WATER QUALITY CONSIDERATIONS IN RESERVOIR MANAGEMENT

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INTRODUCTION

Water quality has become increasingly more important in reservoir management for a number of reasons. Existing reservoirs are being subjected to intense multi-objective demands on limited resources, and thus, water use attracts more attention causing water quality to draw closer scrutiny. Reservoir managers and the public have come to the realization that water quality affects other environmental interests, such as fish and wildlife, and can impact or impair water use. Laws and regulations require consideration of water quality for new reservoir construction and structural or operational modifications of existing reservoirs.

Water quality considerations can vary widely since a host of descriptors can be used to characterize water quality. Temperature and dissolved oxygen (DO) are of primary interest for most reservoirs since temperature regulates biotic growth rates and life stages and defines fishery habitat (warm-, cool-, or cold-water), and oxygen is necessary to sustain aquatic life. Turbidity is of considerable interest because of the effects on light transmission and water clarity. Nutrient enrichment receives frequent attention since it fuels primary productivity that can lead to oxygen depletion and taste and odor problems. Contaminants, e.g., organic chemicals and trace metals, are of increasing concern due to their toxicity and affinity to sediments that can accumulate in reservoir sediments. Total dissolved solids (TDS) may be of interest for water supply and other uses. Total suspended solids (TSS) are a major transport mechanism for nutrients and contaminants and deposit in reservoirs, thus displacing valuable water storage. Water pH regulates aquatic chemistry and can impact water use and habitat. Dissolved iron, manganese, and sulfide, which can accumulate in reservoir hypolimnions that are low in DO, can lead to water quality problems within the pool and when released downstream. Iron and manganese affect water color and can lead to water treatment problems. Sulfide causes odor problems when it escapes during reaeration and can be hazardous at high atmospheric concentrations. Pathogens, such as bacteria, viruses, and protozoa, can present public health problems. Particular concern is for protozoa, such as *Giardia lambia*, which may survive public water treatment.

Consideration is given to both in-pool and release water quality. For many years, reservoir managers have used selective withdrawal to control release temperature to meet downstream targets set for selected species by fishery resource agencies. Although selective withdrawal can provide a relatively effective means of controlling release temperature, especially for deep stratified pools, it is not as effective for controlling multiple water quality variables in the release. Thus, reservoir water quality management in recent years has shifted to an emphasis on techniques that can be implemented within the watershed, in-pool, and within or immediately dowstream of the release structure.

This paper discusses the relationship of water use and water quality. Next, various water quality treatment and control techniques are presented. Finally, mathematical modeling is discussed for evaluating the effects on water quality of reservoir management options.

WATER USE AND WATER QUALITY

Water quality interests are closely related to water use. Reservoir water uses include water supply, flood control, hydropower, navigation, fish and wild life conservation, and recreation. Water quality may be more than a descriptor of water chemistry; it may also be considered a reservoir purpose when water is provided to assimilate waste effluents. Conflicts often arise for reservoirs with multiple water uses. Water quality as a descriptor rarely competes with other water uses, rather it is usually a constraint. For example, hydropower and water supply may conflict due to their respective water demands, but maintenance of water quality standards is a constraint. However, water quality as a reservoir use can compete with other uses. Other water uses can affect water quality which can influence other water uses. Of the various water uses, water supply, fish and wild life conservation, and recreation tend to have the greatest relationship to water quality.

Water supply uses usually place much emphasis on water quality. Large phytoplankton blooms can cause taste problems in drinking water. Impaired water quality, such as the presence of iron and manganese, can increase treatment costs. Pathogens can disrupt drinking water use. High TDS levels are undesirable for municipal and irrigation water supply. The presence of high oxygen demanding substances can adversely impact water used for waste effluent assimilation.

Water quality is particularly important when fishery resource issues are involved. Desirable fisheries habitat is highly dependent on maintenance of suitable water quality conditions. Additionally, the quality of reservoir and tailwater fisheries is influenced by water quality.

Water quality can be important for recreation. Nuisance algal blooms and high suspended sediment concentrations can adversely impact recreation quality. The presence of pathogens can cause closures for body contact recreation. Reservoir tailwater recreation has become increasingly popular in recent years. The presence of hydrogen sulfide in reservoir releases can degrade tailwater recreation quality.

Water quality is usually not an important consideration during flood control operations. Concern for potential loss of life and property tends to overshadow any water quality interests. Hydropower use does not really require water of a particular quality, rather maintaining minimum water quality standards within or downstream of hydropower releases is often a constraint. It can be particularly difficult to meet DO requirements in some hydropower releases since most of the energy of the release is used for power production, leaving little energy for reaeration of low DO water. Substantial efforts have been focused on methods to increase DO in hydropower releases, particularly at Tennessee Valley Authority (TVA) dams (Harshbarger et al. 1997). Also, low DO in releases is a major concern for dams being considered for hydropower retrofit where existing releases are well aerated. Pumped-storage hydropower projects also draw considerable interest in water quality since the influx of return water can significantly alter in-pool and release water quality.

TREATMENT AND CONTROL TECHNIQUES

Reservoir water quality is affected by natural events and human intervention. The effects of natural events are only briefly discussed here since they don't fall directly into the realm of reservoir management. Natural events affect reservoir water quality through hydrology and meteorology. Wet and dry hydrologic periods can have profound effects on reservoir water quality. Wet periods tend to bring in higher nutrient loadings which can fuel algal blooms and degrade water quality. However, higher flows also tend to increase flushing and decrease stratification, potentially improving water quality. It is not possible to make a definitive statement about the net effects of wet years since the effects can depend on the timing of high flows and watershed and reservoir characteristics. A good discussion of the effects of flows on reservoir DO and water quality is provided by Thornton et al. (1990). Warm periods tend to intensify reservoir thermal stratification since differences in water density due to temperature differences are greater at higher temperatures. Increased stratification can be detrimental to water quality due to increased potential for DO depletion in the isolated hypolimnion followed by release of nutrients and other materials from bottom sediments. Additionally, warmer water decreases oxygen solubility and increases biological metabolism and respiration, potentially stressing water quality further.

Simplistically, there are basically only three types of human intervention that can impact water quality: 1) pretreatment or control of reservoir inflows; 2) in-pool management or treatment techniques; and 3) management of reservoir outflows. The first intervention mechanism usually implies upstream settling basins or some type of watershed control or land management activity and is beyond the scope of this paper. There are hosts of in-pool treatment techniques that can be employed to alter reservoir water quality. Management of reservoir outflows is by far the most common method of impacting reservoir in-pool and release water quality, whether intentionally or not. Outflow management can consist of controlling the outflow rate, outlet location and timing of releases, and treating the release, such as aeration. Various in-pool and release treatment and management techniques for improving reservoir water quality are discussed below. A more in-depth discussion of reservoir water quality management/treatment techniques is provided by Cooke and Kennedy (1989) and Price and Meyer (1992).

In-Reservoir Treatment Techniques

There are a number of in-pool water quality management and treatment techniques. These include:

- destratification,
- hypolimnetic aeration/oxygenation,

- underwater dam,
- pool drawdown,
- dilution,
- phosphorus inactivation,
- sediment removal,
- harvesting,
- biological controls, and
- herbicides and algicides.

Each of these is discussed briefly below.

Hydraulic or pneumatic pumping can be used to disrupt or prevent stratification. Hydraulic destratification using relatively small diameter diffuser ports that create high-velocity water jets can be quite effective for inducing destratification (Dortch 1979). Destratification is used to mix hypolimnetic and epilimnetic water to prevent anoxic conditions from occurring in the hypolimnion. Destratification can also reduce sediment nutrient release by eliminating anoxia and can reduce phytoplankton blooms by circulating algae below the photic zone. Destratification produces nearly isothermal warm water conditions which may adversely impact other interests, such as fisheries. Destratification has received considerable interest in California and Australia (Australian Water Resources Council 1981). Air injection has been used for destratification in most of the California cases and has resulted in nitrogen gas supersaturation (Fast and Hulquist 1982).

Hypolimnetic aeration/oxygenation is a method to increase hypolimnetic DO without eliminating thermal stratification. Either air or oxygen is diffused within the hypolimnion in a manner that does not disrupt stratification. A wide variety of systems has been used ranging from airlifts to fine-pore hypolimnetic diffusers. Fast and Lorenzen (1976) and Pastorok et al. (1982) provide reviews of hypolimnetic devices and experiences. Oxygenation of the entire hypolimnion of a large reservoir may not be feasible. However, oxygenation of the lower portion of a reservoir to improve the DO of cold-water releases is feasible. This approach was used at Clarks Hill and Richard B. Russell Dams on the Savannah River, where oxygen was diffused through fine-pore diffusers (Holland and Tate 1984 and Gallagher 1984).

An underwater dam can be used to retain cold water within the hypolimnion to prevent it from being released through fixed, low level outlets. This approach may be of interest for maintaining cool or cold water in-pool fisheries, particularly in coves, which would otherwise not be possible. Underwater structures can trap sediments and interfere with reservoir drawdown.

Pool drawdown is an effective procedure for the control of certain species of nuisance macrophytes. Control is achieved through drying and freezing over a period of at least three to four weeks for projects in colder climates. Longer periods may be required for warmer climates. Drawdown may interfere with other reservoir uses.

Dilution is a procedure in which water of good quality is added to decrease the concentration of poor in-pool water quality. The feasibility of this approach may be limited since an adequate supply of high quality water may be unlikely. Additionally, subjecting the reservoir to additional inflows could impinge on other reservoir uses, such as flood control.

Phosphorus inactivation is achieved through the addition of aluminum sulfate or sodium aluminate (or both) to the reservoir to form aluminum hydroxide, a precipitate that is very sorptive of phosphorus. Phosphorus remains bound to aluminum even during low redox conditions. This treatment method can reduce nuisance algal blooms, increase water transparency, and help seal phosphorus in sediments. However, this treatment technique can be expensive, can lower pH, and can be toxic if overdose occurs.

Sediment removal can be used to deepen reservoirs and increase volume, and secondarily to remove nutrient-rich or toxic sediments and to control rooted plants. This method can be highly effective since the problem source is removed. However, the costs are quite high.

Harvesting of aquatic plants is a procedure that can quickly improve portions of a reservoir for recreation while at the same time improving water quality. However, biological control is potentially the most cost effective long-term control method for nuisance macrophytes and algae. Insects and plant pathogens have been proven to be successful in control of aquatic plants. Restructuring of fish communities offers promise for algal control. The introduction of phytophagous fish, such as grass carp, has proven to be successful for macrophyte control, for example at Lake Conroe (Martyn et al. 1986 and Noble et al. 1986) and Lake Conway (Miller and King 1984). Herbicides and algicides are widely used for the control of nuisance macrophytes and algae. These chemicals provide an excellent and often highly effective means of producing short-term control. However, when one nuisance species is controlled, another species may take its place. Additionally, decaying plants can depress DO and release nutrients to fuel another algal bloom. Some chemicals are toxic to fish and fish food organisms.

Release Treatment Techniques

There are a limited number of water quality treatment methods that can be applied at the point of release. These can include in-structure, forebay, and tailwater techniques. Four such methods are briefly discussed below for increasing DO of releases.

Although turbine venting has been used to increase DO of hydropower releases, there also can be secondary benefits of increasing DO, such as reducing dissolved iron, manganese, and hydrogen sulfide. Turbine venting, which involves the introduction of air or oxygen into the low-pressure region downstream of the turbine blades, has been used at Corps of Engineers (CE) and TVA hydropower dams. The disadvantage of turbine venting is a loss in turbine efficiency on the order of 3 to 4 percent. Bohac et al. (1983), Wilhelms et al. (1987), Franke et al. (1997), Hopping et al. (1997 a & b) discuss turbine venting methods and their effects.

Many non-hydropower dams provide reaeration of release flows. For example, spillways, sluices, gated conduits, and other release structures that use hydraulic jumps downstream of the structure to help dissipate flow energy usually provide a high degree of reaeration. As discussed earlier, hydropower releases experience little reaeration. Reaeration weirs can be added to provide structural reaeration below hydropower dams. Structural reaeration also can be designed into reregulation dams below peaking hydropower dams. Small weirs have been placed below hydropower dams to help smooth out variable hydropower releases to ensure minimum flows and provide reaeration (Hoover et al. 1997 and Hauser and Proctor 1995). The infuser weir (Hauser and Morris 1995 and Hauser and Brock 1996) is a broad-crested weir that allows vertical flow through a series of transverse slots in its crest yielding high performance reaeration. Additionally, labyrinth weirs have been built in the tailrace to provide reaeration (Hauser 1993). The labyrinth weir is usually a vertical, sharp-crested weir and has a "W" shape in plan view to provide a long weir length in a relatively short width of tailrace, thus decreasing the unit discharge and nape thickness allowing improved reaeration. The labyrinth weir also has drawn interest for reaeration below small hydropower retrofit projects, such as Canyon Dam for the Guadalupe-Blanco River Authority. The disadvantage of reaeration weirs is that some hydropower generation capacity is lost due to the increase in water depth in the tailrace upstream of the weir. Hauser (1996) provides guidance for design of aerating weirs.

Oxygen injection in the forebay has been used near the point of release to increase DO of discharge water. At TVA and CE dams (Mobley 1989, Mobley 1993, Mobley and Brock 1994, and Gallagher 1984), oxygen has been injected in-reservoir immediately upstream of hydropower intakes so that most of the injection was contained within the withdrawal flow and released downstream. The disadvantage of this technique is that high rates of oxygen injection are usually required, and oxygen transfer efficiency can be low due to the high injection rates, large bubble sizes, and short retention time in the flow. However, DO of the releases was improved dramatically with this technique for the above mentioned projects.

Many stratified reservoirs with fixed hypolimnetic release ports experience poor downstream water quality due to the release of anoxic water containing dissolved iron, manganese, sulfide, ammonium, and phosphate. Release DO can be lower than normal too, although reaeration at non-hydropower dams helps to alleviate low downstream DO problems. Localized mixing is a technique that induces mixing immediately upstream of the release structure to improve release water quality. A pump in the epilimnion forces an entraining jet of water into the hypolimnion to blend water of better quality with the hypolimnetic release water (see Figure 1).

Localized mixing has been used at a number of reservoirs (Price and Meyer 1992, Tyson and Mobley 1996, and Mobley et al. 1995). This technique is best suited to reservoirs with relatively low release flows during the summer since there is a limit to the amount of dilution that can be achieved, and high flows would demand large expensive pumps. Methods have been developed to help design pumping requirements to meet specified dilution requirements (Moon et al. 1979 and Holland 1983 and 1984).

Selective Withdrawal

Selective Withdrawal is the most common and most effective means of controlling the quality of water released downstream. Selective withdrawal uses stratified flow to pull out water from selected depths of the pool (Figure 2). Thus, density stratification is required for this technique to be effective. Additionally, multi-level intakes are desirable to provide flexibility in the choice of release elevation. The release elevation can also impact in-pool water quality as discussed in the section on operational techniques. Selective withdrawal is such a common and important phenomenon in reservoir mechanics that most reservoir water quality models include algorithms for predicting the outflow profile and release water quality. There have been numerous studies and reports on selective withdrawal research and its use, most of which are cited and discussed by Davis et al. (1987) and Smith et al. (1987).

Selective withdrawal is often used to satisfy downstream water quality targets. In most cases, temperature has been the main target variable. When multiple water quality variables are desired targets, conflicts often arise. For example, a cold water target during the stratification season can conflict with release DO requirements. Since the elevation of selective withdrawal intakes affects release quality, it is important to have enough intakes at appropriate elevations to meet water quality release targets. Dortch and Holland (1984) developed a technique to determine the optimal number of selective withdrawal intakes and their optimal elevations.

Although most selective withdrawal intake structures are built during initial reservoir construction, release structures can be successfully modified for selective withdrawal later following initial construction, such as Sutton Dam on the Elk River, W. VA (George et al. 1980) and Flaming Gorge Dam on the Green River, UT (Peters 1979). However, selective withdrawal add-on is usually expensive. Submerged skimming weirs (Figure 3) have also been used for selective withdrawal. Weirs were installed during construction at two Corps of Engineers hydropower dams (Stockton and Truman) to improve release DO (Linder 1986).

Operational Techniques

Whereas selective withdrawal is used to meet a desired downstream water quality target, reservoir operations can have a profound effect on future water quality. For example, a cold water release objective throughout the stratification season may result in hypolimnion depletion and an inability to meet the cold water target later in the season. The choice of epilimnetic versus hypolimnetic withdrawal can strongly affect reservoir water quality throughout the year since the level of withdrawal ultimately defines vertical distribution of temperature, DO, and nutrients. For example, epilimnetic withdrawal tends to increase the stability of stratification, resulting in less transfer of DO from the epilimnion to the hypolimnion. Hypolimnetic DO depletion is accompanied by sediment nutrient release. However, the hypolimnetic nutrients can remain trapped within the hypolimnion unavailable for algal uptake until lake turnover occurs. Hypolimnetic withdrawal tends to warm the hypolimnion and transport DO into the hypolimnion. However, the warmer hypolimnetic water has lower DO saturation levels and increases respiration rates that deplete oxygen. Sediment-released nutrients are discharged downstream with hypolimnetic withdrawal, and algae can be mixed deeper in the pool possibly out of the photic zone.

Modification of the reservoir operating rule curve for water storage can be used as an operational technique to enhance water quality. By modifying the hydraulic residence time of the reservoir, undesirable inflows can be routed through or retained to allow sedimentation. There are few examples of rule curve modification for water quality purposes since such action usually imposes on other objectives of the reservoir. However, reservoir rule curves have been adjusted for other purposes, such as ensuring minimum downstream flows during low-flow periods. The timing of reservoir operations may be altered without adversely impacting other project purposes. For example, highly turbid inflows during storm events can be quickly passed downstream rather than storing and releasing more slowly over a longer period. The reservoir flood pool is brought down to the normal pool elevation more quickly, which raises downstream water elevations, but shortens the exposure time of the tailwater to turbid water. This technique has been used by the Portland District, CE, at Lost Creek Dam (Legg 1979).

Multiple release structure operation can be used to blend release water quality. For example, surface spillway releases can be added to hypolimnetic hydropower releases to increase downstream DO. The negative aspect of supplementary releases is that additional water is released potentially affecting future water supply or raising downstream water levels.

Reservoir operational strategies can have a complicated effect on future water quality that is difficult to forecast without the assistance of mathematical models. Through the use of models coupled with optimization techniques, it is possible to regulate release strategies such that water quality is optimized throughout a time horizon. Look-ahead optimization (or dynamic optimal) techniques enable reservoir managers to choose the best strategies for the present that will provide the most benefit over the entire time horizon of interest, rather than regulating only for the present release quality objective without regard to the future. A good example involves temperature, where cool water release temperatures are desired in the summer and fall as shown in Figure 4. An operation optimized over the entire period gets closer to the more critical fall temperatures than does the best-daily operation. The optimized strategy trades-off warmer summer releases for cooler fall releases. Fontane et al. (1982) used an objective-space dynamic programming technique to determine the dynamic optimal selective withdrawal release strategy for downstream target temperatures.

It is also possible to operate multiple reservoirs within a river basin to meet water quality targets at downstream points within the basin. For example, releases of good quality from one reservoir can be blended with poor quality releases from another reservoir in an adjacent feeder stream to neutralize the negative water quality attributes. The CE has used multi-reservoir releases to neutralize releases with low pH and to dilute highly turbid releases. The HEC-5Q model (USACE 1986) contains algorithms to calculate release requirements from multiple reservoirs to satisfy a downstream water quality target. The HEC-5Q optimization strategies are myopic, i.e., they do not allow the operators to optimize releases over the future time horizon.

MODELING

Mathematical models offer reservoir managers the predictive tools that they need to assess the effects of their management decisions prior to implementation. For example, the effects on water quality of changes in reservoir release strategies should certainly be evaluated with a water quality simulation model before implementing the new operational strategies. It is highly desirable to have a calibrated, operational water quality model for each major reservoir so that water quality questions and issues can be addressed prior to management actions.

A number of one-dimensional (1D) vertical reservoir water quality models have been in use since the 1980's, such as CE-QUAL-R1 (USAE WES 1995), MINLAKE (Riley and Stefan 1987), and WQRRS (USACE 1985). However, two-dimensional (2D) reservoir water quality modeling has nearly replaced 1D models in the last ten years. With the computer power available on personal computers today and with the additional realism offered by 2D models, there is little reason to use 1D reservoir models. In addition to water quality, the 2D model CE-QUAL-W2 (Cole and Buchak 1995) includes density-dependent hydrodynamic simulation, thus, providing realistic, physics-based transport that is difficult to achieve with 1D models. Reservoirs are usually built along major streams, so they typically have a substantial longitudinal axis that can exhibit strong longitudinal gradients, as well as vertical gradients.

The near-field stratified flow (i.e., selective withdrawal) that occurs near a reservoir outlet is difficult to accurately model even with multi-dimensional hydrodynamic models. There are several reasons for this deficiency. For one, most far-field multi-dimensional hydrodynamic models make the hydrostatic assumption which is not valid near an outlet. Two-dimensional models omit the lateral dimension which becomes important as the flow converges laterally toward an outlet of finite width. Finally, a high degree of spatial resolution is required near the outlet, thus, conflicting with the need to model the entire reservoir for water quality. Fortunately, semi-analytical-empirical models, such as SELECT (Davis et al. 1987), can accurately describe selective withdrawal mechanics. As a result, selective withdrawal algorithms such as those in SELECT are used within reservoir water quality models, such as CE-QUAL-R1 and CE-QUAL-W2, to compute the withdrawal zone which is used as a downstream boundary condition.

Conflicts over water uses are on the increase since few new reservoirs are being built, and existing water resources are being stretched. Attempts to resolve these conflicts have brought about law suites and major studies to resolve the conflicts. Two recent examples of such basin-wide water use conflicts include the Missouri River and two river basins residing in Georgia, Alabama, and Florida. In the case of the Missouri River, the conflict involved the states bordering the upper Missouri River wanting to conserve water in the reservoirs for fish and wildlife concerns and states bordering the lower Missouri River wanting more water released for water supply and navigation. The conflict was brought on by the droughts of the 1980's. The other example involved the Alabama-Coosa-Tallapoosa river basin in Alabama and the Apalachicola-Chattahoochee-Flint river basin in Georgia and Florida, referred to as the ACT/ACF basins. As with the Missouri River, the conflict revolved around water allocation. In both examples, studies were conducted to evaluate the effects of altering the reservoir operating procedures and water allocation. Water quality models were used in these studies to assess the impacts of altered reservoir operations on water quality within the upper Missouri River reservoirs (Cole et al. 1995), in the riverine portion of the lower Missouri River (Tillman 1992), and in reservoirs within the ACT/ACF (Tillman et al. 1997).

CONCLUSIONS

There is an increasing interest in reservoir water quality since water resources are not expanding as fast as water demands. As water becomes more limited, the quality of the water becomes increasingly important. Although water quality can be a reservoir project purpose, it is usually treated as a constraint. Thus, other reservoir management objectives usually take priority while managers strive to operate within acceptable water quality limits. This operational strategy often results in undesirable water quality within and downstream of the reservoir. There are hosts of techniques as highlighted here that can improve reservoir water quality, but most water quality management techniques require trade-offs with other water uses. However, water managers are more willing today to consider reservoir management trade-offs in the interest of water quality in order to avoid costly conflict resolutions.

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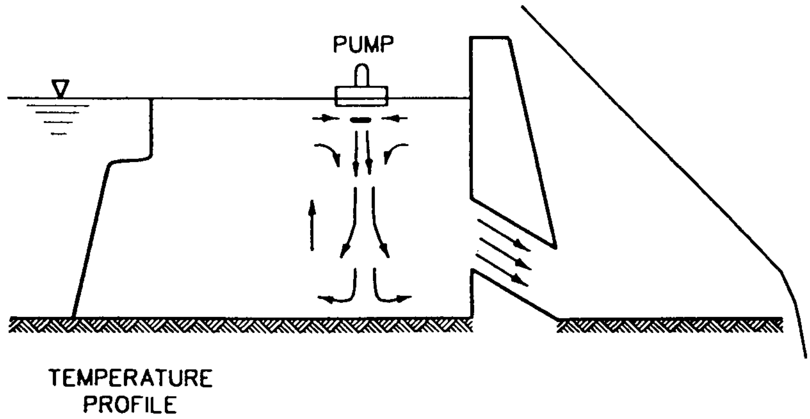

Figure 1. Schematic of localized mixing (after Price and Meyer 1992)

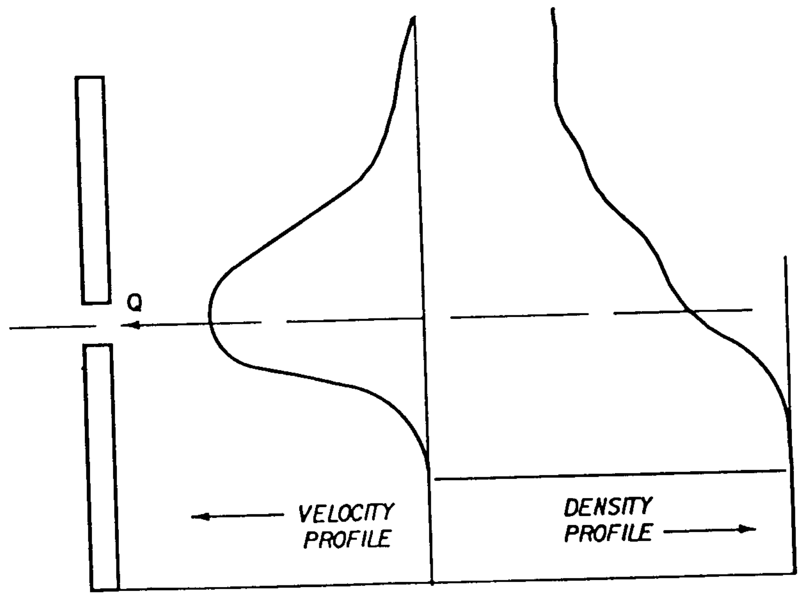

Figure 2. Schematic of withdrawal zone (after Price and Meyer 1992)

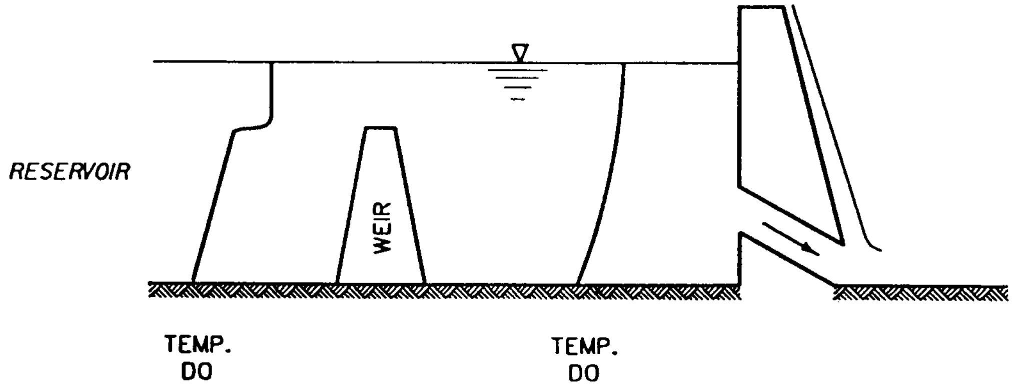

Figure 3. Schematic of submerged skimming weir (after Price and Meyer 1992)

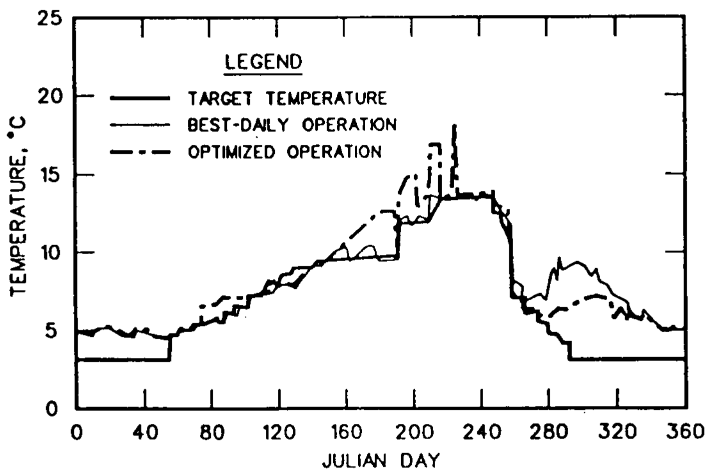

Figure 4. Example of improved release temperature with dynamic optimization technique (after Price and Meyer 1992)