Downstream Pool Elevations of:										
	445.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	446.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.5	640	635	631	626	622	617	612	608	603	599	594
1.0	1390	1380	1370	1360	1350	1340	1330	1320	1310	1300	1290
1.5	2185	2170	2154	2139	2123	2108	2092	2077	2061	2046	2030
2.0	2965	2951	2936	2922	2907	2893	2878	2864	2849	2835	2820
2.5	3755	3743	3730	3718	3705	3693	3680	3668	3655	3643	3630
3.0	4540	4532	4524	4516	4508	4500	4492	4484	4476	4468	4460
3.5	5340	5340	5340	5340	5340	5340	5340	5340	5340	5340	5340
4.0	6020	6020	6020	6020	6020	6020	6020	6020	6020	6020	6020

	446.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	447.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.5	594	590	587	583	579	576	572	568	565	561	558
1.0	1290	1282	1274	1266	1258	1250	1242	1234	1226	1218	1210
1.5	2030	2018	2005	1993	1980	1968	1955	1943	1930	1918	1905
2.0	2820	2803	2785	2768	2750	2733	2713	2698	2680	2663	2645
2.5	3630	3608	3585	3563	3540	3518	3495	3473	3450	3428	3405
3.0	4460	4433	4405	4378	4350	4323	4295	4268	4240	4213	4185
3.5	5340	5306	5272	5238	5204	5170	5136	5102	5068	5034	5000
4.0	6020	5991	5961	5932	5902	5878	5843	5814	5784	5755	5725

	447.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	448.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.5	558	554	550	547	543	539	536	532	528	525	521
1.0	1210	1202	1194	1196	1178	1170	1162	1154	1146	1138	1130
1.5	1905	1893	1880	1868	1855	1843	1830	1818	1805	1793	1780
2.0	2645	2628	2610	2593	2575	2558	2540	2523	2505	2488	2470
2.5	3405	3383	3360	3338	3315	3293	3270	3248	3225	3203	3180
3.0	4185	4158	4130	4103	4075	4048	4020	3993	3965	3938	3910
3.5	5000	4966	4932	4898	4864	4830	4796	4762	4728	4694	4660
4.0	5725	5696	5666	5637	5607	5578	5548	5519	5489	5460	5430

Stage-discharge Rating for One Tainter Gate at Starved Rock Dam and Upstream Pool Elevation of 458.5 feet

Gate Opening (feet)	Discharge, in cfs, for Downstream Pool Elevations of:									
	448.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	449.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.5	521	518	514	511	508	504	501	498	494	491	488
1.0	1130	1123	1116	1109	1101	1094	1087	1080	1073	1066	1059
1.5	1780	1769	1757	1746	1734	1723	1711	1700	1688	1677	1665
2.0	2470	2454	2438	2422	2406	2390	2374	2358	2342	2326	2310
2.5	3180	3160	3139	3119	3098	3078	3057	3037	3016	2996	2975
3.0	3910	3885	3859	3834	3808	3783	3757	3732	3706	3681	3655
3.5	4660	4630	4600	4570	4540	4510	4480	4450	4420	4390	4360
4.0	5430	5395	5360	5325	5290	5255	5220	5185	5150	5115	5080

	449.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	450.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.5	488	484	481	477	474	471	467	464	461	457	454
1.0	1059	1051	1044	1037	1030	1023	1016	1008	1001	994	987
1.5	1665	1654	1642	1631	1619	1608	1596	1585	1573	1562	1550
2.0	2310	2294	2278	2262	2246	2230	2214	2198	2182	2166	2150
2.5	2975	2955	2934	2914	2893	2873	2852	2832	2811	2791	2770
3.0	3655	3630	3604	3579	3553	3528	3502	3477	3451	3426	3400
3.5	4360	4330	4300	4270	4240	4210	4180	4150	4120	4090	4060
4.0	5080	5045	5010	4975	4940	4905	4870	4835	4800	4765	4730

	450.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	451.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.5	454	451	447	444	441	437	434	431	427	424	421
1.0	987	980	972	965	958	951	943	936	929	921	914
1.5	1550	1539	1528	1517	1506	1495	1484	1473	1462	1451	1440
2.0	2150	2134	2118	2102	2086	2070	2054	2038	2022	2006	1990
2.5	2770	2750	2729	2709	2688	2668	2647	2627	2606	2586	2565
3.0	3400	3375	3350	3325	3300	3275	3250	3225	3200	3175	3150
3.5	4060	4030	4000	3970	3940	3910	3880	3850	3820	3790	3760
4.0	4730	4695	4660	4625	4590	4555	4520	4485	4450	4415	4380

Appendix G

Nine Gate Management Methods Developed To Show Various Potential b-Values Which Could Be Achieved

Gate Management Method 1

Flow Dur %	Pool Elev		Flow cfs	Number of Gates Utilized for a Gate Setting (in feet) of:								Gate Flow cfs	Wtd Avg b
	Dpper	Lower		0.5	1.0'	1.5	2.0	2.5	3.0	3.5	4.0		
99.8	459.0	440.6	3698	4								3170	0.228
99	459.0	440.6	4159	5								3962	0.228
98	459.1	440.7	4452	5								3962	0.228
97	459.2	440.7	4642	6								4782	0.228
96	459.3	440.8	4844	6								4795	0.228
95	459.3	440.8	4999	6								4795	0.228
90	459.3	440.8	5470	7								5594	0.228
85	459.4	440.8	5765	7								5610	0.228
80	459.3	441.2	6110	8								6394	0.228
75	459.3	441.3	6350	8								6394	0.228
70	459.3	441.6	6600	8								6394	0.228
65	459.3	441.9	6900	9								7192	0.228
60	459.4	442.0	7202	9								7212	0.228
55	459.4	442.1	7510	10								7962	0.228
50	459.4	442.2	7878	10								7921	0.228
45	459.4	442.3	8357	9	1							8674	0.270
40	459.4	442.3	8851	9	1							8674	0.270
35	459.4	442.4	9512	8	2							9428	0.305
30	459.4	442.4	10293	7	3							10231	0.334
25	459.4	442.6	11368	5	5							11758	0.381
20	459.4	444.0	12809	3	7							12814	0.418
17	459.4	446.0	13777		9	1						13996	0.490
15	459.3	448.0	14637		5	5						14889	0.597
14	459.2	448.1	15126		4	6						15414	0.617
13	459.1	448.2	15711		3	7						15921	0.635
12	459.0	448.4	16327		2	8						16309	0.654
11	458.9	448.9	16921			10						16966	0.685
10	458.7	449.3	17527			8	2					17676	0.744
9	458.9	449.9	19600			4	6					19469	0.840
8	458.9	450.5	19208	1			9					19327	0.857

Gate Management Method 2

Flow Dur %	Pool Elev		Flow cfs	Number of Gates Utilized for a Gate Setting (in feet) of:								Gate Flow cfs	Wtd Avg b
	Upper	Lower		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0		
99.8	459.0	440.6	3698	2	1							3168	0.342
99	459.0	440.6	4159	1	2							3958	0.410
98	459.1	440.7	4452	2	2							4764	0.380
97	459.2	440.7	4642	2	2							4778	0.380
96	459.3	440.8	4844	2	2							4791	0.380
95	459.3	440.8	4999	2	2							4791	0.380
90	459.3	440.8	5470	3	2							5590	0.358
85	459.4	440.8	5765	3	2							5606	0.358
80	459.3	441.2	6110	4	2							6389	0.342
75	459.3	441.3	6350	4	2							6389	0.342
70	459.3	441.6	6600	4	2							6389	0.342
65	459.3	441.9	6900	5	2							7189	0.329
60	459.4	442.0	7202	5	2							7189	0.329
55	459.4	442.1	7510	3	3							7206	0.380
50	459.4	442.2	7878	4	3							7949	0.365
45	459.4	442.3	8357	5	3							8585	0.353
40	459.4	442.3	8851	5	3							8585	0.353
35	459.4	442.4	9512	6	3							9329	0.343
30	459.4	442.4	10293	3	5							10276	0.404
25	459.4	442.6	11368	3	6							11793	0.411
20	459.4	444.0	12809	1	8							12935	0.444
17	459.4	446.0	13777		4	4						13627	0.596
15	459.3	448.0	14637		3	6						14398	0.630
14	459.2	448.1	15126		2	7						14927	0.650
13	459.1	448.2	15711		1	8						15438	0.668
12	459.0	448.4	16327	1		9						16349	0.671
11	458.9	448.9	16921	1		7	2					17080	0.735
10	458.7	449.3	17527		1	6	3					17713	0.760
9	458.9	449.9	19600		2		8					19542	0.867
8	458.9	450.5	19208				8	1				19453	0.946

Gate Management Method 3

Flow Dur %	Pool Elev Upper	Pool Elev Lower	Flow cfs	Number of Gates Utilized for a Gate Setting (in feet) of: 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	Gate Flow cfs	Wtd Avg b
99.8	459.0	440.6	3698		2							3165	0.456
99	459.0	440.6	4159		1	1						3957	0.593
98	459.1	440.7	4452		3							4762	0.456
97	459.2	440.7	4642		3							4775	0.456
96	459.3	440.8	4844		3							4789	0.456
95	459.3	440.8	4999		3							4789	0.456
90	459.3	440.8	5470	1	3							5588	0.423
85	459.4	440.8	5765	1	3							5604	0.423
80	459.3	441.2	6110		4							6385	0.456
75	459.3	441.3	6350		4							6385	0.456
70	459.3	441.6	6600		4							6385	0.456
65	459.3	441.9	6900		3	1						7203	0.532
60	459.4	442.0	7202		3	1						7203	0.532
55	459.4	442.1	7510		3	1						7194	0.532
50	459.4	442.2	7878		5							7988	0.456
45	459.4	442.3	8357	1	5							8744	0.435
40	459.4	442.3	8851	1	5							8744	0.435
35	459.4	442.4	9512	1	4	1						9528	0.495
30	459.4	442.4	10293		5	1						10333	0.509
25	459.4	442.6	11368		6	1						11876	0.502
20	459.4	444.0	12809		7	1						12831	0.498
17	459.4	446.0	13777	1	2	5						13672	0.620
15	459.3	448.0	14637			8						14572	0.685
14	459.2	448.1	15126			7	1					15140	0.723
13	459.1	448.2	15711			6	2					15688	0.757
12	459.0	448.4	16327		1	6	2					16555	0.737
11	458.9	448.9	16921			6	3					17239	0.779
10	458.7	449.3	17527			5	4					17304	0.805
9	458.9	449.9	19600				9					19722	0.914
8	458.9	450.5	19208			1	6	2				19476	0.960

Gate Management Method 4

Flow Dur %	Pool Elev		Flow cfs	Number of Gates Utilized for a Gate Setting (in feet) of:								Gate Flow cfs	Wtd Avg b
	Upper	Lower		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0		
99.8	459.0	440.6	3698	2		1						3959	0.502
99	459.0	440.6	4159		1	1						3957	0.593
98	459.1	440.7	4452			2						4762	0.685
97	459.2	440.7	4642			2						4775	0.685
96	459.3	440.8	4844			2						4789	0.685
95	459.3	440.8	4999			2						4789	0.685
90	459.3	440.8	5470	1		2						5588	0.619
85	459.4	440.8	5765		2	1						5603	0.554
80	459.3	441.2	6110		1	2						6385	0.628
75	459.3	441.3	6350		1	2						6385	0.628
70	459.3	441.6	6600		1	2						6385	0.628
65	459.3	441.9	6900			3						7184	0.685
60	459.4	442.0	7202			3						7203	0.685
55	459.4	442.1	7510			3						7203	0.685
50	459.4	442.2	7878	1		3						7995	0.640
45	459.4	442.3	8357		1	3						8794	0.644
40	459.4	442.3	8851		1	3						8794	0.644
35	459.4	442.4	9512			4						9604	0.685
30	459.4	442.4	10293	1		4						10386	0.651
25	459.4	442.6	11368		1	4						11183	0.653
20	459.4	444.0	12809	1		5						12709	0.660
17	459.4	446.0	13777		1	6						13822	0.663
15	459.3	448.0	14637		1	6	1					14612	0.706
14	459.2	448.1	15126		1	5	2					15233	0.743
13	459.1	448.2	15711		1	4	3					15729	0.777
12	459.0	448.4	16327			5	3					16120	0.789
11	458.9	448.9	16921		1	4	4					17278	0.795
10	458.7	449.3	17527		1	3	5					17342	0.821
9	458.9	449.9	19600			1	7	1				19730	0.929
8	458.9	450.5	19208				4	4				19174	1.044

Gate Management Method 5

Flow Dur	Pool Elev		Flow	Number of Gates Utilized for a Gate Setting (in feet) of:								Gate Flow	Wtd Avg
%	Upper	Lower	cfs	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	cfs	b
99.8	459.0	440.6	3698	1			1					3948	0.776
99	459.0	440.6	4159	1			1					3948	0.776
98	459.1	440.7	4452		1		1					4752	0.761
97	459.2	440.7	4642		1		1					4765	0.761
%	459.3	440.8	4844		1		1					4779	0.761
95	459.3	440.8	4999		1		1					4779	0.761
90	459.3	440.8	5470			1	1					5577	0.816
85	459.4	440.8	5765			1	1					5577	0.816
80	459.3	441.2	6110				2					6365	0.914
75	459.3	441.3	6350				2					6365	0.914
70	459.3	441.6	6600				2					6365	0.914
65	459.3	441.9	6900		1	1	1					7175	0.736
60	459.4	442.0	7202	1			2					7184	0.837
55	459.4	442.1	7510	1			2					7184	0.837
50	459.4	442.2	7878		1		2					7980	0.822
45	459.4	442.3	8357		1		2					7980	0.822
40	459.4	442.3	8851			1	2					8783	0.851
35	459.4	442.4	9512				3					9574	0.914
30	459.4	442.4	10293	1			3					10355	0.862
25	459.4	442.6	11368		1		3					11153	0.849
20	459.4	444.0	12809				4					12765	0.914
17	459.4	446.0	13777			1	4					13657	0.879
15	459.3	448.0	14637			1	5					14459	0.885
14	459.2	448.1	15126				6					15024	0.914
13	459.1	448.2	15711		1		6					16020	0.882
12	459.0	448.4	16327			1	6					16406	0.889
11	458.9	448.9	16921				7					16472	0.914
10	458.7	449.3	17527			1	7					17568	0.893
9	458.9	449.9	19600				9					19722	0.914
8	458.9	450.5	19208		1	2	1	5				19351	1.015

Gate Management Method 6

Flow Dur %	Pool Elev Upper	Pool Elev Lower	Flow cfs	Number of Gates Utilized for a Gate Setting (in feet) of: 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	Gate Flow cfs	Wtd Avg b
99.8	459.0	440.6	3698					1				3937	1.145
99	459.0	440.6	4159					1				3937	1.145
98	459.1	440.7	4452					1				3948	1.145
97	459.2	440.7	4642	1				1				4756	0.991
96	459.3	440.8	4844	1				1				4770	0.991
95	459.3	440.8	4999	1				1				4770	0.991
90	459.3	440.8	5470		1			1				5567	0.947
85	459.4	440.8	5765		1			1				5567	0.947
80	459.3	441.2	6110			1		1				6365	0.972
75	459.3	441.3	6350			1		1				6365	0.972
70	459.3	441.6	6600			1		1				6365	0.972
65	459.3	441.9	6900				1	1				7153	1.042
60	459.4	442.0	7202				1	1				7172	1.042
55	459.4	442.1	7510				1	1				7172	1.042
50	459.4	442.2	7878	1			1	1				7959	0.961
45	459.4	442.3	8357		1		1	1				8763	0.936
40	459.4	442.3	8851		1		1	1				8763	0.936
35	459.4	442.4	9512		1			2				9549	1.031
30	459.4	442.4	10293			1		2				10364	1.038
25	459.4	442.6	11368				1	2				11154	1.079
20	459.4	444.0	12809		1		1	2				12683	1.004
17	459.4	446.0	13777	1		1		3				13857	1.073
15	459.3	448.0	14637			1		4				14838	1.089
14	459.2	448.1	15126	1		1		4				15232	1.089
13	459.1	448.2	15711		1	1		4				15699	1.043
12	459.0	448.4	16327			2		4				16092	1.044
11	458.9	448.9	16921				2	4				16831	1.080
10	458.7	449.3	17527		1	1		5				17339	1.060
9	458.9	449.9	19600		1		2	5				19507	1.044
8	458.9	450.5	19208			1	2	5				19197	1.058

Gate Management Method 7

Flow Dur %	Pool Elev Upper	Pool Elev Lower	Flow cfs	Number of Gates Utilized for a Gate Setting (in feet) of: 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	Gate Flow cfs	Wtd Avg b
99.8	459.0	440.6	3698					1				3937	1.145
99	459.0	440.6	4159					1				3937	1.145
98	459.1	440.7	4452						1			4701	1.375
97	459.2	440.7	4642						1			4714	1.375
%	459.3	440.8	4844						1			4728	1.375
95	459.3	440.8	4999						1			4728	1.375
90	459.3	440.8	5470	1					1			5527	1.209
85	459.4	440.8	5765	1					1			5527	1.209
80	459.3	441.2	6110		1				1			6324	1.143
75	459.3	441.3	6350		1				1			6324	1.143
70	459.3	441.6	6600		1				1			6324	1.143
65	459.3	441.9	6900			1			1			7122	1.143
60	459.4	442.0	7202			1			1			7142	1.143
55	459.4	442.1	7510			1			1			7142	1.143
50	459.4	442.2	7878				1		1			7932	1.190
45	459.4	442.3	8357				1		1			7932	1.190
40	459.4	442.3	8851					1	1			8722	1.270
35	459.4	442.4	9512						2			9481	1.375
30	459.4	442.4	10293	1					2			10263	1.288
25	459.4	442.6	11368		1				2			11060	1.244
20	459.4	444.0	12809				1		2			12672	1.259
17	459.4	446.0	13777	1				1	2			13487	1.260
15	459.3	448.0	14637					2	2			14510	1.272
14	459.2	448.1	15126	1				2	2			14906	1.235
13	459.1	448.2	15711		1			2	2			15376	1.212
12	459.0	448.4	16327				1	2	2			16455	1.219
11	458.9	448.9	16921	1				3	2			17038	1.219
10	458.7	449.3	17527			1		3	2			17634	1.196
9	458.9	449.9	19600		1			3	3			19875	1.230
8	458.9	450.5	19208		1			3	3			19000	1.230

Gate Management Method 8

Flow Dur %	Pool Elev Upper	Pool Elev Lower	Flow cfs	Number of Gates Utilized for a Gate Setting (in feet) of: 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	Gate Flow cfs	Wtd Avg b
99.8	459.0	440.6	3698					1				3937	1.145
99	459.0	440.6	4159					1				3937	1.145
98	459.1	440.7	4452						1			4701	1.375
97	459.2	440.7	4642						1			4714	1.375
96	459.3	440.8	4844						1			4728	1.375
95	459.3	440.8	4999						1			4728	1.375
90	459.3	440.8	5470							1		5464	1.610
85	459.4	440.8	5765							1		5479	1.610
80	459.3	441.2	6110	1						1		6264	1.434
75	459.3	441.3	6350	1						1		6264	1.434
70	459.3	441.6	6600	1						1		6264	1.434
65	459.3	441.9	6900		1					1		7061	1.349
60	459.4	442.0	7202		1					1		7080	1.349
55	459.4	442.1	7510		1					1		7080	1.349
50	459.4	442.2	7878			1				1		7880	1.328
45	459.4	442.3	8357				1			1		8671	1.354
40	459.4	442.3	8851				1			1		8671	1.354
35	459.4	442.4	9512					1		1		9461	1.414
30	459.4	442.4	10293						1	1		10220	1.501
25	459.4	442.6	11368	1						2		11731	1.519
20	459.4	444.0	12809		1					2		12488	1.469
17	459.4	446.0	13777				1			2		13852	1.465
15	459.3	448.0	14637	1						3		14839	1.560
14	459.2	448.1	15126		1					3		15319	1.524
13	459.1	448.2	15711			1				3		15829	1.506
12	459.0	448.4	16327				1			3		16260	1.506
11	458.9	448.9	16921						1	3		17048	1.559
10	458.7	449.3	17527	1						4		17661	1.572
9	458.9	449.9	19600	1				1		4		19837	1.512
8	458.9	450.5	19208						1	4		19136	1.569

Gate Management Method 9

Flow Dur %	Pool Elev Upper	Pool Elev Lower	Flow cfs	Number of Gates Utilized for a Gate Setting (in feet) of: 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	Gate Flow cfs	Wtd Avg b
99.8	459.0	440.6	3698					1				3937	1.145
99	459.0	440.6	4159					1				3937	1.145
98	459.1	440.7	4452						1			4701	1.375
97	459.2	440.7	4642						1			4714	1.375
96	459.3	440.8	4844						1			4728	1.375
95	459.3	440.8	4999						1			4728	1.375
90	459.3	440.8	5470							1		5464	1.610
85	459.4	440.8	5765							1		5479	1.610
80	459.3	441.2	6110								1	6160	1.860
75	459.3	441.3	6350								1	6160	1.860
70	459.3	441.6	6600	1							1	6959	1.673
65	459.3	441.9	6900	1							1	6959	1.673
60	459.4	442.0	7202	1							1	6979	1.673
55	459.4	442.1	7510		1						1	7775	1.571
50	459.4	442.2	7878		1						1	7771	1.571
45	459.4	442.3	8357			1					1	8578	1.531
40	459.4	442.3	8851			1					1	8578	1.531
35	459.4	442.4	9512				1				1	9368	1.538
30	459.4	442.4	10293	1			1				1	10150	1.437
25	459.4	442.6	11368							1	1	11656	1.742
20	459.4	444.0	12809	1							2	13058	1.772
17	459.4	446.0	13777		1						2	13678	1.724
15	459.3	448.0	14637			2					2	14756	1.570
14	459.2	448.1	15126	1		2					2	15149	1.523
13	459.1	448.2	15711							1	2	15588	1.785
12	459.0	448.4	16327		1					1	2	16458	1.695
11	458.9	448.9	16921				1			1	2	17144	1.665
10	458.7	449.3	17527						1	1	2	17904	1.719
9	458.9	449.9	19600	1							4	19745	1.822
8	458.9	450.5	19208		1						4	19395	1.730