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US Army Corps
of Engineers

WATER QUALITY MANAGEMENT FOR RESERVOIRS AND TAILWATERS

Report 2

OPERATIONAL AND STRUCTURAL WATER QUALITY ENHANCEMENT TECHNIQUES
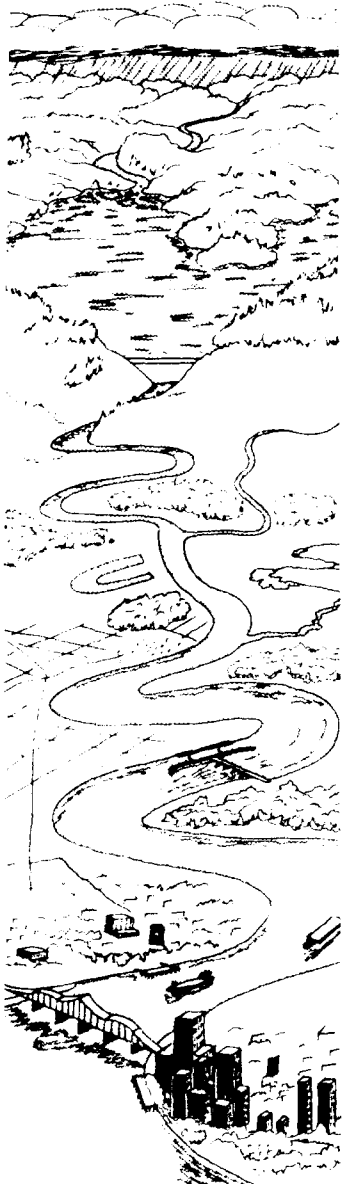
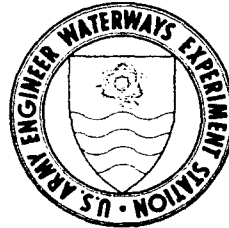by

Richard E. Price, Edward B. Meyer

Hydraulics Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

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This report is the second of a series of reports on experimental and working water quality enhancement techniques. The methods included in this report are limited to operational or structural modifications to prevent physical and chemical problems typically encountered in CE reservoirs. Descriptive information on hydraulic structure types and their functional and structural characteristics is given. Enhancement techniques discussed include guide curve changes, inflow routing, supplemental releases, concentration of flow through one gate, release strategy optimization, hypolimnetic withdrawal, pneumatic destratification, underwater dam, aeration-oxygenation systems, turbine venting, submerged skimming weir, multilevel selective withdrawal, and localized mixing. The problem that each technique is designed to address is discussed, along with the theory and methodology; referenced applications, a summary, and references are included.

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PREFACE

This report is the second in a series of reports describing water quality management technology for reservoirs and tailwaters. The work was conducted as part of the Water Operations Technical Support Program (WOTS). The WOTS is is sponsored by the Headquarters, US Army Corps of Engineers (HQUSACE), and is assigned to the US Army Engineer Waterways Experiment Station (WES) under the purview of the Environmental Laboratory (EL). Funding was provided under Department of the Army Appropriation No. 96X3123, Operations and Maintenance. The WOTS is managed under the Environmental Resources Research and Assistance Programs (ERRAP), Mr. J. L. Decell, Manager. Dr. A. J. Anderson was Assistant Manager, ERRAP, for the WOTS. Technical Monitors during this study were Dr. John Bushman and Messrs. David Buelow and James Gottesman, HQUSACE.

The report was prepared by Dr. Richard E. Price and CPT Edward B. Meyer, Reservoir Water Quality Branch (RWQB), Hydraulic Structures Division (HS), Hydraulics Laboratory (HL), WES.

The work was conducted under the direct supervision of Dr. Jeffery P. Holland, Chief, RWQB, and Dr. Robert H. Kennedy of the Aquatic Processes and Effects Group (APEG), Ecosystem Research and Simulation Division (ERSD), EL. Dr. Thomas L. Hart, Chief, APEG, Mr. Donald L. Robey, Chief, ERSD, and Mr. Glenn A. Pickering, Chief, HS, provided general supervision and review. Dr. John Harrison was Chief, EL, and Mr. Frank A. Herrmann, Jr., was Chief, HL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

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CONVERSION FACTORS, NON-SI TO SI
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
gallons (US liquid)	3.785412	liters
inches	2.54	centimeters
miles (US statute)	1.609347	kilometers
tons (2,000 pounds, mass)	907.1847	kilograms

WATER QUALITY MANAGEMENT FOR

RESERVOIRS AND TAILWATERS

OPERATIONAL AND STUCTURAL WATER QUALITY

ENHANCEMENT TECHNIQUES

PART I: INTRODUCTION

This report is the second of a series of reports written to provide reservoir managers with a reference document of experimental as well as working water quality enhancement techniques. Although a number of wa⁺er quality problems at Corp of Engineers (CE) reservoirs stem from eutrophication, many are related to physical aspects such as release temperature and turbidity, as well as chemical concerns related to iron, manganese, and hydrogen sulfide. The methods presented in this report may be used to control some eutrophic as well as physical and chemical problems and are limited to operational or structural modifications to the outlet structure or within its immediate vicinity. Techniques applicable to watershed, tributary, or in-reservoir problems were addressed in the first report of this series.

In the evaluation of a particular problem, more than one technique discussed in this report may be applicable. This document does not attempt to consolidate techniques into a systems approach, nor does it provide analytical procedures to identify a particular technique. It is intended to be a reference document of water quality enhancement techniques.

In the first report of this series, a basic description of reservoir limnology was presented, and eutrophication processes and control techniques for in-reservoir management were discussed. Part II of the first report included a discussion of problem diagnosis and selection of management methods. Since this basic approach would apply as well to identification of operational or structural techniques, the reader is referred to the first report for a general approach to the solution of a water quality problem.

Inasmuch as the techniques discussed in this report deal with operational and structural modifications, the particular operation or guide curve that is being used to regulate the project should be considered during the evaluation of techniques. In some techniques, reference is made to a particular type of project or structure. Parts II and III provide basic descriptions of the various structures and facilities found throughout the CE. These parts

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are presented as background information only and are not intended to serve as a primer on hydraulic structures.

The remaining parts of this report (Parts IV-XVI) follow a format similar to the first report, discussing the problem addressed by the technique, the theory of the water quality technique, design methodology, review of applications of the particular technique, and a summary. References used with each technique are included to provide original sources.

The information provided in this report should be used to screen techniques that may be used with a particular problem; however, implementation of a particular procedure should occur only after consultation with appropriate references included in the particular section.

The methods discussed in this report were compiled from literature reviews of journal and CE publications. In some cases, where no general procedure was published, a technique was formulated using information from CE publications.

PART II: WATER CONTROL STRUCTURES/FACILITIES

Background

Part II and III were written to provide persons interested in reservoir water quality with a basic understanding of water control structures--typical features and how they operate. This information can be used to make more informed decisions on project operations or the abilities of a project to meet water quality goals. This part should be used only as an introduction to hydraulic structures and their features. The reader is directed to the references at the end of this part for a more detailed discussion.

Corps reservoirs serve a variety of purposes; typically, they provide flood protection, hydroelectric power, water quality and supply, navigation, and recreation. While a few projects are constructed and operated for a single specific purpose, most are operated for multiple purposes.

In accordance with the authorized purposes of a project, a water control plan is developed to regulate reservoir levels and discharges. This plan details how the reservoir should be filled or emptied as the year progresses and gives guidance as to the water surface elevations to be maintained on the reservoir. The result is a time frame for operation of the project to create a stable pool, provide specific downstream releases, or increase flood control Storage (Figure 1).
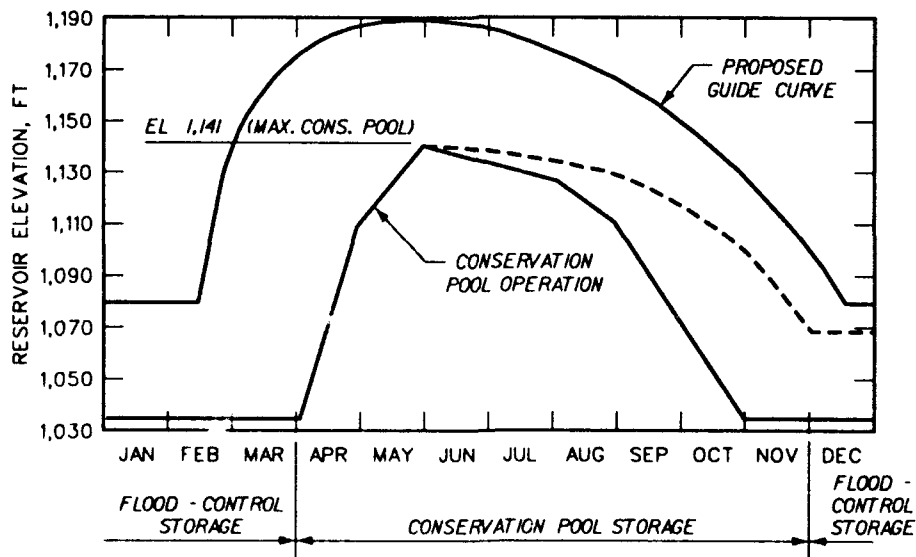
Figure 1. Example guide curve for CE project

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Project Flexibility

With today's increasing demands on water resources, and the need to maximize the benefits realized from any project, it is extremely rare to find a project being operated solely for one purpose. The exceptions to this rule are projects that were authorized and constructed some time ago, or those that are very small. In fact, more and more single-purpose projects are being retrofitted or their operations reevaluated to allow for multiple use. While single-purpose projects usually perform their jobs very well, there is often capacity for additional uses with little impact to the original goal.

Some uses, however, seemingly conflict with one another, such as hydropower and flood control. A hydropower operation relies on maintaining the greatest amount of water or elevation behind the dam, and releases water only when electrical power generation is demanded. Flood control operation attempts to maintain as small a reservoir as possible so that it can absorb a large flood inflow to prevent flooding downstream and slowly release it later.

In a case such as this, the compromise lies in the proper design and execution of the water control plan by providing a minimum pool and outflows for power generation, while allowing enough storage for the reservoir to absorb flood flows (Headquarters, US Army Corps of Engineers (HQUSACE) 1987). For a flood control project, this is not a great sacrifice because the majority of storage in the lake is in the upper elevations of the reservoir.

PART III: PROJECT TYPES AND FEATURES

Functional Characteristics

Flood control

Many Corps of Engineers projects provide some measure of downstream flood control, even if this is not already a primary purpose. Reservoirs and lakes provide temporary storage for flood events so they can be slowly released. In effect they decrease the magnitude of the flood by increasing the duration of the hydrograph. The key to an effective flood control reservoir is the ability to provide enough storage in the pool so the flow can be absorbed and then released gradually.

Typical flood control projects have very specific water control plans. Normally they are drawn down during the fall and early winter to a minimum pool elevation. They are kept at this level through the winter until the spring or typical flood season. The reservoir is then able to provide the maximum amount of flood protection through the spring runoff or wet season (HQUSACE 1987).

Some drawbacks are associated with the operation of a purely flood control project. First, the reservoir water surface level can go through a wide range of fluctuations, from being very low prior to the wet season to being at maximum pool capacity after an exceptionally wet rainy season or a particularly large flood event. After such an event, the reservoir is usually drawn down to provide storage for the next flood, dependent on the water control plan. The second drawback is that release of water after a flood event may maintain bank-full conditions downstream of the project for an extended period of time. This may cause saturation of the bank material, allowing erosion and increased sediment transport.

The combination of these factors can severely limit the use of the reservoir for other than flood control purposes. For example, water supply, recreation, and hydropower operation all generally rely on a stable pool elevation to provide the greatest amount of benefits to the project. A reservoir level that fluctuates widely may severely reduce the usefulness of the project for other than flood control purposes.

Hydropower

Hydropower projects can be broken down into two categories: storage reservoirs, can provide sufficient storage or capacity to regulate streamflow

and deliver sufficient water power over seasonal cycles, and run-of-the-river projects, which can provide minimal storage for power generation and provide power based on seasonal streamflow. Storage projects are usually multipurpose, providing additional benefits from the reservoir upstream, such as recreation, irrigation, and water supply. Run-of-the-river projects are normally found in conjunction with navigation projects (HQUSACE 1987).

The purpose of a project operated solely for hydropower is to provide water with the greatest amount of energy to generate electrical power on a regular basis or peak power demand periods. The energy of water is dependent on the amount being discharged and the head or pressure of the water. For example, energy can be maximized by providing a large discharge under a high head, as opposed to the same discharge at a lower head. This pressure is referred to as the hydraulic head and is a result of the difference between the water surface elevation of the reservoir upstream and the tailwater downstream of the dam.

Hydropower facilities range in size, from small one- or two-unit projects producing a few megawatts to massive projects such as Hoover Dam producing well over 100,000 MW. However, independent of the size, the purpose of the reservoir is the same: to act as a storage facility for potential power. The reservoir should provide a specific discharge of water for a given length of time and provide it at the maximum elevation difference possible for the geographic area.

Some CE hydropower projects house the turbines and powerhouse as part of the dam structure. Others place the dam at some distance upstream and then use a canal or conduit (known as a penstock) to transport the water from the reservoir to the powerhouse. This enables the powerhouse to make use of the greatest amount of elevation change to maximize power output.

A drawback to operating a hydropower project is the reduction or elimination of flow downstream of a project during nongeneration periods. The ideal project from a hydropower perspective would release no water during periods of nongeneration since water passed during these periods represents lost generation potential. Typically, however, projects are required to release a minimum flow to prevent a dry streambed downstream. Further, the change from nongeneration to generation modes usually produces a rapid rise in the stream level downstream, which may be hazardous to downstream uses such as recreation or boating.

Water quality and supply

Water supply reservoirs are operated to provide a constant suitable quality and quantity of water to a community or sponsor for municipal or industrial uses. For example, a town that draws its water supply directly from a river source may encounter shortages during times of extended drought or side fluctuations in water quality due to storm events. Such a town may benefit form a water supply reservoir that may provide a better consistency of water in terms of quality and quantity. A river is typically subject to storm events that can rapidly change the water quality; this requires constant attention to the treatment of the water to maintain water quality. On the other hand, a reservoir can typically provide a relatively constant water quality, meeting the needs of local industrial, agricultural, and municipal interests.

Water supply reservoirs also provide water to farms and agricultural centers for irrigation. This is especially true in the western United States and in other areas where the amount of seasonal rainfall fails to meet the demands (HQUSACE 1987).

Some water supply reservoirs are managed specifically for water quality for municipal and industrial uses, while others are managed for water quality for recreation or fish and wildlife purposes. Such reservoirs may have selective withdrawal facilities which consist of an outlet structure with multiple intake ports each at a different elevation in the lake. This enables the project manager to withdraw water from a number of different levels in the reservoir to achieve a given release quality during stratified periods or to remove or maintain water of a specific quality in the reservoir.

Generally, projects are concerned with the quality of the water that is released downstream from the structure. Many states have strict water quality standards that apply to water releases from projects. As a result, projects authorized or constructed with little regard for water quality in the past must now be managed to meet these downstream standards.

Some water supply reservoirs are managed to provide the water required during times of low rainfall or drought. As such, they are managed so that they are at or near capacity prior to the typical dry season. Typically they experience significant drawdown during the dry season as a result of water demands and release requirements.

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<u>Navigation</u>

Many of the larger river systems across the United States are used extensively for transportation and shipping, and many require aids to navigation. Among the most important are locks and dams. In essence, these structures are used to regulate reiver stages by creating an upstream pool capable of being navigated, as well as providing a portage across the dam. During periods of low flow, they can provide temporary or sustained supplemental releases to aid in the navigation of the river downstream of the project (HQUSACE 1987).

In general, a typical lock and dam consists of a number of release or spillway gates across the face of the dam. The lock, by which ships navigate from the lower to upper pool and vice versa, is positioned within the dam at a location dependent primarily on approach navigation considerations. It consists of a gate upstream and downstream as well as a number of internal conduits to allow water in or out of the lock itself to change the water surface elevation.

Structural Characteristics

<u>Dams</u>

Dams are also classified according to their structural geometry, such as arch or buttress, or construction materials such as earth, rock, or concrete (Roberson, Cassidy, and Chaudry 1988). Some designs are better suited for certain sites because of their materials, construction costs, geometry or site topography, geology, or climate (Linsley and Franzini 1979). To accommodate all the authorized project features, many structures are a combination of two or more types of dams to take advantage of the best of all attributes.

A gravity dam is usually constructed of concrete or masonry. As the name implies, it relies primarily on the weight or mass of the structure to resist the vertical, horizontal, and uplift forces of the water. Although it is usually straight in plan, it is sometimes slightly curved (Linsley and Franzini 1979). Because of the amount of concrete involved in its construction, the concrete section is sometimes tied into earth dams on either side, thereby cutting down on materials cost.

Gravity dams are among the most common type of dam, and have been used at high-head projects (although the large forces involved significantly increase the size of the structure required). One of the largest dams of this

type, Grand Coulee Dam in Washington State, is 168 m high, 1,270 m long, and required 7,450,000 m^3 of concrete to construct (Linsley and Franzini 1979).

Arch dams are also typically constructed of concrete. They are relatively thin structures that receive their strength primarily from their shape. Generally, their construction is limited to relatively narrow canyons where the geology of the walls is able to resist the thrust of the dam (Linsley and Franzini 1979). Their arch shape transfers the horizonal forces of the water outwards to the canyon walls.

Because of their inherent strength, and the fact that they use relatively little concrete, arch dams are often used at high-head projects where conditions permit. Among the largest is Hoover Dam on the Arizona-Nevada border. It has a height of 222 m, a length of 380 m, and required 2,485,000 m^3 of concrete to construct (Linsley and Franzini 1979).

A buttress dam is basically a hollow gravity dam that is constructed of concrete, timber, or steel. These structures receive their strength from their watertight face, which spans a series of support columns or buttresses. The face may be either a slab or, for added strength, a series of small arches. The upstream face is usually sloped about 45 deg* to take advantage of the vertical force of the water to increase the ability of the dam to resist sliding and overturning (Linsley and Franzini 1979).

Earth dams, as the name implies, use compacted soils and rock in their construction. As most types of soils, even compacted ones, are permeable, dams of this nature rely on an impermeable core to control seepage. This core is typically constructed out of some highly compacted clay material or concrete. On either side of this core are compacted earthen shells of well-graded soils. These shells serve as supports to the core as well as acting as filters to prevent the washout of material (Roberson, Cassidy, and Chaudry 1988).

In general, the slopes of earth dams are fairly gentle compared to other dams and extend a good distance both upstream and downstream. This serves not only to increase the mass of the dam but also to increase the resistance to seepage through the dam.

Earth dams are perhaps the most common type of dam, especially for smaller projects, because the construction material is generally readily

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* A table of factors for converting non-SI units of measurement to SI units is presented on page 5.

available. Because of the massive nature of these dams, they are not gener-
ally used as high-head facilities although they have been used at dams as high
as 310 m, such as Nurek Dam on the Vaksh River in the USSR (Linsley and
Franzini 1979). They are also typically used in concert with gravity dams to
minimize materials and construction costs.

Spillways

Spillways provide a way to rapidly release large flows from the reser-
voir within operational constraints of the project (Roberson, Cassidy, and
Chaudry 1988). They are primarily a safety valve for the dam to prevent over-
topping from large inflows and damage or possible failure of the structure
itself (Linsley and Franzini 1979, HQUSACE 1987). They are also used to some
extent to control the water levels of the reservoir, but are typically
designed to handle large flood events that might otherwise harm the structure.

An overflow spillway is a part of the dam structure itself that is
designed to permit water to flow over the crest (Linsley and Franzini 1979).
Their shape, while not critical at small projects, is extremely important at
larger facilities. For the most efficient design, the crest and slope of the
spillway should closely approximate the underside of a nape of a sharp-crested
weir. This prevents the flows from separating from the structure and causing
cavitation damage to the face of the spillway.

Chute spillways are generally located separately from the dam structure
and are commonly used at earth dams (HQUSACE 1987). Water flows over a crest
and into a steep-sloped open channel and eventually into a stilling basin
(Linsley and Franzini 1979). Chute spillways are usually sloped relatively
gently as compared to the overflow spillway. These are generally used when a
crest spillway is impractical or when it is important to keep the spillway
away from the dam (such as an earth dam).

Side channel spillways are characterized by the flow path of the water
rather than a morphological feature. As water passes over the crest, the flow
is routed through a channel that parallels the crest. This is especially
useful in designs where the required crest length cannot be met due to space
limitations and in areas where overflow or chute spillways will not fit within
project boundaries (Linsley and Franzini 1979).

Shaft spillways utilize a vertical standing pipe in the reservoir that
extends from near the surface of the reservoir, down, and through the dam to a
stilling basin (Roberson, Cassidy and Chaudry 1988). This type spillway is
commonly used at earth dams (where standard spillways cannot be constructed on

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the embankment) or in areas where space is a concern. A common example of this type is a morning glory spillway (Linsley and Franzini 1979).

Gates

Spillway gates are used to control the water surface elevation of the reservoir above the elevation of the crest of the spillway as well as flow from the project. Thus, the potential for use of the reservoir can be maximized without sacrificing the flood protection of the dam itself (Linsley and Franzini 1979).

Vertical lift gates are constructed of timber or steel. The gates slide in vertical guide slots at the crest of the spillway between two piers (Roberson, Cassidy, and Chaudry 1988). They are limited by the high friction developed between the gate and the slot due to the hydrostatic forces on the gate. By using rollers between the two surfaces, the friction can be significantly reduced (Roberson, Cassidy, and Chaudry 1988). These gates are raised or lowered by mechanical means either manually or using a winch or hydraulic systems. They are most commonly used at small facilities.

Tainter gates, constructed of steel, are the most common type of crest gate in use at CE facilities. They are used at many larger projects, mainly because of their simplicity and ease of operation even under high hydrostatic loadings. The gates are usually raised or lowered using a winch. Friction or resistance to movement is usually reduced to the area of the trunnion pin, making the force required to lift one of these gates nearly constant at all openings (Linsley and Franzini 1979).

Drum gates are basically cylinder segments that, when the gate is opened, fit into a recess in the spillway crest (Linsley and Franzini 1979). They are usually hollow, and thus buoyant, and are generally operated hydraulically. To close the gate, water is admitted to the recess area and the gate is forced into a raised configuration (HQUSACE 1987). They can, however, also be mechanically operated.

Intake structures

While spillways are generally designed to rapidly release large volumes of water in a relatively short time, such as during flood flows, it is often necessary to make smaller, more controlled releases. Various outlet works allow the reservoir manager the ability to make more controlled and selective releases for many different purposes.

The term intake structure is usually used to describe facilities in the reservoir that allow for a controlled withdrawal of water. They can be an

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integral part of the dam or a separate structure, usually dependent on their purpose. Depending on their design, they may have a port or ports located at one elevation, or they may have multiple ports at several different elevations throughout the water column. The latter generally provides access to a range of water qualities during stratified periods and may be important for water quality management, while the former may provide for release of a greater quantity of water.

In some CE structures, multiple ports may be located in a single wet well or distributed in two wet wells. This usually allows operation of multiple ports to blend water of two different qualities to achieve a desired release quality. Some projects have intregrated multiple-port intake structures with flood control outlets to maximize flexibility in operation of the structure.

Trashracks

Trashracks serve an important function for any intake structure. They prevent debris such as large sticks and logs from being swept into the intake structure and blocking the flow of water or damaging the structure or machinery. They are typically constructed of large steel beams with smaller cross beams for bracing. On projects with large flow rates, such as in front of the turbine intakes, the trashracks usually require regular cleaning to prevent debris buildup and efficiency loss.

Sluiceways

A sluiceway is a pipe or tunnel that extends from the reservoir usually through the dam to the stilling basin or tailrace. Sluiceways provide dam operators with a means of rapidly drawing down the reservoir beyond the crest of the spillway (Roberson, Cassidy, and Chaudry 1988). Many dams have a number of these at different elevations in the reservoir. This not only allows the operators to release water down to a certain level but also provides a means of accessing and releasing water from a range of elevations for maximum water quality.

Most sluiceway and intake structures have some type of gate at their entrance or somewhere along the conduit to control the flow. These gates are similar to the vertical lift spillway gates but may have some modifications to allow for less friction and provide a tighter seal when closed.

Under heads of less that 100 ft, these gates may be used to vary the flow rate. However, at higher heads these gates typically develop cavitation problems; thus, they are used more to totally stop flow for inspections and

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maintenance of the conduits. At higher heads, specialized valves are used to regulate the flow rate due to the effects of cavitation (Linsley and Franzini 1979, HQUSACE 1987).

Ring follower gates are normally used internally to the dam structure. At lower heads (<75 ft) they can be used to control the flow rate, but at higher heads cavitation typically becomes a problem. As a result, they are usually operated either in the fully open or closed position.

The unique feature of this gate is that, when it is fully open, the discontinuities in the wall of the conduit are small, which results in better flow conditions and fewer cavitation effects, especially at high heads (>250 ft) (Linsley and Franzini 1979).

Valves

A needle valve is a high-head valve used to control flow rates. Its configuration is such that pressures within internal chambers of the valve can be regulated, which results in the valve sliding to either expand or contract the opening in the conduit. Water exiting this type of valve retains much of its energy. Tube valves are basically the same as needle valves, but are mechanically operated rather then relying on hydraulic pressure (Linsley and Franzini 1979).

A Howell-Bunger valve employs a cone and a movable sleeve to regulate high head flow. It slides up or down the pipe, thus closing or opening the conduit. An advantage to this type of valve is that it disperses the flow over a large spray area and consequently dissipates the energy (Linsley and Franzini 1979).

A butterfly valve consists of a circular gate pivoted around a shaft located in a pipe. This valve is used primarily for intermediate head flows. A common problem is its inability to seal tightly in the closed position.

Turbines

The primary function of a turbine is to convert the hydraulic energy of the water to mechanical power and ultimately electrical energy. The two basic types of turbines in use at CE projects are the Francis and propeller turbines. Each has advantages that make them suitable for certain situations.

Francis turbines utilize a scroll case to redirect water from the penstock (the penstock is the conduit that supplies water to the turbine). The scroll case has a diminishing diameter that serves to increase the water velocity. On the inside of the scroll case is a series of vanes known as wicket gates. These gates are used to adjust and redirect the flow so that it

impacts the runners of the turbine at an optimum angle and thus produces the most energy for the amount of water.

After the water impacts the runners of the turbine and turns the shaft, the water flows downward and then horizontally through the draft tube. The draft tube is a conduit with a constantly increasing cross section. This allows the water to flow away from the turbine with as little resistance as possible. The draft tube leads to the tailrace where the water is released and allowed to flow downstream. This type of turbine is used primarly on high-head projects.

Propeller turbines usually have four to eight blades on the runner that extend from the hub to very near to the conduit walls, which greatly limits flow past the runner. These turbines usually rely on adjustable gates upstream to control the flow (Linsley and Franzini 1979). The most common type of propeller turbine used at CE projects is the Kaplin turbine. This turbine does not use wicket gates but rather relies on the ability of adjusting the angle of the propeller blades to fit the flow conditions and optimize efficiency.

Bulb turbines, which also rely on propellers, are enclosed in a bulb and located within the flow in the draft tube, usually in front of the propellers. Both types of propeller turbines are used on low-head projects.

Tailrace

The tailrace of a project is that portion of channel that leads form the draft tubes of the powerhouse back to the river channel. These are typically short sections of channel (almost nonexistent on some projects) but can be long depending on the location of the powerhouse in relation to the river channel. They normally have a concrete-lined basin directly below the draft tubes to prevent erosion and provide some flow guidance. The primary purpose of a tailrace is to guide the water away from the powerhouse and into the river channel.

Stilling basins

Stilling basins are located downstream of a project's gates, sluiceways, or spillways. They are usually concrete-lined basins that lead directly back into the river channel. Their main purpose is to dissipate the energy of the incoming flow pby providing an area and conditions for a hydraulic jump to occur either through proper depth or increased resistance in the form of baffle blocks. This energy dissipation is required to prevent erosion of the river channel downstream.

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PART IV: GUIDE CURVE CHANGE

Problem Addressed

Many reservoir projects operate under some type of water control plan
that relies on seasonal change of reservoir elevations. This sequence of
reservoir elevation change is usually termed a guide (or rule) curve. Depend-
ing on the project authorization, the guide curve may permit rather large
pool-level fluctuations on an annual basis. For example, operation of a flood
control project usually involves drawing down the reservoir level during the
fall and winter and filling during the spring and early summer to a stable
pool through the summer and early fall.

In some cases where the summer pool elevation is maintained at a rela-
tively stable elevation, water quality may be a concern. Water quality con-
cerns in the reservoir which result from poor quality inflows may be averted
by pooling up later in the year. In another approach, the retention time of
the reservoir may be modified by adjusting the guide curve. Constituents of
water quality that may be affected by this technique include inflow with unde-
sirable qualities, nutrient loading of the reservoir (and, in turn, the
effects on algal growth and fisheries), turbidity, and sedimentation.

For example, inflows with a high sediment load may be delayed in the
upper reaches of a reservoir and allowed to settle out before reaching the
outlet works. Therefore, some modification of the guide curve to reduce or
increase the residence time may enhance the water quality of the reservoir.

Theory

Modification of the guide curve is a technique that relies on changing
the hydraulic residence time of inflows in the pool to control poor quality
inflows. This can be accomplished by maintaining a small pool through most of
the flood control season and allowing undesirable inflows entering the reser-
voir to be flushed through. The reservoir is then allowed to fill to summer
pool elevation later in the season, when the inflow water quality is typically
better. If inflow quality is governed more by discharge than season, main-
taining a larger pool with a greater retention time may allow suspended
material to settle in the headwaters, and thereby improve the quality of the
main portion of the reservoir.

Another variation of this technique relies on changing the minimum pool elevation of the reservoir and allowing additional storage for water quality maintanence or conservation of a quality resource, such as cool water for downstream release. Adjusting the guide curve may also have a significant benefit to the wildlife of the reservoir by creating additional habitat at critical times or controlling aquatic plant growth. An example of a modification of a guide curve is shown in Figure 2.
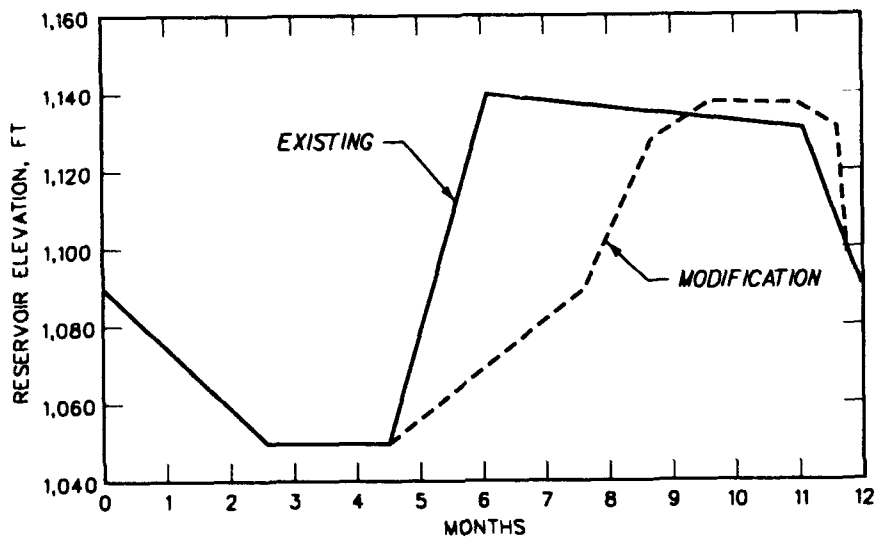
Figure 2. Example of guide curve modification

Evaluation Methodology

The implementation of a proposed change to the water control plan or guide curve should occur only after the water quality objectives of a proposed change are stated. This will involve identification of existing water quality parameters of concern and the desired goals. Since no general procedure for the evaluation of a proposed change in the water control plan for a reservoir project has been published, a method for evaluating a guide curve change is given below.

The specific objective of the guide curve change must be determined, such as reduced turbidity in the reservoir. This will involve determination of existing water quality parameter concentrations, such as turbidity levels, in the reservoir relative to the existing guide curve.

Next, the flexibility for change of the guide curve or the upper and lower limits of the curve must be examined to determine the amount of change available. This must be considered within the context of the authorized project purposes.

The impacts of the proposed change of the guide curve on the water quality objective must then be determined. This may require a variety of assessment techniques ranging from simple computations of hydraulic residence time to two-dimensional numerical models. The level of computational sophistication required is predicated on the water quality objective and degree of change of the guide curve. Relatively small changes in the guide curve, which may have minimal impacts on the water quality objective or other project purpose, may be evaluated with residence time and stability computations. Large changes, which may expand the size and volume of the pool, may require a numerical model investigation to evaluate the impacts of the change.

The impacts of the proposed change on the release water quality must be evaluated. If a significant change in the guide curve is proposed, impacts to the release water quality may be possible. For example, increased residence time to allow settling of suspended solids may enhance thermal stratification and subsequent depletion of oxygen in the hypolimnion. Withdrawing water from the lower elevations of the reservoir could result in poor downstream water quality and possibly offset any benefits achieved by the guide curve change. The delay in reservoir filling may also affect other areas. These include recreation and access to fishing and swimming areas, as well as docks and marinas; possible erosion of the exposed lake bottom due to wave action and the lack of a stabilizing plant cover; the aesthetics of the exposed shoreline; management of aquatic plants; impacts on fish and wildlife habitat; and effects on access to wetlands and spawning areas.

Applications of Guide Curve Changes

Applications of guide curve changes or modifications to guide curves have not been widely reported in the literature. However, the control of hydraulic residence time has been reported from laboratory studies to be a feasible technique in certain instances to enhance reservoir water quality (Schiebe and Dendy 1978). In addition, this technique is a recognized method to enhance water quality at CE projects (HQUSACE 1987b).

A general evaluation technique for water quality forecasting for short-
and long-term impacts of a guide curve modification may be found in "Manage-
ment of Water Control Systems" (HQUSACE 1987a). This technique relies on the
expertise of the water control manager in deciding on which approach to take
with a particular guide curve modification. The use of computer models to
simulate short- and long-term impacts is recommended.

A number of techniques that use numerical models have been developed to
evaluate guide curves for water quantity or volume perspectives (Newman and
Loucks 1975). Recent investigations have added water quality objectives to
the development of guide curves (Hogan 1986). This technique has combined
numerical optimization methods with a numerical model that simulates the
physical processes in the reservoir to optimize the real-time operation of a
reservoir.

This technique has been used to improve water quality during the initial
filling sequence of new reservoirs. Many new reservoirs, especially large
ones, are filled in stages over a number of years to minimize the inundation
of new sediment and the oxygen demand of this material. Van Pagee et al.
(1982) identified a delayed filling period as one alternative to minimize the
impacts of filling of a new rese voir in the tropics region in Suriname. A
similar technique is discussed in Engineer Manual 1110-2-1201 (HQUSACE 1987b).

Summary

The modification of guide or rule curves to water storage in reservoirs
can be used as an operational technique to enhance water quality. By modify-
ing the hydraulic residence time of the reservoir, undesirable inflows can be
routed through the reservoir or retained to allow sedimentation to occur.

An evaluation technique for this water quality enhancement technique was
presented. Although few examples of guide curve changes have been published,
some referenced examples indicate positive benefits to this technique.
Table 1 summarizes the guide curve change technique.

Table 1

Summary of Guide Curve Change

Characteristic	Description
Targets	Nutrient and sediment loading, turbidity, and poor water quality inflows.
Mode of action	Adjust scheduled reservoir pool-up to change residence time and minimize the effects of poor water quality inflows.
Effectiveness	Highly effective on small- to medium-sized reservoirs.
Logevity	Seasonal.
Negative features	Possible loss of fish and wildlife habitat and/or access to wetlands or spawning areas.
	Access to recreation areas limited.
	Aesthetics, shoreline erosion, and aquatic weed control affected.
	Risk as to being able to fill the reservoir to summer levels in the season.
Costs	Minimal.
Applicability to reservoirs	Applicable to small- to medium-sized reservoirs or reservoirs or reservoirs where volume change will significantly affect the residence time.

References

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Hogan, K. B. 1986. "Development of Reservoir Operating Rules with Water Quality Objectives," Ph.D. dissertation, Johns Hopkins University, Baltimore, MD.

Newman, B. A., and Loucks, D. P. 1975. "Derivation and Evaluation of Reservoir Rule Curves," Report No. W76-04014, Office of Water Research and Technology, Washington, DC.

Schiebe, F. R., and Dendy, F. E. 1978. "Control of Water Residence Time in Small Reservoirs," _Transactions of the American Society of Agricultural Engineers_, Vol 21, No. 4, pp 666-670.

Van Pagee, J. A., Groot, S., Klomp, R., and Verhagen, J. H. G. 1982. "Some Ecological Consequences of a Projected Deep Reservoir in the Kabalebo River in Suriname," _Hydrobiological Bulletin_, Vol 16, No. 2-3, pp 241-254.

PART V: INFLOW ROUTING

Problem Addressed

Inflows to reservoirs can create problems with reservoir water quality.
If the inflow quality is poor, containing high concentrations of nutrients,
suspended solids, or other undesirable constituents, poor reservoir water
quality may result. Depending on the volume of the inflow and the retention
time of the reservoir, the inflow constituents may settle and be trapped in
the reservoir. This could contribute to eutrophication processes as well as
filling of the reservoir with sediment. If inflow quality is identified as a
concern, it may be possible to route the inflow through the reservoir for
release downstream, without significantly impacting the quality of the
reservoir, or hold the inflow in the project for treatment while releasing
nonaffected stored water downstream.

Theory

Routing of inflows is a technique based on the water control operation
or plan for the reservoir. Undesirable inflows are identified and routed
through the reservoir to minimize impacts to the existing reservoir water
quality, similar to routing of flood flows through a basin. Upon identifica-
tion of an undesirable inflow, the route the inflow will take in the reservoir
as well as the volume of the inflow must be predicted.   This can be accom-
plished through a combination of upstream flow gauging and density flow calcu-
lations similar to the techniques derived by Akiyama and Stefan (1985).

Since the inflow will seek its layer of neutral density in a density-
stratified reservoir, a density current will develop and proceed through the
reservoir on the surface or at some elevation, depending on the stratifica-
tion. Using the existing release structure and operation within the existing
water control plan, the project is operated to move the undesirable water
through the pool as quickly as possible (Figure 3).

Selective withdrawal capability greatly enhances this technique if the
inflow occurs at some intermediate depth. However, depending on the equilib-
rium elevation of the inflow, it may be possible to use other outlet works
(i.e., spillways or sluiceways) to release the inflow. Because no structural

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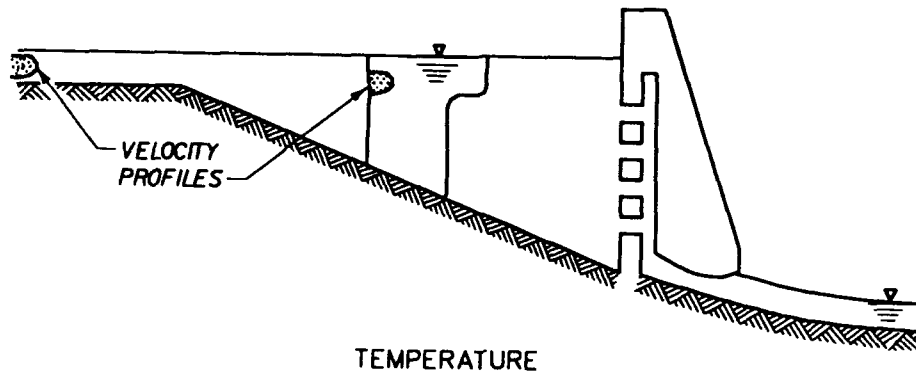
Figure 3. Routing of undesirable inflows

modification or addition is involved in this technique, costs are associated
only with evaluation and change of operation.

Evaluation Methodology

The methodology for this technique involves definition of the goals to
be achieved relative to the reservoir water quality. This will usually
involve determination of the reservoir water quality that exists prior to some
inflow event, predicted quality of the inflow, and its impacts on the reser-
voir. A general procedure for routing of undesirable inflows is given below.

The specific water quality of the reservoir and inflow as well as the
resulting reservoir quality must be determined or predicted. This will
usually involve inflow temperature, turbidity, suspended solids, nutrients or
other constituents, and corresponding concentrations in the reservoir.

Using the data collected, as well as a knowledge of the flow patterns
through the reservoir, the location and elevation of the inflow in the pool
must be predicted. Akiyama and Stefan (1985) derive the equations necessary
to predict the routing of turbidity currents (a form of density current)
through a reservoir. It amy be possible to incorporate these equations into a
numerical model to help the reservoir manager make accurate, real-time predic-
tions of the flow events. However, mixing of the inflow with reservoir water,

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as well as dispersion in the reservoir, may be difficult to predict, even with a numerical model.

Using the predicted location of the undesirable inflow in the reservoir, the water control plan should be evaluated to determine appropriate operations to minimize impacts to the reservoir. This may involve varying the release flow rate or changing the selective withdrawal port elevation to withdraw the inflowing water from a specific elevation more efficently. Since retention of the undesirable inflow in the pool is detrimental to the water quality of the reservoir, release of these flows should be maximized.

Applications of Inflow Routing

Although application of this technique may be standard procedure for most water quality managers, published accounts of inflow routing are limited.

Nix (1981) reported that the advective transport of organic matter resulting from an inflow event contributed to the oxygen demand of a reservoir metalimnion during the stratified periods. He indicated that residence time of this organic matter could be minimized by increasing the discharge rate of the project through the stratification season.

Iwasa and Matsuo (1981) discussed the problem of turbid inflows and the impacts to the reservoir water quality. When the reservoir lacks thermal stratification, turbid inflows mix the entire reservoir and create a linear turbidity profile from surface to the bottom. When thermal stratification is present, the turbid inflow remains near the thermocline and does not easily settle into the hypolimnion. The authors indicated that mathematical modeling techniques could be used to control reservoir turbidity by withdrawing the turbid layer.

In some reservoir systems, inflows occurring in the absence of thermal stratification may be routed through the reservoir without mixing the entire reservoir. Although published accounts of this phenonmenon are unavailable, this has been reported through personal communications.*

Murota and Michioku (1986) described a selective withdrawal technique for reservoirs that have a three-layer stratification. Their discussion also indicated the usefulness of removing layers in the reservoir that are highly turbid and may contribute to sedimentation in the reservoir.

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* Pete Juhle, Headquarters, US Army Corps of Engineers, Washington, DC.

Summary

Inflows to reservoirs can create problems with water quality if they contain significant concentrations of suspended solids, turbidity, or other undesirable constituents. One method to control these undesirable constituents is to route them quickly through the reservoir, minimizing the impacts on the reservoir water quality.

A simple concept is presented to evaluate the effectiveness of routing of inflows for water quality purposes. Although few references are available for this technique, the approach may be useful for some projects. A summary of information concerning this technique is presented in Table 2.

Table 2

Summary of Inflows Routing

Characteristic	Description
Targets	Inflows with undesirable water quality consitutents.
Mode of action	Selective withdrawal of the inflow.
Effectiveness	Dependent on lake size, distance of inflow to outlet works, and strength of density difference between inflow and reservoir.
Longevity	Days to months.
Negative features	Technique less effective without selective withdrawal structure.
	Requires density difference between the inflow and the reservoir (the greater the better).
	May pass the quality problem on to a lower reservoir.
Costs	Minimal to none (operating changes and perhaps lost hydropower generation revenue).
Applicability to reservoirs	Works best with reservoirs with selective withdrawal; however, the use of other outlet works is possible.

References

Akiyama, J., and Stefan, H. 1985. "Turbidity Current with Erosion and Deposition," _Journal of Hydraulic Engineering._ Vol III, No. 12, pp 1473-1496.

Nix, J. 1981. "Contribution of Hypolimnetic Water on Metalimnetic Dissolved Oxygen Minima in a Reservoir," Water Resources Research. Vol. 17, No. 2. pp. 329-332.

Iwasa, Y. and Matsuo, N. 1981. "Estimation of Turbidity in Reservoirs," Proceedings of International Association for Hydraulic Research. New Delhi, India.

Murota, A. and Michioku, K. 1986. "Analysis on Selective Withdrawal from Three-Layered Stratified Systems and Its Practical Application," Journal of Hydroscience and Hydraulic Engineering. Vol. 4(1). pp. 31-50.

PART VI: SUPPLEMENTAL RELEASES FOR WATER QUALITY

Problem Addressed

Many CE hydropower projects incorporate several types of release struc-
tures, usually each with a specific purpose. For example, projects authorized
for flood control, hydropower, and navigation will have release structures for
each purpose. In most cases, water control plans do not call for simultaneous
operation of the various release structures during the stratification season.
For example, flood control and hydropower releases will not generally be made
at the same time. Therefore, it may be possible to simultaneously operate two
or more release structures and in effect create a selective withdrawal config-
uration, provided the intake center-line elevations for the various structures
are not the same.

Thus, selective withdrawal techniques, described elsewhere in this
report, may be used to enhance reservoir as well as release water quality.
This can be achieved by reducing the stability of stratification through hypo-
limnetic withdrawal, enhancing mixing conditions in the reservoir, withdrawing
undesirable water, or diluting an otherwise poor-quality release flow.

Theory

This method relies on selective withdrawal techniques to modify the
water quality of the reservoir or its release. It relies on evaluating all of
the release structures at a given project and determining whether it is possi-
ble to meet the water quality goals by operating a combination of structures
even though they may not be intended for this purpose. This is similar to
operating a project that contains a selective withdrawal structure.

For example, during the stratification season, release structures that
withdraw hypolimnetic water may degrade reservoir releases because of signifi-
cant concentrations of iron, manganese, and hydrogen sulfide. An operational
technique that may be used to enhance the release quality is to release water
from the epilimnion through a spillway gate (selective withdrawal), or if the
elevation of the flood control intake is the same as that for hydropower, to
release through a flood control gate to increase reaeration through the flood
control outlet and stilling basin (Figure 4). Therefore, for this example,
this technique relies on selective withdrawal techniques to withdraw water of

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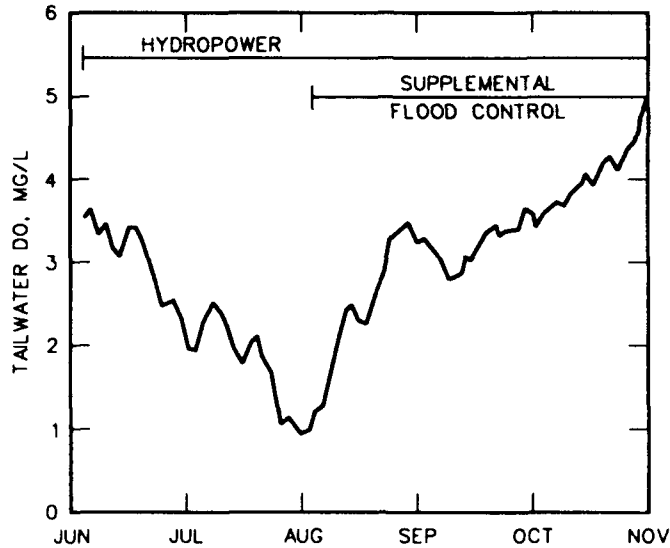
Figure 4.   Example of improved dissolved oxygen
with supplemental releases

a improved quality, or on increased air entrainment for reaeration after being withdrawn.

Evaluation Methodology

This operational technique has been used at a number of CE projects to enhance the release quality during the stratification season. However, the evaluation of the technique has been based on tests in the field. A general procedure for evaluating this technique for the potential to improve reservoir or release water quality is given below.

Identify the specific water quality concern and objectives. For example, the water quality parameter, such as dissolved oxygen (DO), must be quantified in the reservoir and the release. The existing release characteristics must be determined, including discharge volume and withdrawal characteristics in the pool.

Determine the various release options for a given project. This will involve consideration of the project authorization to ensure compliance with authorized purposes. It may also involve examination of release options that typically are not made, such as low-flow (minimum) releases from a flood control gate. The improvement of release quality with a modification of the release schedule to include releases from this optional structure must then be

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evaluated. In the case of selective withdrawal, the SELECT model (Davis et al. 1987) can be used to predict release quality for most high-head release structure options. If reaeration through the structure is a desired outcome, computational methods to predict the amount of reaeration through a gated conduit, which have been developed by Wilhelms and Smith (1981), may be used.

Once the release options have been identified, determine the volume of water required to achieve the stated water quality goal. In most cases, this can be determined using a mass balance approach, where the existing release quantity is diluted with the water quality release.

This procedure has been implemented in a real time frame at several hydropower projects, using a downstream monitoring scheme to identify the need for water quality releases. Once the monitoring scheme identifies the need, the water quality release is made.

Review of Applications

This technique h? ∋en applied at several CE projects to improve downstream DO, usua'l' ⅈn conjunction with a hydropower operation. However, it can be used witn any project in which the water quality concern is a result of stratifica⁺ion in the reservoir, such as release temperature or pH.

At Ti.ns Ford Project, a multipurpose hydropower project operated by the Tennessee Valley Authority (TVA), the need to establish a minimum release from the project during nongeneration periods to maintain the downstream fisheries resource was identified (Goranflo and Adams 1987). The study indicated that 80 cfs should be released. Alternatives that were evaluated included an option to sluice water through the flood control structure. This would provide the required flow and increase the release DO oxygen without requiring a structural modification to the project. A similar evaluation was conducted at the Norris Project with similar conclusions.

Walter F. George Lock and Dam on the Chattahoochee River near Fort Gaines, GA, has experienced problems with low DO in the tailwaters during nongeneration periods in the late summer and early fall. An operational technique that relies on downstream monitoring to identify the onset of low DO conditions is used to enhance the downstream water quality. With the identification of low DO conditions downstream, spillway gates are opened in an ordered manner until downstream DO levels stabilize (Findley and Day 1986). A similar operation that relies on downstream monitoring to identify the need

for flood control gate releases has been implemented at Lake Texoma (Price 1990).

Table Rock Dam, located on the White River in Missouri, experiences difficulty meeting DO criteria in the release during the stratification season. Among the alternatives investigated to correct this situation was the use of supplemental releases from the hypolimnion through Howell-Bunger valves. This release would be aerated by the aspiration process associated with these types of valves. The costs associated with loss of generation capacity due to the releases was significantly greater than other alternatives for this project (US Army Engineer District, Little Rock 1985).

Summary

A technique that may enhance water quality in either the reservoir or downstream is modification of the operation of the various release structures at a project. This involves identification of water quality concerns and enhancement objectives, followed by evaluation of optional release capabilities through numerical procedures and determination of desired release volumes.

Several example applications of this technique at TVA and CE projects (with references) were discussed. Table 3 summarizes this technique.

Table 3

Summary of Supplemental Releases For Water Quality

Characteristics	Description
Targets	Water quality constituents such as dissolved oxygen (along with related concerns), turbidity, temperature, etc.
Mode of action	USe of release structures, regardless of original purpose, to improve water quality in the reservoir and downstream releases.
Effectiveness	Dependent upon location and elevation of intake of release structures.
Longevity	Days to months.
Negative features	Additional releases of water.
Costs	Minimal (lost hydropower revenue).
Applicability to reservoirs	Very applicable to projects with multiple release structures.

References

Davis, J. E., Holland, J. P., Schneider, M. L., and Wilhelms, S. C. 1987. "SELECT: A Numerical, One-Dimensional Model for Selective Withdrawal," Instruction Report E-87-2, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Findley, D. I., and Day, K. 1987 (Jul). "Dissolved Oxygen Studies Below Walter F. George Dam," Proceedings: CE Workshop on Reservoir Releases, Miscellaneous Paper E-87-3, US Army Engineer Waterways Experiment Station, Vicksburg, MS, pp 71-76.

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Wilhelms, S. C., and Smith, D. R. 1981. "Reaeration Through Gated-Conduit Outlet Works," Technical Report E-81-5, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

PART VII: CONCENTRATION OF FLOW THROUGH ONE GATE

Problem Addressed

Lock and dam structures, which are designed primarily for navigation, maintain a pool for upstream navigation as well as regulating flow for downstream navigation. During the summer and early fall, typically the low-water period, flows from these structures may be minimal. These low flows may allow some thermal or chemical stratification to occur in the upstream pool, somewhat similar to a storage reservoir. This condition may prevent reaeration of bottom water, which upon release may impact downstream water quality.

Operation of a typical lock and dam calls for operation of all gates in a similar manner. For example, all gates would be set at the same gate opening to distribute the flow evenly across the stilling basin. As the flow curtails during the low-water period, gates are lowered simultaneously. To facilitate reaeration downstream, gate operations could be modified to permit closing most gates and concentrating flow through a minimum number of gates.

As an example, a structure consisting of six gates, with a flow condition calling for all gates to be open 0.5 ft, could possibly be modified to allow a single gate to be open 3.0 ft, with the remaining gates closed, to achieve the same discharge. This concentrates the flow through fewer gates and increases turbulence and reaeration downstream.

Theory

The operation of water control structures with multiple horizontal gates, such as a lock and dam structure, usually requires that all gates be operated the same for a given release condition, to achieve as even a flow distribuiton downstream as possible. The reasons for this type of operation are usually a result of concern for preventing scour and erosion to the stilling basin and downstream, or to provide the best flow conditions for ship movement. While hydraulic conditions may require this operation during higher flow events to minimize scour and erosion downstream, low-flow conditions may not require this type of operation.

Also, during these low-flow periods, the dissolved oxygen may be low due to reservoir type conditions in the upstream pool. Therefore, a modification of the gate operation during low-flow periods to increase the unit discharge

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may be used to enhance the DO by concentrating the flow, which normally would pass through all gates to pass through a minimum number of gates (a few or perhaps only one) (Figure 5). This would increase turbulence in the stilling basin and enhance reaeration.
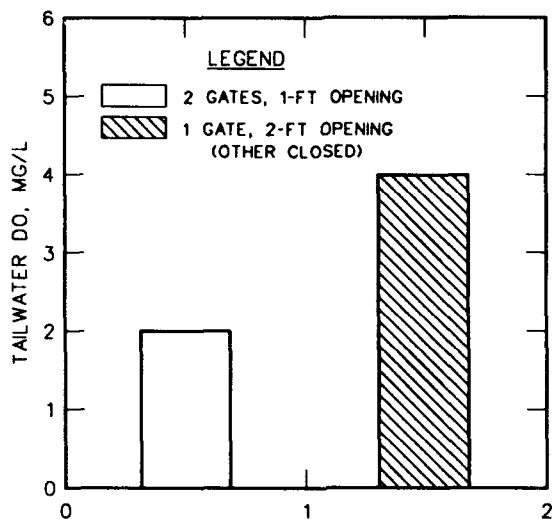
Figure 5. Example of effect of flow concentration through a single gate

Evaluation Methodology

This technique can be used to evaluate modifications of gate operation at any structure where multiple gates extend horizontally across a dam. Although this technique has been used at some lock and dams on the Ohio River (Price 1990), it has not been widely used to enhance spillway releases at navigation structures. A general evaluation method for this technique is given below.

The specific objectives of this technique are to increase the dissolved oxygen downstream of a spillway gate. Therefore, water temperature and DO concentration upstream and downstream of the project must be known. If the upstream DO is at or near saturation, little will be gained by implementation of this technique.

The specific structural and operational characteristics of the structure must then be determined. This includes the unit discharge and gate sill elevation as well as the upstream and downstream water surface elevations.

The reaeration that is occurring with the existing gate operation must be computed. A relationship for some types of lock and dams was developed by

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Wilhelms (1988) and may be used to compute the reaeration that occurs with those types of structures. Caution is advised in that some research suggests that as the unit discharge increases, a decrease in reaeration may occur (Thene, Daniil, and Stefan 1989).

Since the computational methods require caution in application, verification of the results is necessary. This requires field tests at the specific structure. Using the experimental method developed by Wilhelms (1988) at several lock and dams on the Ouachita River in Louisiana, the computations can be verified. This will involve monitoring the release DO with various gate settings during the time when the dissolved oxygen deficit is exerted.

If the evaluation indicates an improvement in downstream DO with this technique, evaluation of hydraulic concerns should be addressed prior to complete implementation. Since most stilling basins and energy dissipators were designed for equal gate operations, unequal gate operation may create scour or erosion problems downstream. The operating limits for this technique must be determined.

Applications of Flow Concentration

The only known use of this technique is on the Ohio River. Several of the lock and dams are operated to maximize the unit discharge through a few gates to increase DO downstream (Price 1990). Field investigations at Montgomery Lock and Dam on the Ohio River indicated that a 2-ft gate opening on one gate achieved 1.5 times the DO downstream as two gates open 1 ft (US Army Engineer District, Pittsburgh 1975).

Summary

Concentration of flow is a technique that can be used to improve the DO level in flow releases from navigation facilities. While it could be used at almost any facility that operates a number of gates across the face of the structure, it is especially useful at lock and dam projects. The method relies on increasing the turbulence (and thus the aeration) of the flow through and downstream of the structure. This can be accomplished by concentrating the release flow through a minimum number of gates.

Although reported applications of this technique are limited, it holds much potential for increased flow aeration with little or no structural modification. Information concerning this technique is summarized in Table 4.

Table 4

Summary of Concentration of Flow Through One Gate

Characteristics	Description
Targets	Low dissolved oxygen levels (and associated concerns).
Mode of action	Reaeration of flow through increased turbulence as a result of concentrating the flow through a minimum number of release gates.
Effectiveness	Moderate.
Negative features	Possible increased scour and erosion of stilling basin and downstream.
	Change in the flow conditions and patterns for ship traffic.
Costs	Minimal.
Applicability to reservoirs	Most applicable to lock and dam projects but can be used at other projects where the flow is usually spread out over multiple outlets.

References

Price, R. E. 1990. "Water Quality Enhancement Techniques Used Within the Corps of Engineers," Technical Report E-90-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

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US Army Engineer District, Pittsburgh. 1975 (Jun). "An Evaluation of the Effects of Mainstem Navigation Dams on the Water Quality of the Upper Ohio River," US Army Engineer District, Pittsburgh, Pittsburgh, PA.

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PART VIII: RELEASE STRATEGY OPTIMIZATION

Problem Addressed

Reservoirs are authorized for many purposes, most commonly flood control, hydropower, navigation, recreation, and water quality. These various authorizations may rely on a specific storage volume to meet the multipurpose authorization. Water quality concerns can arise when two or more of these purposes require releases from the reservoir. For example, during the stratified period, releases from the hypolimnion may be made through a hydropower project. However, the anoxic nature of this water may adversely impact the water quality of the river downstream. Optimization techniques may be used to evaluate various withdrawal schemes to operate the project for the optimum water quality downstream and still meet authorized purposes.

Another example concerns the limitation of resources relative to water quality goals. In the case of release temperature, in which the downstream temperature objective is for a cool-water fishery, optimization techniques could be used to minimize deviations from an objective over a long-term period rather than operating simply on a day-by-day basis.

Theory

This technique relies on numerical modeling techniques to predict the release water quality under a variety of operational scenarios. Using an existing selective withdrawal or release structure configuration, and a release water quality objective stated in terms of a numerical function over time, a numerical model is used to predict in-reservoir and release quality over time. From this, a measure of achieving the release objective for each scenario can be computed.

The various release scenarios are simulated iteratively and systematically using optimization techniques to compute deviations from the present water quality over time to arrive at the scenario with the lowest objective. This, in turn, provides the optimum release quality for the simulation period (Figure 6).
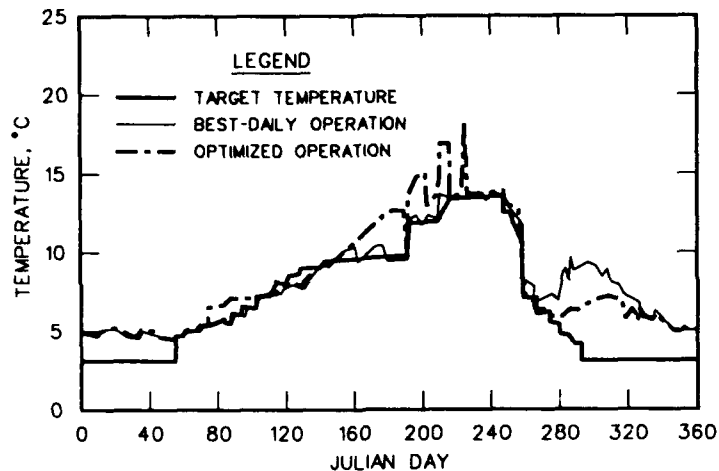
Figure 6. Example of improved release temperature
with optimization technique

Evaluation Methodology

Optimization techniques have been used in a variety of modeling applica-
tions, particularly in water supply investigations and design and operation of
selective withdrawal structures. Although the techniques can become compli-
cated because of the number of water quality objectives, the general approach
remains the same as for a one-parameter optimization process.

This approach for the optimization technique is outlined below.

a. Identify release water quality concern(s). This must be definable
in scaler terms, such that an objective function can be formulated
for use in a numerical model. For example, if the objective is to
increase the release temperature during the fall period, the temper-
ture objective must be defined in specific increments over time.

b. Identify release operational concerns. This will include the number
of ports, their center-line elevations, heights, widths, and minimum
and maximum discharges. If the reservoir is operated under a guide
curve, this must also be considered prior to optimization.

c. Select a numerical procedure (coupling simulation and optimization)
for simulation of the impacts of the operational scenarios on
temporal water quality. Although the optimization process could be
implemented by hand, using a numerical model for simulation of
operational scenarios, it is most often implemented as a part of the
numerical model, thereby allowing a computer routine to select the
optimum scenario based on the water quality objectives specified. A
detailed description of an optimization algorithm and its associated
parameters is given in Poore and Loftis (1983), and application is
given in Dortch and Holland (1984). The numerical model selected
should accurately simulate the parameter(s) specified in the release

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water quality objective(s). The model must be adjusted and verified to ensure that predictions are accurate.

d. Conduct optimization simulations, using all viable operational scenarios to identify the optimum operation. Since meteorological conditions will play an important role in the reservoir water quality, extreme as well as average meteorological conditions should also be simulated.

This general procedure can be used to develop operational procedures as well as used in a real-time operational mode.

Applications of Optimization Techniques

The most extensive use of optimization techniques for water quality enhancement has been in the area of selective withdrawal structure design. Numerous investigations using this technique have proven effective for these purposes, particularly for an increase in reservoir storage for water supply (Holland 1982, Schneider and Price 1988, Price and Holland 1989).

Wilhelms and Schneider (1986) describe an optimization technique using a one-dimensional thermal model to operate a project to minimize temperature deviations over a long period of time. This investigation assumed that small deviations over a long period of time were more acceptable than large deviations over a short period of time (Figure 6).

Kaplan (1974) used a water quality index composed of several parameters linked to a reservoir water quality model to optimize reservoir releases for both downstream and in-lake water quality. His research concluded that the technique could be used to operate a reservoir to meet both flood control and water quality objectives with a selective withdrawal structure.

Others have extended the optimization technique to assist in operation of multireservoir systems. Fontane and Labadie (1982) developed a methodology for optimizing water storage strategies in the West. This approach used an optimization simulation model to locate water supply reservoirs while considering constraints such as water quality, flood control, and minimum flow needs.

Fontaine, Labadie, and Loftis (1982) developed an objective-space dynamic programming tool to determine the optimum reservoir operational for long-term operation. This tool involved minimizing or maximizing the deviation between some in-reservoir or release water quality and a predetermined water quality criteria.

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Howington (1989) used this technique to develop an operational strategy for the Lost Creek intake structure. In this investigation, the objective was to minimize the deviation between the release water temperature and downstream temperature target.

Bonazountas and Camboulives (1981) investigated the use of optimization in operating a series of reservoirs with flood control and water quality constraints. Their investigation used three objective functions and involved a complicated hierarchical optimization process to arrive at operating conditions.

Willey, Smith, and Duke (1985) developed a reservoir system analysis model to simulate water quality within a large reservoir system. This model, which can simulate up to 10 reservoirs with eight water quality parameters, uses a linear programming algorithm to determine operating conditions for a system of reservoirs with user-specified control points. It has been applied to the Sacramento River system, which has five reservoirs.

Summary

Operation of multipurpose reservoirs may lead to difficulties when authorized purposes conflict, such as hydropower and release quality. Optimization techniques may be used to minimize the deviations from project objectives where project purposes may conflict. This technique requires the coupling of a numerical model with mathematical optimization techniques to conduct simulations of reservoir operations on release.

Applications of this technique are found primarily in the operation of multilevel outlet structures. Several examples of applications to reservoir projects were presented. Table 5 presents a summary of information on this technique.

Table 5

Summary of Release Strategy Optimization

Characteristic	Descriptions
Targets	Water quality of the reservoir as well as downstream releases.
Mode of action	Numberical modeling of reservoir operations to optimize the quantity and or quality of reservoir releases.
Effectiveness	Dependent on reservoir storage capacity and objectives.
Longevity	Seasonal.
Negative features	Conflicting release requirements may reduce some operations in order to benefit others.
Costs	Minimal.

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PART IX: HYPOLIMNETIC WITHDRAWAL

Problem Addressed

In many reservoirs and lakes, thermal stratification during summer iso-
lates the hypolimnion from the surface layers. The oxygen demand associated
with decomposition of organics in the hypolimnion usually results in the
development of anoxic conditions. This anoxic condition allows phosphorus
from internal sinks to be released to the hypolimnion and ultimately contrib-
utes to the eutrophication of the lake. Selective evacuation of the hypolim-
nion, termed hypolimnetic withdrawal, can be used to remove excess phosphorus
concentrations from the lake and reduce the rate of eutrophication (Figure 7).

NUTRIENTS   DO   TEMPERATURE
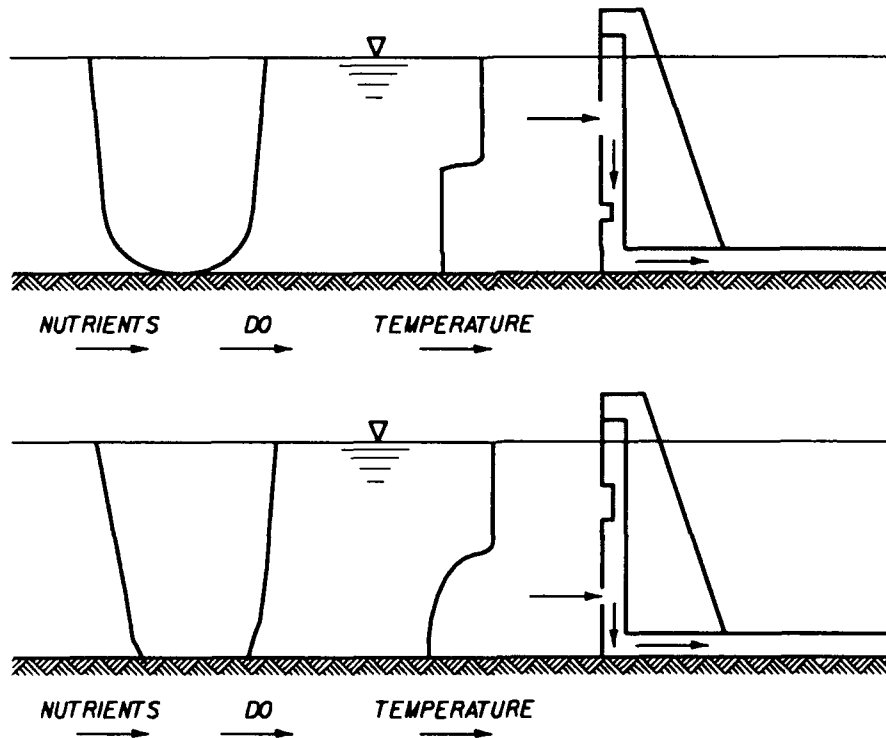
NUTRIENTS   DO   TEMPERATURE

Figure 7. Nutrient reduction through hypolimnetic withdrawal

Theory

Hypolimnetic withdrawal is a form of selective withdrawal that involves
the release of water from the hypolimnion during stratified periods to reduce
the internal phosphorus load to the lake. Epilimnetic water, which maintains

adequate concentrations of dissolved oxygen, is retained in the lake. According to Nurnberg (1987), the major objective is the reduction of anoxic conditions in the hypolimnion which, in turn, will limit the release of phosphorus from the sediments and reduce the cycling of nutrients to the epilimnion. This can be accomplished by changing the location of the withdrawal from the epilimnion to the hypolimnion. On an annual basis, the volume of water released remains unchanged but the thermal stability will probably be reduced (depending upon the lake's mophology).

This would not necessarily lead to destratification in the traditional sense, since it involves only removing the hypolimnetic water and not mixing it with the epilimnetic waters. Tradizional destratification would enhance nutrient transport frcm the hypolimnion to the epilimnion and accelerate eutrophication. A possible consequence of this tehcnique is the release of poor-quality (low dissolved oxygen and high dissolved soldis) hypolimnetic water downstream.

Evaluation Methodology

General design guidance was given by Nurnberg (1987) for hypolimnetic withdrawal in lakes. The design approach given below is that of Nurnberg with additional criteria for CE reservoirs.

The design of a hypolimnetic withdrawal system should begin with a clear definition of the existing stratification structure and nutrient budget of the lake. The analysis of the thermal structure requires temperature and DO profiles during the stratified period. These should be at sufficient intervals to describe the stratification process, the development of anoxic conditions in the hypolimnion, and the subsequent breakup of stratification in the fall. Concurrent nutrient profile data are also required to determine the contribution of nutrients from the hypolimnion.

The analysis should continue by determining the impact of release of a portion of the hypolimnion on the nutrient budget as compared with the existing release scenario. A number of numerical techniques and simulation models are available which may assist in this process. If this results in a positive impact by indicating a reduction of nutrient concentiation in the epilimnion without significantly impacting the total lake volume, analysis of thermal stability can proceed. If no significant impact is predicted by hypolimnetic withdrawal, further analysis is not recommended.

If the above procedure indicates a positive impact to the lake, the evaluation process should proceed. Since the thermal stratification pattern in the reservoir will control the vertical limits of withdrawal, the numerical model SELECT (Davis et al. 1987) should be used to simulate the withdrawal limits with various proposed methods of hypolimnetic withdrawal.

If a bottom port exists in the release structure, the model can be used to determine the maximum flow rate possible under a given stratification to minimize the release of eplimnetic water. This analysis should be conducted over the entire stratification season and may require the use of a one- or two-dimensional water quality model. If a new port is proposed, the elevation as well as the flow rate can be determined.

Review of Applications

This technique has been used on a number of lakes that are relatively small, with the largest being 78,570 acre-ft (97 million cubic meters) (Nurnberg, Hartley, and Davis 1987). Although some of the smaller CE reservoirs may be suited for this technique, application has not been attempted. Analysis of the results of hypolimnetic withdrawal at a number of lakes indicated that hypolimnetic withdrawal is an effective technique for the reduction of nutrients in the epilimnion; however, impacts on anoxia in the hypolimnion are inconclusive. A summary of hypolimnetic withdrawal projects with relevant hydrologic and morphometric information is given in Nurnberg (1987).

Summary

Hypolimnetic withdrawal is an application of selective withdrawal designed to remove anoxic hypolimnetic water from a reservoir. This technique is based on the stratification of the reservoir and the anoxic conditions that result in the hypolimnion. The anoxic conditions allow nutrients to be released into the epilimnion, contributing to eutrophic conditions. By releasing hypolimnetic water instead of epilimnetic water, a reduction in the internal nutrient cycling can be achieved.

An approach for evaluation of this technique was presented. Pertinent information is summarized in Table 6. Although applications of this technique to CE reservoirs have not been made, the technique may be applicable to smaller CE reservoirs.

Table 6

Summary of Hypolimnetic Withdrawal

Characteristic	Description
Targets	Reservoir nutrient cycling and anoxic conditions (and associated concerns) in the hypolimnion.
Mode of action	Removal of hypolimnetic waters through bottom withdrawal.
Effectiveness	Effective on small lakes with strong stratification, dependent on lake volume.
Longevity	Seasonal.
Negative features	Removal of hypolimnetic zone will reduce or eliminate habitat for cold-water fisheries. Downstream release water will typically be of poor quality.
Costs	Minimal.
Applicability to reservoirs	Applicable to reservoirs with withdrawal facilities whose intakes are located in the hypolimnetic region of the reservoir.

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PART X: PNEUMATIC DESTRATIFICATION

Problem Addressed

The thermal stratification that develops in most reservoirs during the summer months can isolate the hypolimnion from the epilimnion and block the transfer of oxygen from the surface to the bottom waters. This can result in anoxic conditions in the lower reaches of the reservoir, which can expand as biological and chemical activity continues to deplete the dissolved oxygen. Anoxic conditions can lead to serious problems, in terms of both water quality and impacts on biological activity.

Reservoir destratification is a technique that can be used to mix hypolimnetic with epilimnetic water to prevent anoxic conditions from occurring. If total reservoir destratification is not practical or desired, a system can be designed to affect a specific region of the lake, such as in front of intake structures to improve the water quality of the releases. Although destratification can be achieved with mechanical pumps, pneumatic systems have been the most commonly used systems in large reserovirs.

Destratification can also be used when it is desirable to maintain uniform conditions through the water column. For example, algal blooms can be reduced by limiting the amount of sunlight the algae receive (by circulating the algae to below the photic zone).

Destratification may have adverse effects on the reservoir and release water as well. Initial start-up of the system can actually increase nutrient loading and DO depletion as bottom sediments are resuspended and exposed to water currents. Destratification of the reservoir will tend to reduce the habitat available for coldwater fisheries. It will also warm the release waters, which may impact the users downstream. Lorenzen and Fast (1977) outline some of the additional benefits and consequences for reservoir destratification.

Theory

Destratification of a specific portion of the lake or reservoir can be accomplished by the introduction of a diffused bubble plume in the water column. The rising bubbles induce a flow pattern by entraining bottom water toward the surface, where it aerates and moves out laterally. Additional

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water moves in to replace the upward flow, and a circulation cell is created (Figure 8). The size and volume of these cells are usually determined by the physical boundaries of the reservoir, the strength of the generation source, and the configuration of the diffusers.
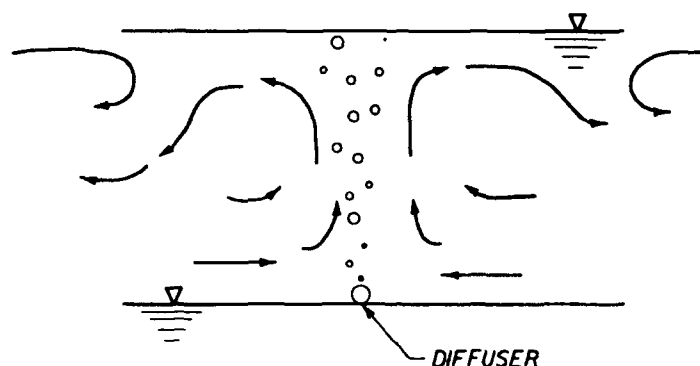

Figure 8. Destratification induced by bubble column

Design Procedures

Johnson (1984) provides a good overview of the various types of aeration/destratification systems in use and how they operate. Also provided are some guidelines for system selection based upon the lake characteristics and the goals of the system to be installed.

In general, the system design is based on the volume of water to be fully mixed, a representative temperature profile, and the stability of the reservoir (the potential energy of the mixed system minus the potential energy of the stratified system). The pneumatic system must input enough energy into the reservoir to overcome the computed stability and thereby destratify the region of interest.

A total or partial-lake destratification system can be designed according to the guidelines for total lake destratification presented by Davis (1980). This design relies on a single perforated pipe (linear diffuser) to create a bubble curtain in the water column and thereby induce vertical mixing. The guidance presented in the following paragraphs is a summary of the procedures outlined by Davis (1980) used for sizing a system to totally destratify a lake.

The first step in the design process is the computation of stability of the reservoir under a particular stratification. For a given temperature

profile and reservoir bathymetry, the stability of the volume to be destrati-
fied, defined as the potential energy of the mixed system minus the potential
energy of the stratified system, is determined. Davis recommends use of a
temperature profile with a 4 °C change through the thermocline for this
process.

The total theoretical energy required to destratify the system is based
on this stability and the solar and wind energy input to the reservoir volume.
An estimate of the solar and wind energy input must be determined. Davis
(1980) provides guidelines for estimating the extent of solar and wind input
to the system.

Next, the quantity (flow rate) of air required to destratify the volume
is calculated based on the total theoretical energy, the time required to
destratify the volume, and the depth of water above the perforated pipe.
Davis (1980) recommends a minimum air flow rate of 20 L/sec.

A diffuser system that can accommodate the required air flow rate is
then sized based on the volume, depth, air flow, and time to destratify. This
diffuser system consists of a perforated (1-mm-diam holes located 0.3 m on
center) linear system of pipe anchored to the bottom of the lake. The recom-
mended minimum limit of perforated pipe length is 50 m (Davis 1980).

The compressor must be sized to provide the required air flow at a pres-
sure sufficient to overcome the pressure losses in the system. This pressure
must account for the hydrostatic pressure head, pressure loss due to friction
and at the bends in the pipe, and excess pressure at the end of the pipe.
Davis (1980) provides the necessary equations to calculate all of the required
pressures.

Next, the free air flow through one diffuser hole is determined using
the relationship between the ratio of absolute hydraulic pressure (pressure
due to the water depth and atmospheric pressure) to the mean internal absolute
pressure (pressure at the end of the diffuser pipe plus the absolute hydraulic
pressure). This value is multiplied by the number of holes in the diffuser
pipe. The result should be equal to or greater than the air flow required.
If not, the length of pipe is increased and the pressure requirements are
recalculated. Several iterations through the pressure and length calculations
and checks may be required to arrive at a satisfactory solution.

To complete the system, an anchoring system that is capable of keeping
the diffuser pipe submerged must be designed.

According to the design criteria (Davis 1980), the system should be activated at the beginning of the stratified period or when the oxygen content of the hypolimnion falls to 50 percent of the saturation level. Operation should continue throughout the stratification season to maintain isothermal conditions or the desired DO level.

Applications of Pneumatic Destratification

A number of pneumatic destratification systems have been installed in the United States and in the United Kingdom. Summarized in Table 7 are reservoir characteristics and the pneumatic destratification system parameters for several systems that have been installed and tested.

Equipment design and testing were conducted by the US Army Engineer District (USAED), Savannah, on the destratification system installed and operated in Allatoona Lake, Georgia (USAED, Savannah 1973). This configuration used a multiple-port diffuser system consisting of five cross-type diffusers (approximately 19.8 m across) clustered about 2,000 ft upstream of the dam face. Each diffuser was supplied with a 250-cfm compressor. These tests were used to determine design criteria for these types of systems and their effectiveness on the destratification of the reservoir.

Two years of testing, one operating with 80-percent capacity of the system and the other at full capacity, were conducted. This system was operated continuously from May through September 1968 and from mid-March through mid-September 1969. While neither was successful in destratifying the entire lake, the tests did reduce the thermal stratification, particularly in the area around the diffusers and dam. The extent of the zone of influence could not be determined; however, some data indicated that the system affected the DO levels as far as 4 miles upstream from the dam.

Other prototype experiments were conducted in 1976, 1977, and 1978 (Kranenburg 1979) using a point diffuser system. All of these tests were were begun under stratified conditions and were operated and monitored for approximately 1 week. During the 1976 tests, the air flow rate was not sufficient to cause total lake destratification but did succeed in affecting the portion of the eservoir in the area of the diffuser. There was minimal change in the temperature of the epilimnion, but the metalimnion and hypolimnion increased approximately 3 °C over time (assumed to be a result of vertical mixing).

Table 7

Pneumatic Destratification Installations

Source[1]	Reservoir Location	Volume m³	Surface Area m²	Depth Avg. m	Depth Max. m	Temperature[2] T_e °C	Temperature[2] T_h °C	Air Flow Rate L/sec	Diffuser Type	Diffuser Size	Remarks
1	"Hundred en dertig"	32E6	2.2E6	13	27	19	13.5	200	Point		
1	"Petrus plaat" '77	13E6	1.0E6	13	15	17	14	170	Point		
	'78	13E6	1.0E6	13	15	18	13	170	Point		
2	Tarago Res (Aus) '76	37.6E6	3.6E6	10.5	23	22	13	150 50	Linear	40 m	To start To maintain
	'77	37.6E6	3.6E6	10.5	23	14	12	50 100	Linear	40 m	To start To maintain
3	Cotter Res (Aus)	4.7E6			30.5	24	11	120	Point	6.1 m	Cross type[3]
4	Kangaroo Res (S. Aus)	24.4E6	1.2E6	20.2	50	21	12.5	250	Linear	2-12.2 m	
4	Little Para (S. Aus)	21.4E6	1.5E6	14.2	49.5	17	12	300	Linear	2-15 m	
5	Prospect Res (Aus)	50.1E6	12.6E6	9.8	24	19.5	16	75 150	Linear	98 m	To start To maintain
6	Allatoona L.	453E6	48.0E6	9.4	45.7	26	15	590	Point	19.8 m	Cross type[3]

[1] Sources: 1 - Kranenburg 1979, 2 - Burns 1981, 3 - Smith 1981, 4 - Croome 1981, 5 - Bowen 1981, 6 - USAED, Savannah 1973.

[2] T_e and T_h refer to the average temperature of the epilimnion and hypolimnion, respectively.

[3] Cross type diffusers are measured from end-to-end of one arm.

In the 1977 and 1978 tests, the influence of the bubble plume was found to extend over the entire reservoir. The water temperature profile became fairly uniform top to bottom over the course of the tests, indicating substantial vertical mixing due to either the bubble plume and/or wind mixing. These tests were used to verify laboratory predictions of the destratification process and did not consider DO in the process.

Burns (1981) details some of the design and installation procedures used at Tarago Reservoir in Victoria, Australia. The design uses two 20-m lengths of pipe containing diffusers. Two operational configurations were tested (one in 1976 and the other in 1977), and both were successful in destratifying the majority of the reservoir. The 1976 test began with operation of the air system under strongly stratified conditions. A high air flow rate (150 L/sec) was used to destratify the reservoir (in 14 hr) initially. This was reduced to 50 L/sec to maintain the destratification. During the 1977 test, the system was started at the beginning of the stratification season. Initially, 50 L/sec was used, but as the season progressed the air rate had to be increased to 100 L/sec to maintain destratification.

The destratification system designed for the Cotter Reservoir as part of the water supply system for Canberra, Australia (Smith 1981) used a cross-shaped diffuser system, similar in design to the diffusers used at Allatoona Lake, Georgia, but smaller. This system was to be used to alleviate high iron and manganese problems experienced as the hypolimnion became anoxic through the summer. At the time of publication of the report, the system had been installed, and preliminary testing was taking place to determine optimum air flow rate and operating schedule. However, further information about the success of this system has not been published.

Croome (1981) describes two destratification systems used on Kangaroo Creek Reservoir and Little Para Reservoir, both in South Australia. Kangaroo Creek Reservoir was destratified twice, once in 1977 and again in 1978 under different stratification intensities. The system utilized two 12.2-m-long (100-mm-diam) galvanized steel pipes located approximately at the heel of the dam. Sixteen fine bubble dome diffusers were equally spaced along each length of pipe (32 diffusers total). During both tests, the reservoir was allowed to stratify before the system was started.

Destratification of the entire reservoir occurred in 15 days and significantly reduced the iron and manganese levels. The reservoir was allowed to

begin to restratify afterwards. The effects on turbidity, algae, iron, manganese, dissolved oxygen, and nutrients were monitored.

A similar system was tested and monitored on the Little Para Reservoir, South Australia (Croome 1981). Two 15-m-long pipes, each with 20 diffusers (40 total), were located on the face of the dam near the level of the lowest intake port. Total destratification of the reservoir was accomplished in approximately 10 days. A smaller compressor (175 L/sec) will be installed permanently for continuous operation through the stratification season, beginning once the thermocline has established itself (or the hypolimnion begins to become anoxic).

Bowen (1981) examined a system installed on Prospect Reservoir, Sydney, Australia, to correct hypolimnetic oxygen deficiency. Rather than formed diffusers, holes were drilled in the pipe to act as diffusers (this system is similar to the design procedure proposed by Davis 1980). The system was started after stratification had been established and was stopped after the reservoir had become isothermal (about 30 days).

Summary

Pneumatic destratification is a method that can be used to improve the water quality within a reservoir. This technique uses a linear or point air diffuser apparatus strategically positioned on the lake bottom and supplied by a compressor located on the shore. The air bubbles released through the diffusers rise through the water column and create an upward water current that spreads out laterally upon reaching the surface. Circulation cells are set up to replace the upward moving water, and eventually the water column becomes mixed down to the level of the diffuser(s).

A method for designing a system utilizing a linear diffuser was presented, along with references for computational procedures. Table 8 summarizes information concerning this technique. Various forms of pneumatic destratification systems have been installed and tested with varying degrees of success.

Table 8

Summary of Pneumatic Destrification

Characteristic	Description
Targets	Reservoir conditions that are initiated or aggravated by thermal stratification or that may be improved by mixing (i.e. anoxic conditions, nutrient cycling, chemical resuspension, algal blooms, etc.).
Mode of action	A continuous bubble stream is used to create recirculation cells in the reservoir to mix or circulate hypolimnetic and epilimnetic waters.
Effectiveness	Very effective.
Longevity	Months to years.

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PART XI: UNDERWATER DAM

Problem Addressed

Reservoirs that exhibit strong thermal stratification with a cool hypolimnion throughout the summer months may be able to maintain a cool-water fishery in the hypolimnion. Some southeastern reservoirs that operate a bottom withdrawal structure, such as a hydropower project, deplete the cool hypolimnetic water during the summer months. Therefore, maintenance of a cool-water fishery is difficult, if not impossible.

One alternative to releasing the hypolimnion is to install a submerged barrier curtain or dam on a portion of the reservoir to retain the cool water during the summer by preventing its release downstream. This technique would prevent movement of the hypolimnion and effectively create a trap in the reservoir for cool water. On the other hand, depending upon their construction, underwater dams may prevent reservoir drawdown and act as a sediment trap. They may also impede fish migration patterns and effectively limit lateral water exchange between the created reservoir and the main lake.

Theory

In the normal operation of a reservoir with a low-level intake, the hypolimnion is gradually withdrawn and released downstream through the summer. Thus, the cooler hypolimnetic water is gradually replaced with warmer water from the mixed surface layer. Although thermal stratification may be retained, the degree of stratification is weakened such that the surface-to-bottom temperature difference is continually being reduced. This reduces the available habitat for cool-water fish and may threaten their survival.

The approach taken with this technique is to prevent the release of cool hypolimnetic water with an underwater dam constructed of an impervious material. This underwater dam is usually placed in an embayment or side arm to minimize the size and subsequent costs of the dam, although it may be placed in any portion of the reservoir provided the desired resources are available.

The development of stratification in the reservoir during the spring will result in thermal profiles being similar on both sides of the dam. However, as the summer progresses and the hypolimnion in the main part of the reservoir is withdrawn, the profiles will differ, with the hypolimnetic volume

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retained by the dam being cooler than the main part of the reservoir (Figure 9). The location of the underwater refuge should provide sufficient depth to prevent warming to the bottom by meteorological conditions during the summer.
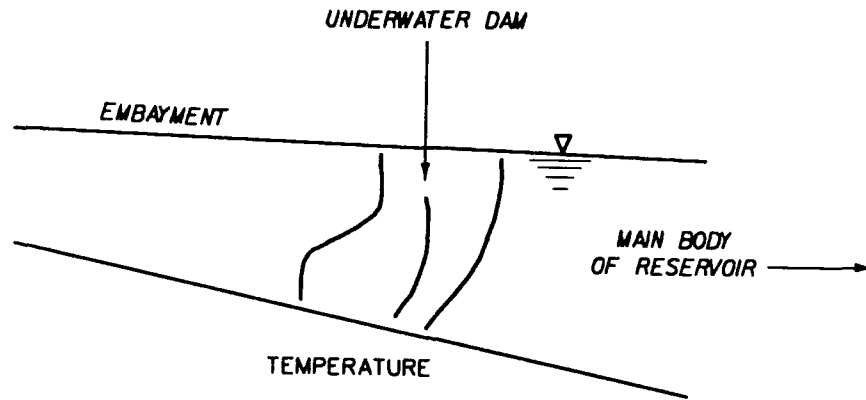
UNDERWATER DAM

EMBAYMENT

MAIN BODY
OF RESERVOIR

TEMPERATURE

Figure 9. Schematic of submerged dam

Design Methodology

The design procedure used by the TVA for the submerged dam constructed at Cherokee Reservoir was given by Bohac (1989). This approach, with some modifications for general reservoir applications, is summarized as follows:

a. Determine the requirements for an underwater dam. If insufficient cool-water resources exist in the reservoir during the summer months, the volume of cool water to be retained should be determined. The thermal stratification history of the reservoir should be reviewed to determine the lowest elevation of the thermocline which will be the crest elevation for the underwater dam.

b. Select the location of the underwater dam to retain the desired volume of water for the underwater refuge. This determination should also consider the logistics of installation and take advantage of site-specific features that could minimize construction costs.

c. Determine the construction material for the underwater dam. Although rock or stone, sheet pile, and fabric liners are feasible construction materials, the TVA constructed the Cherokee underwater dam from an impermeable fabric material. This required the design to consider the force the cooler denser water behind the dam would put on the dam when the hypolimnion in the reservoir was depleted. Construction consisted of grouting anchors into the reservoir bottom on both ends of the dam crest connected by 3/8-in. steel cable to support the crest of the dam. The bottom of the dam was weighted with wire gabions filled with sandbags to prevent leakage. Underwater buoys were placed approximately every 4 ft to support the

vertical load of the underwater dam. Additional site-specific design information for this dam is presented in Bohac, Baker, and Shane (1986).

<u>d</u>. Following installation of the underwater dam, determine the effectiveness by monitoring of the temperature and DO profiles. If hypolimnetic DO demand is sufficient to create low-DO conditions in the refuge, hypolimnetic aeration/oxygenation may be considered to increase the DO.

Applications

This relatively new technique has been implemented in only one project, Cherokee Reservoir. The technique has been successful in maintaining a cool-water refuge for fish (Bohac 1989). However, the use by cool-water species has been limited due to DO limitations in the refuge. During the summer, DO depletion rates are such that little or no DO exists in the refuge, making survival by cool-water species difficult. Therefore, an oxygenation system was installed to maintain DO levels in the refuge. Operation of this system attracted some fish; however, further refinements were recommended for optimum benefits.

Summary

An underwater dam is a technique that provides a cool-water habitat during the summer by preventing its release downstream. This habitat is provided as a refuge for cool-water species during the summer months. Construction guidelines were given along with an example from the TVA at Cherokee Reservoir in Tennessee.

This is a relatively new technique with only a single installation; however, it may be viable at other projects to enhance in-reservoir water quality and provide a fish refuge. Information concerning this technique is summarized in Table 9.

Table 9

Summary of Underwater Dam

Characteristic	Description
Targets	To create an underwater refuge and provide habitat for cold-water fisheries.
Mode of action	An underwater dam is constructed to retain a portion of the hypolimnion and prevent it from being released downstream.
Effectiveness	Depends on stratification.
Longevity	Years.
Negative features	May limit the lateral exchange of waters between the main lake and the cold-water refuge.
	May act as a sediment trap.
	Limits the migration patterns of certain species of fish.
	May require an aeration system to prevent anoxic conditions in the underwater refuge.
Costs	Moderate to high (site and construction specific).
Applicability to reservoirs	Very applicable, but feasibility and effectiveness are site specific.

References

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PART XII: AERATION-OXYGENATION SYSTEMS

Problem Addressed

The thermal stratification that occurs in most reservoirs isolates the hypolimnion from circulation with the surface. Through hypolimnetic oxygen depletion, the hypolimnion may become devoid of oxygen and therefore allow oxidized elements and compounds to be reduced into solution. These constituents, such as iron, manganese, and hydrogen sulfide, are toxic to aquatic life.

Destratification techniques may eliminate the anoxic conditions but will also warm the hypolimnetic water to a temperature near that of the epilimnion. If the thermal stratification is required, such as that necessary for a cool-water fishery, reaeration of the hypolimnion without impacting the thermal stratification is necessary. Hypolimnetic aeration or oxygenation is a technique that introduces oxygen into the hypolimnion without significantly impacting the thermal stratification.

Theory

Hypolimnetic aeration/oxygenation can be accomplished through a variety of approaches, ranging from pumping the hypolimnetic water to the surface for aeration and returning it to the hypolimnion, to fine-pore pneumatic diffusers placed in the hypolimnion for the introduction of gaseous oxygen (Figure 10). These systems use either air or liquid oxygen as the oxygen source.

The volume of oxygen required for reaeration of the hypolimnion is based on the volume of the hypolimnion and the hypolimnetic oxygen depletion rate. Pneumatic diffuser systems are designed such that the rising bubble plume does not entrain hypolimnetic water into the thermocline and thus begin destratification. Systems that pump hypolimnetic water to the surface for reaeration are designed to minimize the velocity of the return flow so that the momentum of the return flow does not induce destratification. Destratification systems which pump hypolimnetic water to the surface are designed to maximize mixing of hypolimnetic water with epilimnetic water and monentum of the return flow is seldom considered a design factor.
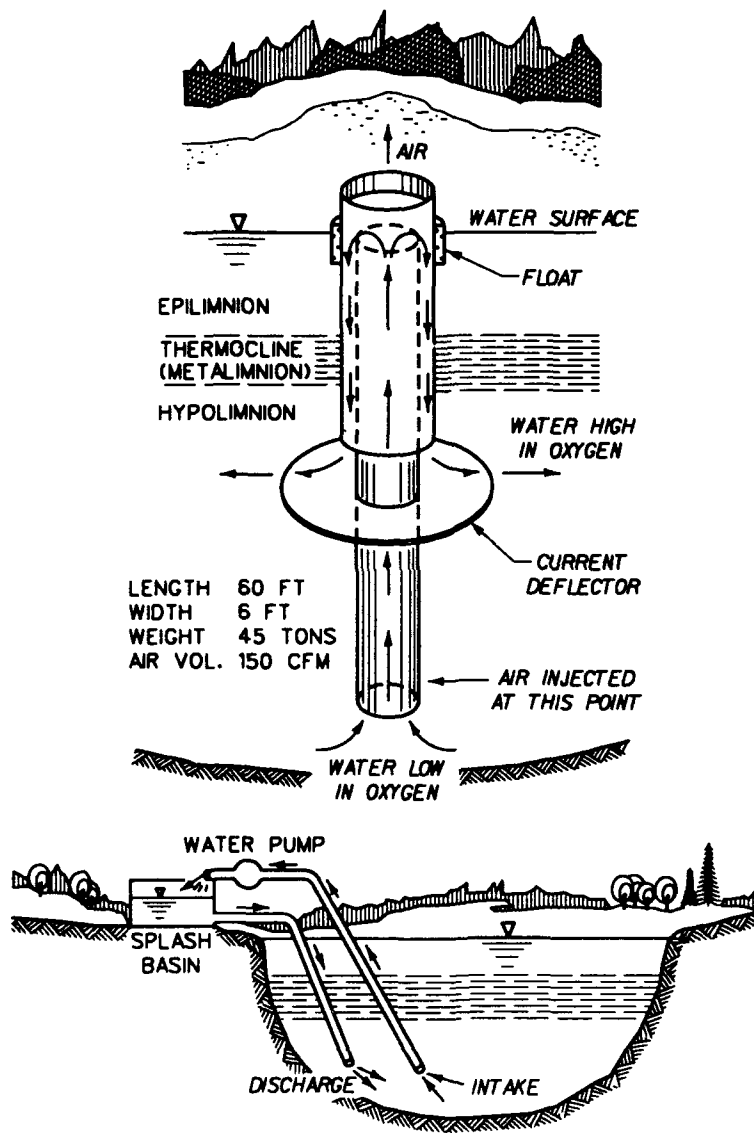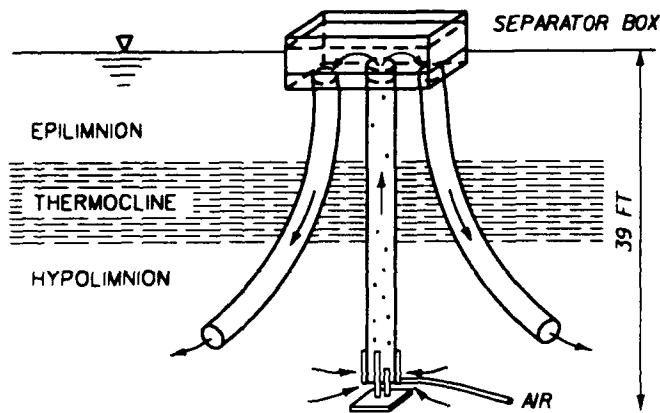
a. Full airlift hypolimnetic aeration
used in Hemlock Lake, Michigan

Figure 10. Example hypolimnetic aeration devices (Continued)
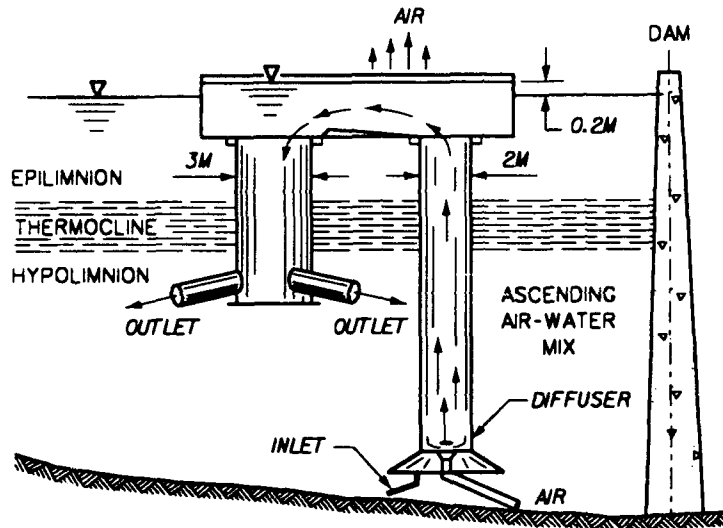
b. Full airlift hypolimnetic aerator, used in
   Wahnbach Reservoir, West Germany

c. Full airlift hypolimnetic aerator, used in Mirror
   and Larson Lakes, Wisconsin

Figure 10. (Concluded)

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Design Methodology

The design of a hypolimnetic aeration or oxygenation system should begin with a clear definition of the reservoir thermal and dissolved oxygen stratification. If the hypolimnetic DO concentration drops below an acceptable level relative to the project objectives, hypolimnetic oxygenation may be evaluated as an enhancement alternative.

The general methodology described below is adapted from Lorenzen and Fast (1977). Modifications have been made to include developments since 1977.

a. The hypolimnetic volume must be determined. Using historical thermal profiles during the summer months, the highest elevation of the hypolimnion must be determined. Then, using a depth-volume curve, the volume of water residing in the hypolimnion must be determined.

b. The hypolimnetic oxygen depletion (HOD) rate must then be determined. Once the thermal stratification has begun, the hypolimnetic DO content is determined for each sampling period until the bottom DO concentration reaches 0.0 mg/L. The hypolimnetic DO for each sample period is then plotted against time. The slope of the resulting curve is the HOD. The empirical model PROFILE (Walker 1987) can be used to compute the HOD and provide an analysis of various thermocline elevations on the HOD.

c. The HOD rate is the minimum rate at which oxygen should be supplied to maintain aerobic conditions in the hypolimnion. The determination of the rate of oxygenation that the aeration system should be designed for should be made based on the desired DO concentration to be maintained in the hypolimnion.

d. The type of system to be designed should be determined next. Since the depth of the aeration device as well as the gas flow rate will impact the system efficiency, specific design criteria will be dependent on the type of system selected. Some manufacturers of hypolimnetic devices supply the oxygen delivery rate for their products. If a linear diffuser is to be designed, manufacturers of fine bubble diffusers should be contacted to determine oxygen delivery rate and efficiency for the various types of diffusers available.

Applications

Fast and Lorenzen (1976) compiled an overview of hypolimnetic aeration system designs and experiences. They describe the three basic designs: mechanical agitation, oxygen injection, and air injection. Fast, Lorenzen, and Glenn (1976) also provided comparative costs for various hypolimnetic aeration devices and concluded that each approach must be evaluated relative to the aeration site to determine construction and operation costs.

Pastorok, Lorenzen, and Ginn (1982) provide a review of hypolimnetic aeration and oxygenation experiences from 15 case studies along with theoretical aspects and impacts on various components in a lake. Toetz, Wilhm, and Summerfelt (1972) provided a similar review of the impacts on biological components along with an extensive bibliography of selected abstracts.

The hypolimnetic aeration or oxygenation cases referenced above were on a variety of lake types, none of which are CE reservoirs. However, an oxygenation system was installed at Richard B. Russell Reservoir (RBR), operated by the Savannah District. This system was designed to increase the release DO and to impact the hypolimnion only in the lower portion of the reservoir. The system capacity of 150 tons of oxygen per day was designed to maintain 6 mg/L DO in the hydropower releases without increasing the release temperature (USAED, Savannah 1981). Additional details and design information can be found in Design Memorandum No. 3 (USAED, Savannah 1981) and Gallagher (1984).

The TVA conducted tests of an oxygen injection system on Fort Patrick Henry Dam to determine an optimum configuration to improve hydropower releases (Fain 1978). Various types of diffusers and configurations were tested, with the optimum configuration achieving 98-percent efficiency in oxygen absorption. As with the RBR system, this system was designed to maintain 6 mg/L DO in the release with no impact on the hypolimnion of the lake.

Summary

Hypolimnetic aeration/oxygenation is a technique designed to increase the hypolimnetic oxygen concentration without impacting the thermal stratification. The theory of operation is to add oxygen without creating mixing cells in the lake that would induce destratification. The design approach consists of defining the hypolimnetic oxygen depletion rate and the subsequent volume of oxygen required to prevent oxygen depletion. Determination of a DO objective is followed by evaluation of devices for aeration.

Although a number of installations have been made on reservoirs, the system at Richard B. Russell Reservoir is the only CE installation. This system was designed to aerate the hypolimnion in the lower portion of the reservoir and maintain 6 mg/L dissolved oxygen in the release.

Summary information on aeration/oxygenation systems is presented in Table 10.

Table 10

Summary of Aeration-Oxygenation Systems

Characteristic	Description
Targets	Anoxic or low dissolved oxygen conditions (and associated concerns) in the reservoir as well as the release water without destratifying the reservoir.
Mode of action	Injection of oxygen or air into the lower reaches of the reservoir to increase the dissolved oxygen levels.
Effectiveness	Very.
Longevity	Years.
Negative features	Air systems require approximately five times the volume gas compared to pure oxygen systems.
	High maintenance levels required for diffuser lines.
	Partial destratification possible, especially with higher volume gas flow rates if the diffusers are not spaced properly.
Costs	High (installation and maintenance).
Applicability to reservoirs	Very applicable to reservoirs with anoxic or low-DO conditions.

References

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PART XIII: TURBINE VENTING

Problem Addressed

The release of water with low dissolved oxygen has been recognized as a problem at some CE hydropower projects. This is the result of hypolimnetic withdrawal of water low in DO during hydropower generation in the stratified periods. The operation of hydropower offers the reservoir manager an opportunity to reaerate the riverflow to some extent. As the flow passes through the turbines, conditions become very favorable for reaeration to occur. However, reaeration does not occur at this point because of the lack of a source of oxygen. Turbine venting is a technique that allows oxygen to enter the draft tube downstream of the turbine and increase the dissolved oxygen in the release water.

Although dissolved oxygen is the primary constituent impacted, secondary impacts of increased DO in the water downstream, such as a reduction in iron, manganese, or hydrogen sulfide, may be achieved. The most serious consequence turbine venting is a slight reduction in generating efficiency and corresponding loss of hydropower revenues. This process will also satisfy only approximately 30 percent of the DO deficit (the difference between the actual and saturation DO levels) of the flow.

Theory

The theory of turbine venting involves the introduction of air into the low-pressure region downstream of the turbine blades. The low pressure in this region is controlled by the geometry of the turbine and draft tube, flow rate, operating conditions, headwater, and tailwater elevations. This low pressure controls the air flow rate into the draft tube, which impacts the amount of oxygen that ultimately remains in solution. Once this introduced air is entrained into the flow in the draft tube, the hydrostatic pressure increase with the movement down the draft tube increases the oxygen transfer efficiency over that which normally occurs at the surface (Figure 11). This results from the increase in the saturation deficit, which is a measure of the driving force for oxygen transfer, associated with the increased hydrostatic pressure throughout the draft tube.
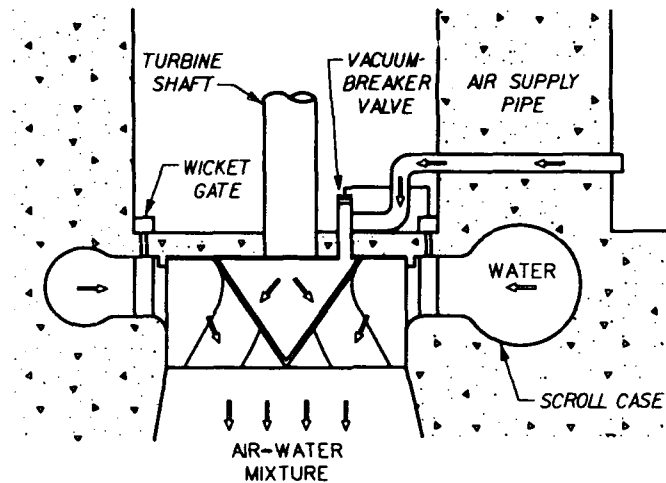
Figure 11. Vacuum-breaker venting system

Design Methodology

The implementation of this technique will require a combination of both numerical modeling and field tests to determine the most effective method for introducing air into the draft tube. The following paragraphs describe a general methodology based on previous tests and applications of turbine venting.

The analysis should begin with a description of existing hydrologic and water quality conditions. This can be accomplished by interpretation of temperature and DO profiles collected in the reservoir in front of the hydropower intake and measurements in the stilling basin collected during generation.

Using the steady-state numerical model SELECT (Davis et al. 1987), the observed water quality data can be used to verify predicted release quality under observed operating conditions. The SELECT model can then be used to determine the impacts of turbine venting by conducting simulations using the venting subroutine in the model. Previous research indicates that a maximum of 30 percent of the upstream DO deficit can be satisfied by turbine venting.

If the results of the SELECT simulations indicate that an acceptable increase in release DO is predicted, field tests of an appropriate design are warranted. This testing should consider the specific turbine design and operating conditions to identify the optimum location for introduction of air into the draft tube. This may involve modification of the vacuum-breaker system to allow more air to enter through the vacuum-breaker ports. At a number of

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projects, the vacuum-breaker valve has been modified and maintained in an open position.

In some cases deflectors have been added to the turbine hub just upstream of the vacuum-breaker ports. These deflectors create a low-pressure region in their wake, causing increased air flow into the draft tube. Research by TVA has indicated that a diffuser ring attached to the draft tube downstream of the turbine runner is effective in introducing air. In conjunction with these tests, turbine performance should be monitored since research has indicated that a loss in efficiency has occurred during some turbine venting tests (Wilhelms, Schneider, and Howington 1987).

Applications

Several applications of turbine venting have been made at CE projects. The report by Wilhelms, Schneider, and Howington (1987) includes the most comprehensive analysis of a turbine venting application to date. In tests on Clarks Hill Dam powerhouse, hub baffles were added to the vacuum-breaker system to increase air flow. Turbine efficiency was monitored during the tests, which indicated that an approximate 2- to 3-percent efficiency loss was observed as a result of the venting. However, there was an increase in the release DO of approximately 2.5 mg/L or a reduction of the DO deficit of approximately 30 percent. A numerical model of turbine venting was developed from this work to predict the impacts of various air flow rates on release dissolved oxygen.

J. Percy Priest Reservoir on the Stones River in the Nashville District has operated with turbine venting for a number of years. At this project, the vacuum-breaker system is blocked open so that air can be entrained in the draft tube at all generation cycles. This results in a deficit reduction of approximately 27 percent, with an increase in the release DO of up to 2.0 mg/L (Price 1988).

The TVA has conducted tests of turbine venting at several of their projects. These tests indicated that the highest air to turbine discharge rate of 3 percent achieved an increase in release DO of 3 to 4 mg/L. This increase is dependent on the DO deficit that exists. As observed by Wilhelms, Schneider, and Howington (1987), the TVA also observed a loss of power capacity of between 3 and 5 percent. A summary of the various turbine venting designs and hub baffles tested is included in Bohac et al. (1983). This

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report also includes turbine venting tests conducted by a number of public power companies and a report of similar work conducted in Europe.

Summary

Turbine venting is a technique used to increase the DO in hydropower releases. This technique involves the introduction of air into the low-pressure region downstream of the turbine blades. As this entrained air moves through the draft tube, the increase in the hydrostatic pressure increases the oxygen transfer efficiency, thereby increasing the DO uptake in the release.

In this part, a general approach to evaluation and design was described which involves the use a numerical model and prototype testing. Several tests of turbine venting have been conducted by various agencies, with results indicating that a maximum of 30 percent of the oxygen deficit in the release can be satisfied by turbine venting. These tests also indicated that some loss in generation efficiency, on the order of 3 percent, can be anticipated with the addition of air, and another 1-percent loss can be observed with the addition of deflectors. Summary information is presented in Table 11.

Table 11

Summary of Turbine Venting

Characteristic	Description
Targets	Low DO levels of the release waters commonly associatd with hydropower generation during stratified periods and anoxic conditions.
Mode of action	Injection of air downstream of the turbine runner blades to increase the DO levels of the release waters.
Effectiveness	Up to 30 percent of the DO deficit may be satisfied by this technique.
Longevity	Based on the life of the turbine; years.
Negative features	Slight reduction in the generating efficiency and, consequently, the related revenues. Possible nitrogen supersaturation. Possible increase in the wear on the turbines.
Costs	Moderate to high depending on the required modifications to the turbines.
Applicability to reservoirs	Very applicable to hydropower projects.

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PART XIV: SUBMERGED SKIMMING WEIR

Problem Addressed

The thermal stratification that occurs at most reservoirs can create problems with release water quality. If the intake structure withdraws water from the hypolimnion, the release may be low in dissolved oxygen or contain high concentrations of undesirable trace constituents. In this case, withdrawal of water primarily from the epilimnion may be desirable. If the project must release high discharges, as for a hydropower project, discharge through a port (single port or horizontal line of ports) will result in a large withdrawal zone that usually extends surface to bottom. To increase the amount of epilimnetic water in large releases, a submerged skimming weir can be designed and installed. This structure is designed to extend to the top of the reservoir thermocline and prevent the withdrawal of the hyplimnion.

This technique should be used only at projects with minimal lake surface elevation fluctuation during the period of hypolimnetic anoxia, since the effectiveness of the weir will diminish as a function of the drawdown on the reservoir. In addition, a weir can strengthen the thermocline in the main portion of the lake. This can affect a number of related concerns, such as anoxic conditions in the hypolimnion and nutrient cycling. A weir may also act as a sediment trap, which may or may not be beneficial.

Theory

The theory of operation of a submerged skimming weir is based on the modification of the withdrawal limits by the weir crest. Using the epilimnetic water quality as the desired release quality, operation of a weir can be simulated, and the resulting quality predicted for a given weir crest elevation, thermal stratification, and discharge. A numerical model can be used to simulate various stratification patterns and discharges and to determine the optimum crest elevation for the weir (Figure 12). The effects of various meteorological and hydrological events on the reservoir operating with a submerged weir can then also be simulated.
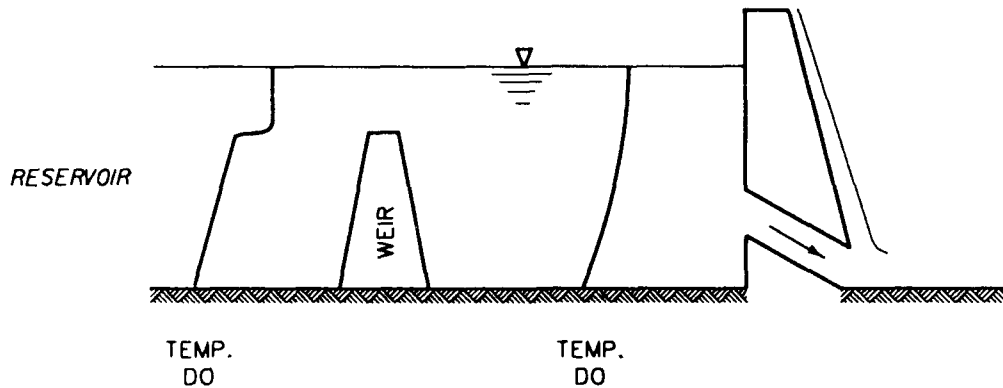
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Figure 12.   Schematic of submerged skimming weir

Design Methodology

Design of a submerged skimming weir should begin only after clearly defining the existing release water quality problems. The design methodology is based on installation of submerged skimming weirs at existing CE projects.

To determine this, a numerical model simulation can be used to predict the reservoir quality and stratification under a variety of meteorological, hydrological, and operational conditions. If the project is already operational, simple examination of release quality and in-reservoir quality profiles will indicate if a problem exists. If the problem involves release of hypolimnetic water, such as low DO during stratified periods, a submerged skimming weir may be a viable alternative to minimize hypolimnetic releases.

The numerical model simulations described above, conducted to determine the viability of a submerged weir, can also be used to determine the crest elevation of the weir. The crest is usually set at an elevation equal to or higher than the highest thermocline elevation observed during the summer. If the thermocline elevation is above the weir crest elevation, withdrawal of hypolimnetic water can occur, thereby diminishing weir effectiveness.

Once the crest elevation has been selected, the crest length must be determined. Although the shorter weir lengths are less expensive to construct, their effectiveness can also be reduced. For example, a weir crest with the same length as the intake port may develop a withdrawal zone very similar to the port because of the withdrawal of hypolimnetic water over the weir. Therefore, some reasonable length must be determined to begin design. Using an initial length, the numerical simulations are repeated as in the

initial evaluation of a submerged weir. Examination of the results for the depth of the withdrawal zone and the resulting release water quality will determine the optimum weir length.

Some discretion in the length of the weir must be used, as well as site-specific knowledge of the area in front of the intake. In most applications, the weir crest should tie into the same elevation on either bank in front of the structure to prevent the withdrawal of hypolimnetic water from around the weir.

Applications of Submerged Skimming Weirs

Submerged skimming weirs have been used at several CE projects to prevent the release of low-DO hypolimnetic water. Linder (1986) described the design and evaluation process for submerged skimming weirs at two hydropower projects in the Kansas City District. These projects, Stockton and Harry S. Truman Dams, were predicted to have low dissolved oxygen in the hydropower releases. During construction, provisions were made to construct weirs as part of the project. Evaluation of this technique at these projects indicates that the release quality is improved, with some minor elevation of release temperature in the fall and some cooling in the spring.

Another concern that developed after construction of the projects was that, during long periods of nongeneration, stratification of the area between the weir and the dam can occur. Upon start-up of generation, some low-DO water is released downstream. This problem has also been documented at Clarence Cannon Dam in the St. Louis District (Wilhelms and Furdek 1987). However, the submerged weir at Clarence Cannon functions as designed during generation and maintains adequate levels of dissolved oxygen in the hydropower releases.

An evaluation of a skimming weir for temperature control at Meramec Park Dam, a project planned for the Meramec River in Missouri, indicated that a weir would be effective for controlling cool-water releases during the stratified period (Bohan 1970). However, the project was deauthorized and never constructed. An evaluation of a submerged skimming weir at Richard B. Russell was performed to assist in release water quality enhancement (Smith et al. 1981). Results indicated that the weir, which was proposed as a modification of an existing cofferdam, would interfere with the hydrodynamics of proposed pumpback operations and therefore was not recommended for construction.

The Bureau of Reclamation has also considered the use of submerged weirs to enhance release water quality. Shasta Dam, located on the Sacramento River, was evaluated for retrofit of a plastic curtain to serve as a submerged weir and allow the release of warmer surface water. It was also to be designed such that it could be raised to permit the release of bottom water (CH2M Hill 1977). Although evaluation of this technique indicated that release quality could be met, some concern over potential blockage of hydropower intakes if the curtain broke free from moorings has delayed implementation of this technique.

Summary

The submerged skimming weir is a technique that will modify the withdrawal zone of the release structure, thereby modifying the release quality during the stratified periods. This technique has been used at large CE projects for maintaining release quality at peaking hydropower projects that maintain a relatively stable pool elevation. A design approach using numerical models to simulate the effects of hydrological and meteorological conditions on the reservoir was identified. Several projects for which weirs have been evaluated and/or installed were discussed. Summary information on this technique is presented in Table 12.

Table 12

Summary of Submerged Skimming Weir

Characteristic	Description
Target	Improvement of the release water quality by restricting the withdrawal to the equilimnion of the reservoir.
Mode of action	A submerged weir in the vicinity of the intake is used to block the withdrawal of hypolimnetic water and allow the release of epilimnetic water.
Effectiveness	Effective at given flow rates.
Longevity	Years.
Negative features	May strengthen the thermocline in the main part of the lake.
	Limits the transport of sediments through the project.
	May increase the anoxic conditions (and related concerns) in the hypolimnion.
Costs	Expensive (construction).
Applicability to reservoirs	Very applicable, even to reservoirs with selective withdrawal structures.

References

Bohan, J. P 1970. "Water Temperature Control Weir for Meramec Park Dam, Meramec River, Missouri," Technical Report H-70-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

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PART XV: MULTILEVEL SELECTIVE WITHDRAWAL

Problem Addressed

The operation of a multilevel intake structure requires the consider-
ation of numerous project conditions and constraints, the most important of
which is thermal stratification. As stratification develops, the limits of
withdrawal for a given port are reduced because of the density differences
imparted by the thermal stratification. Thus, flow through a port at a given
elevation may not result in a release temperature similar to that observed at
the center-line elevation of the port or that desired to meet a downstream
objective.

Selective withdrawal, which is defined as the capability to describe the
vertical distribution of withdrawal from a density-stratified reservoir and
then use that capability to selectively release the quality of water that is
desired, can be used to determine the appropriate or best available operation
of a release structure. It can also be used in the design of multilevel
intakes as well as in the modification of existing projects to achieve a given
release water quality criteria.

Theory

This technique relies on manipulation of the density-impacted withdrawal
pattern to control the release quality from a structure. The withdrawal pat-
tern that is set up as the result of release of water through a port during
stratified conditions is defined as the withdrawal zone (Figure 13). Water
within this zone will ultimately be released through the port, even though the
rate of release from individual strata of the pool varies. By identifying the
portion of each layer released under a given operating condition, the release
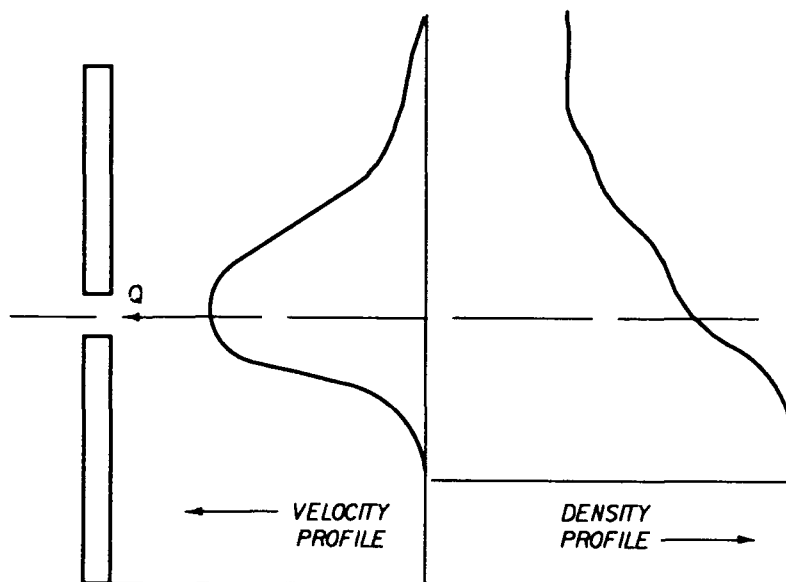quality can be predicted.

Figure 13. Schematic of withdrawal zone

Selective Withdrawal Methodology

Much research has been performed in the area of water withdrawal through a point sink (such as a single port) or through a linear sink (such as a line of penstock openings for hydropower). The effort has focused on the withdrawal profile that is created and on the way in which density stratification and physical boundaries affect the withdrawal limits (beyond which, water is not drawn into the port). When water is withdrawn through a single port, water from well above and below the horizonal center line of that port is withdrawn.

The development of these upper and lower withdrawal limits is dependent on the density gradient present in the water column, the flow through that port, and local geometric effects. Beyond the upper and lower limits of withdrawal, insufficient energy is available in the flow to entrain the water from these levels into the main flow (Wilhelms 1986).

The design methodology for a selective withdrawal system, given in the following paragraphs, is based on physical and numerical model investigations.

Since the density gradient in the water column has a direct influence on the potential energy of the water at various levels, it strongly affects the development of the withdrawal limits. For example, if the stratification is weak or nonexistent, the withdrawal limits may extend from the bottom to the

water surface. If the water column is strongly stratified, this will cause the withdrawal limits to shrink so that the port is withdrawing from a smaller cross-sectional area. Therefore, the density stratification (usually temperature) for design conditions must first be determined.

If the selective withdrawal investigation involves an existing reservoir, existing profiles may be used. If the selective withdrwal investigation is for a reservoir not yet constructed, a one-dimensional numerical model can be used to predict typical temperature profiles. Additional information relative to the selective withdrawal investigation, such as local topography and operating criteria (hydraulic and water quality), should also be compiled.

The development of the withdrawal zone often is modified by a physical boundary. The port may be too close to the top or bottom of the reservoir to permit full development of the withdrawal limits. The result is that the unobstructed limit is moved vertically to draw in the required flow. Also, the approach geometry to the outlet structure may affect the withdrawal zone through reduction of the lateral extent of withdrawal or the withdrawal angle.

For example, an outlet structure placed at the end of a long, narrow channel will have a greater vertical withdrawal zone as compared to a similar structure that is located on the main body of a lake and is able to withdraw water from a full 180 deg or greater around it.

For existing projects for which selective withdrawal is being considered, the existing release quality must then be simulated. This may involve the use of a numerical model, such as SELECT, or a one-dimensional model such as WESTEX or CE-QUAL-R1. For proposed projects, simulation will require a one-dimensional model. In some cases where local topography may influence the withdrawal zone, a physical model of the intake structure and local topogrpahy may be necessary to determine impacts. Simulations should then be verified against project conditions.

All of these options and scenarios have been incorporated into the computer program SELECT (Davis et al. 1987). Given a particular water surface elevation, temperature profile and center-line elevation, and the dimensions and withdrawal flows of a port, the withdrawal zone can be predicted. The results predict the upper and lower withdrawal limits as well as a withdrawal velocity profile and the resulting average outflow parameters (i.e., temperature).

If profiles of other conservative parameters (such as dissolved oxygen and algal profiles) are used in combination with the temperature profile,

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SELECT will also predict the resulting average outflow qualities. It is also possible to adjust the program to account for many differing entrance conditions.

At this point in the design, the location of potential new ports should be determined. The numerical model used above to verify existing conditons is then used to predict release conditions with the new port(s) location(s). If multiple ports are necessary, optimization routines are available to determine the optimum number and location for new ports.

By knowing the temperature profile as well as profiles of any other important qualities in front of the outlet structure, and having ports at different elevations throughout the water column, it is possible to withdraw a wide range of qualities provided they are available in the lake. By operating multiple ports, it becomes possible to mix water of different qualities to produce a desired quality.

Applications of Selective Withdrawal

The selective withdrawal phenomenon has been of interest to researchers for the past 40 years. As such, there are many reports detailing lakes and reservoirs in which this technique has been tested and used successfully to solve water quality concerns. In addition, several other techniques discussed in this report utilize selective withdrawal for identification or evaluation purposes.

Much work has been done toward describing and predicting how water will behave when withdrawn from a stratified environment. Gariel (1949), Bohan and Grace (1969), Monkmeyer et al. (1977), Fontane, Labadie, and Loftis (1982), and Smith et al. (1987) have performed research into density-influenced flow and selective withdrawal. These references examine some of the governing equations as well as theoretical, laboratory, and field work to document this phenomenon.

The US Army Engineer Waterways Experiment Station (1986) compiled a reference document on selective withdrawal which presents design consider-ations for selective withdrawal structures as well as operational experiences and guidance.

Results and descriptions of numerical modeling of the selective with-drawal process are presented by Howington (1989) for operation of a selective withdrawal structure at Lost Creek Reservoir in Oregon. Selective withdrawal

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was also used in the thermal analysis of Prompton Reservoir (Price and Holland 1989). In this investigation, the number and location of selective withdrawal ports were identified for a proposed modification to raise the pool elevation. Optimization techniques included with the model that was used resulted in a minimum number of ports required to maintain downstream release temperature.

Maynord, Loftis, and Fontane (1978) conducted a study of the proposed Tallahala Creek Lake in Mississippi to determine an optimum design for the intake structure to supply the necessary water quality. Davis et al. (1987) documented the one-dimensional numerical model SELECT and described its operation and limitations.

Summary

Selective withdrawal is a technique used to identify the withdrawal zone for a given structure. Using this knowledge, modification of the structure or operation to achieve a given release objective may be possible. Selective withdrawal is used as part of several of the other techniques mentioned in this report. The theory is based on identification of the density-impacted withdrawal pattern. Numerous research and specific reports have been published on selective withdrawal. Most computational methods for selective withdrawal have been included in the computer program SELECT. This program provides predicted release characteristics based on input profiles and operating conditions. Table 13 presents a summary of this technique.

Table 13

Summary of Multilevel Selective Withdrawal

Characteristic	Description
Target	To withdraw water from a range of elevations in the reservoir to obtain the highest quality possible.
Mode of action	Release ports at different elevations in the reservoir allow access to a wide range of water quality conditions under stratified conditions.
Effectiveness	Very effective.
Longevity	Years, life of the project.
Negative features	Additional maintenance and operational costs over a simpler structure.
Costs	Expensive.
Applicability to reservoirs	Very applicable to reservoirs with a range of conditions that vary vertically in the reservoir.

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PART XVI: LOCALIZED MIXING

Problem Addressed

The thermal stratification that occurs at most reservoir projects can create problems with release water quality. If the hypolimnion becomes isolated from the surface and turns anoxic, reducing conditions for iron, manganese, and hydrogen sulfide will prevail. If a CE structure withdraws water from the hypolimnion, release of these soluble constituents as well as low DO could create water quality problems downstream. Localized mixing is a technique that has been tested as a means to improve the release quality of some projects which exhibit these characteristics. It can also be used to improve the water quality in localized areas by mixing epilimnetic with hyplimnetic waters.

Theory

Localized mixing is a technique that provides enough mixing in a local area to reduce, if not eliminate, the thermal stratification. This is usually accomplished by pumping surface water down into the hypolimnion to achieve a locally uniform vertical temperature profile (Figure 14). The jet from the pump provides the energy needed to disrupt the stratification and causes entrainment of the epilimnetic waters in the release discharge to enhance the water quality.

This technique, as indicated by its name, is used to mix only a small or localized area of the reservoir. Therefore, only the area of concern as related to the localized mixing objective is impacted. In the case of improvement of release quality, the intended impacts are related only to the release volume, not the entire reservoir. If this technique were used to improve the water quality of a small cove or marina, only the area under consideration (such as the cove or marina) enters into the design methodology. This also minimizes costs of the system.
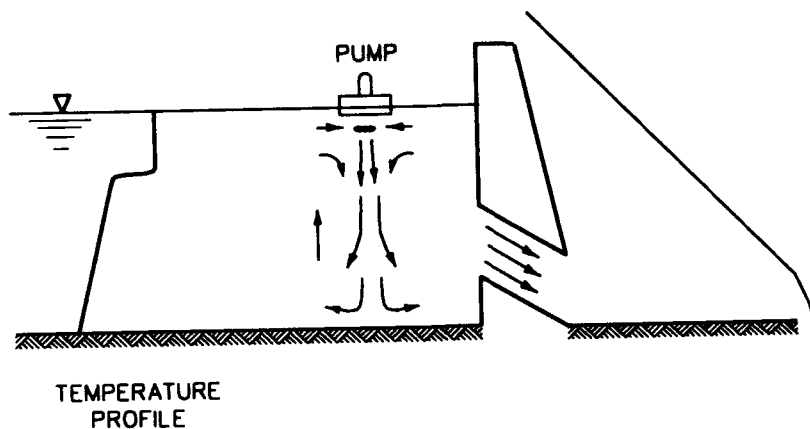
PUMP

TEMPERATURE
PROFILE

Figure 14. Schematic of localized mixing application

Design Methodology

The design of a localized mixing system will usually involve determination of the desired water quality to be achieved in the release. A general procedure for design of a system was given by Holland (1983). The procedure described below is modified from Holland (1983) to include recent developments.

  <u>a</u>. The specific objective of the localized mixing application must be determined, such as improvement of release water quality. This will involve determination of release temperature, dissolved oxygen, and/or trace constituents such as iron, manganese, and hydrogen sulfide in the existing release water. The desired release quality and the vertical profile of the water quality in front of the intake must then be determined. This involves the parameter(s) defined above as the specific objective. If the desired release quality does not exist in the profile taken in the reservoir, localized mixing will not meet the objectives.

  <u>b</u>. Assuming that the desired release quality exists in the reservoir, the next task is the determination of the withdrawal zone characteristics of the intake structure. This determination is formulated through the use of the SELECT model (Davis et al. 1987). This model requires input of the thermal and quality profile of concern, release quantity, and structure intake configuration for computation of the vertical withdrawal profile and predicted release quality. Verification of the prediction is made through comparison with observed releases. The results of this model will indicate the relative proportions of water in the release coming from a given layer, as well as the limits of the withdrawal zone.

  <u>c</u>. With the withdrawal description, the volume of the desired quality water needed to achieve the release quality goal should be

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determined. This can be determined using a simple mass balance criterion by diluting the release with epilimnetic water. The dilution factor, which is the ratio of epilimnetic volume to release volume, can be used in this determination. However, there are some limitations to the amount of dilution that can be achieved. According to Moon, McLaughlin, and Moretti (1979), the maximum dilution that can be achieved is approximately 75 percent. This means that for a total release volume of 1,000 cfs, only 750 cfs could be replaced by epilimnetic water.

d. The next task is the determination of the depth of penetration of the jet required to ensure release of the pumped water. This depth will usually be the center-line elevation of the intake. Computational methods for depth of penetration of a jet are given in Holland (1984).

e. The initial jet characteristics are to be determined next. Using computations of Albertson et al. (1950) and Holland (1984), the initial jet diameter and velocity can be determined. The selection of a pump to meet these criteria, which can be obtained from pump manufacturers, can then be made.

Applications of Localized Mixing

A number of applications of localized mixing have been made. Mechanical pumps used in these applications range from large-diameter axial flow pumps to relatively small-diameter direct-drive mixers. The earliest reported use of a pump to locally mix a reservoir for release improvement was Garton and Rice (1976). This work was based on a large-diameter (16.5-ft) axial flow pump used in lake destratification experiments on Lake Arbuckle in Oklahoma. The 16.5-ft-diam axial flow pump generated up to 207,000 gal/min of discharge and was successful in improving the release DO by 1 to 2 mg/L.

In 1977, localized mixing tests were conducted at Lake Okatibbee in Mississippi. These tests used a 1.83-m-diam axial flow pump designed to pump 1.7 m^3/sec while the release structure released 1.4 m^3/sec. Results of these tests indicated an improvement in release DO of 1.0 mg/L and warmed the release by 3.6 °C (Dortch and Wilhelms 1978). Although the pumping rate was nearly 50 percent of the discharge rate from the structure, additional improvement could have been possible with an improved design. In addition, these researchers stated that the application of this technique at other projects with higher discharges or deeper pools may not be as successful (Okatibbee Lake is approximately 9 m deep).

In 1980, a series of localized mixing tests were conducted on Pine Creek Lake and Lake Texoma in Oklahoma (Robinson 1981; Robinson, Garton, and Punnett

1982). These tests, using axial flow pumps with diameters of 1.22, 1.83, and 2.44 m, were designed to investigate pump performance with varying propeller diameter and reservoir release rates.

Conclusions from these tests indicated that improvement in release quality was feasible, but only for water quality constituents that display an increase with depth (excluding DO and temperature), and that increases in the pump propeller diameter increased the discharge ratio or dilution factor. However, a reduction in water quality was observed when the pumping rate exceeded the release rate. This may have been due to overpenetration of the pumped jet since the outlet level for these tests was at an intermediate level in the pool. The researchers indicated that an optimum ratio of pumped to release rate was observed for each series of tests.

In 1987, a series of localized mixing tests were conducted at J. Percy Priest Reservoir in Tennessee (Price 1988, Sneed 1988). These tests were designed to investigate the feasibility of direct-drive mixers to improve release quality from the hydropower project. Results of these tests indicated that three pumps generating 45 cfs each improved the release DO by 1 mg/L (release discharge of 4,600 cfs). These tests also demonstrated that the location of the jet relative to the intake structure had a significant impact on the efficiency of the localized mixing application.

Similar tests were conducted at Douglas Reservoir by the Tennessee Valley Authority (Mobley and Harshbarger 1987). These tests, using three axial flow pumps, each with a propeller diameter of 4.5 m, indicated that the hydropower release DO could be improved by as much as 2.0 mg/L (Brown, Mobley, and Nubbe 1988).

Holland (1984) developed computational methods to predict the depth of penetration of a hydraulic jet as well as the entrained flow that crosses the thermocline. In addition, a method for designing a localized mixing system was developed (Holland 1983). Brown, Mobley, and Nubbe (1988) formulated a one-dimensional numerical model of a hydraulic jet in a withdrawal zone of the hydropower project at Douglas Dam.

Summary

Localized mixing is a technique that can be used to improve the release quality from reservoirs. This technique requires the use of a mechanical pump to jet surface water down into the hypolimnion with enough energy to penetrate

to the center-line elevation of the intake port. A method for designing a localized mixing system was discussed, along with references for computational procedures. Applications of localized mixing have been tested in a number of locations with axial flow and direct-drive mixers. Several numerical techniques have been formulated which may assist in the design of a localized mixing system. Summary information on this technique is given in Table 14.

Table 14

Summary of Localized Mixing

Characteristic	Description
Targets	Improved water quality by mixing or diluting hypolimnetic waters with epilimnetic waters.
Mode of action	Surface pumps are used to force surface waters down into the hypolimnion and the withdrawal zone.
Effectiveness	Effective for stable stratification.
Longevity	Seasonal.
Negative features	Possible overpenetration of the jet may strike the bottom and cause resuspension of sediment and erosion. Partial destratification of an area is possible.
Costs	Moderate.
Applicability to reservoirs	Very applicable to reservoirs without selective withdrawal structures to increase the withdrawal of surface waters.

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