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EFFECT OF IN-RESERVOIR COFFERDAM ON WATER QUALITY

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Background

A cold water release (less than 21° *C) with a dissolved oxygen (DO) concentration of 6 mg/l* is desired from the proposed Richard B. Russell Reservoir (RBRR) and pumped storage hydropower facilities. During the expected stratification of the reservoir, the respective vertical distributions of temperature and DO essentially preclude withdrawal and release of water that will meet both objectives. If sufficient epilimnetic water were withdrawn to meet the DO objective, the upper bound of the temperature criterion would be exceeded. Conversely, if adequate cold hypolimnetic water were withdrawn to meet the temperature objective, the withdrawn DO concentration would be less than desired. Thus, if adequate reaeration does not occur in or below the hydropower structure, the DO objective will not be met. To circumvent this potential problem, the U.S. Army Engineer District, Savannah (SAS), will place the center line of the hydropower intakes approximately 70 ft below the surface of the pool to withdraw cold water and install an innovative oxygenation system to increase the DO concentration in the withdrawal zone of the reservoir. Obviously, large quantities of molecular oxygen are involved in this procedure. As a result, the U.S. Army Engineer Division, South Atlantic (SAD), and SAS requested the Waterways Experiment Station (WES) to investigate the relative effectiveness and/or feasibility of various in-reservoir structural alternatives in enhancing the DO expected in the reservoir withdrawal zone, thereby reducing the quantity (or rate) of oxygen required for injection. The in-reservoir design options identified by SAS and SAD were:

a. *Option A.* Removal of the cofferdam (as originally planned).

b. *Option B.* Continuous cofferdam as constucted with a crest at el 378.* Diversion breach would be filled.

c. *Option C.* Cofferdam left in place as constructed and without filling the second-stage 50-ft-long diversion breach (bottom at el 310).

d. *Option D.* A sheet-pile cutoff wall installed on the crest of the continuous cofferdam with the top at el 400.

A schematic of the geometries is presented in Figure 1.

A hybrid modeling approach was used to simulate the reservoir hydrodynamics. A numerical simulation model, WESTEX, was adopted from previous analyses of pumped storage projects (Dortch, et al., 1976, and Fontane, et al., 1977). Details of the numerical model are provided by Smith (1981). Algorithms that addressed the selective-withdrawal and pumpback processes were developed and calibrated with data obtained from an undistorted-scale physical model that simulated the hydrodynamics occurring near the dam. The physical model was constructed to a 1:150 scale and reproduced the dam and approximately 3000 ft of the upstream topography. Additional details of the physical model and the selective withdrawal and the pumpback descriptions developed from the model data are also provided by Smith (1981). The numerical model was used with historical hydrology and meteorology for 1955, 1958, 1966, and 1967 to simulate the reservoir vertical distributions of temperature and DO and the released temperature and DO concentrations expected during the four study years with each of the in-reservoir design alternatives.

*All elevations (el) cited herein are in feet referred to mean sea level (NVGD).

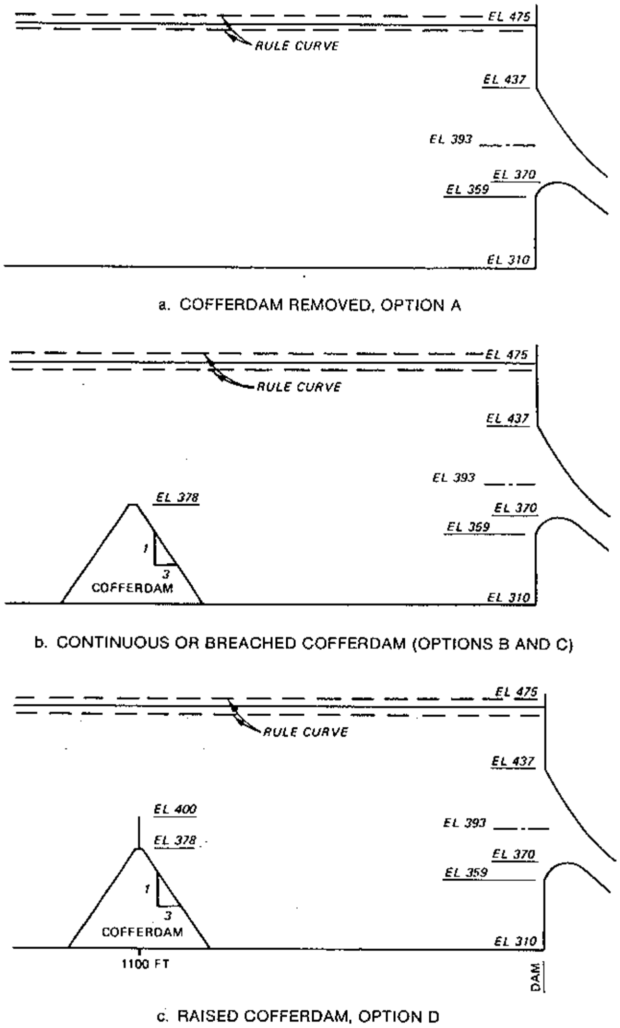

Figure 1. Schematic of in-reservoir geometrical alternatives

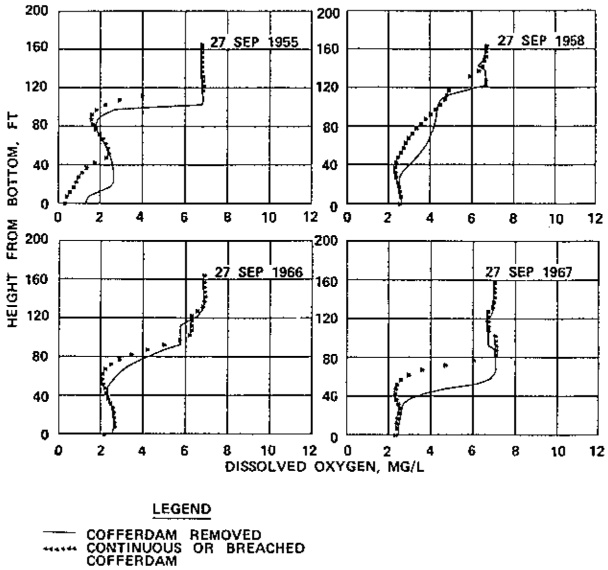

Figure 2. Predicted DO distribution without the cofferdam and with the continuous or breached cofferdam

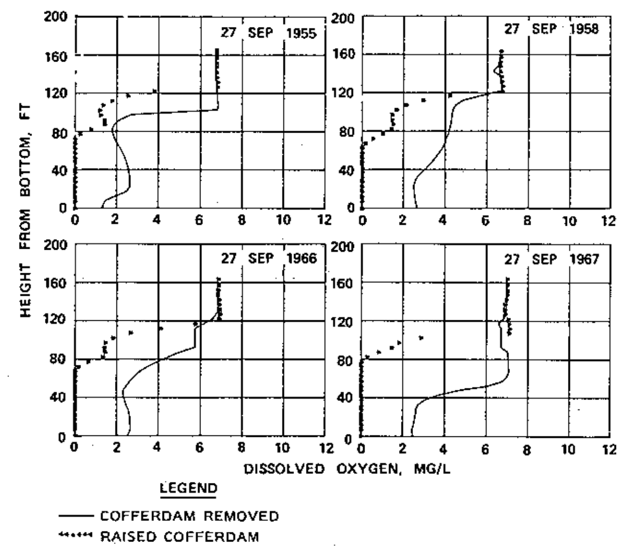

Figure 3. Predicted DO distribution with the cofferdam removed and with the raised cofferdam

Results

The relative impact of the respective geometrical configurations upon the in-reservoir and released water quality can be demonstrated by comparing representative in situ and released water quality predictions. The in-reservoir results will be discussed first.

In-Reservoir DO and Temperature

Dissolved Oxygen. Predicted profiles for 27 September of each study year (Figures 2 and 3) are indicative of the relative effects that each geometry has upon the DO distribution during the late phases of stratification. The most favorable DO distribution during the late phases of stratification is obtained if the cofferdam is removed because a larger volume of water is entrained from the hypolimnion into the pumpback jet. After entrainment, the low DO hypolimnetic water mixes with metalimnetic (or epilimnetic) waters. Simultaneously, water with higher DO from the epilimnion (or metalimnion) moves downward. Since oxygen is continually supplied to the epilimnion through the air-water interface, and since the volume from the hypolimnion pumped during a pumpback operation is small compared to the total volume of the epilimnion or metalimnion, significant DO depletion in the upper region does not occur. The continual supply of high DO water and the redistribution of this water result in a tendency to improve the DO distribution in the reservoir.

Any horizontal obstruction in the reservoir that reduces the quantity of water withdrawn from the hypolimnion by entrainment will tend to decrease vertical mixing during pumpback. With the continuous and breached cofferdams (Options B and C, Figure 1), the physical model indicated 13 percent less entrainment from the hypolimnion than would occur if the cofferdam were removed. Thus, a less favorable DO distribution develops in the reservoir during the late phases of stratification (Figure 2) with the cofferdam than with its removal.

The numerical simulations for the breached cofferdam (Option C, Figure 1) were basically identical with the results obtained for the continuous cofferdam. This similarity occurred because the breach is small compared to the length of the dam and the area available for flow above the cofferdam. Although not simulated in the mathematical model, qualitative observations of physical simulations indicated transient flow through the breach between pumpback and withdrawal phases. As a result, if the cofferdam is breached and poor water quality exists in the lower layers, gravity flow through the breach during the time interval between pumpback and generation could result in poor water quality between the dam and the cofferdam. During subsequent hydropower release, a pulse of low DO water could occur.

Placing a sheet-pile cutoff wall with a crest at el 400 (Option D, Figure 1) would severely reduce vertical mixing during pumpback. As compared to removal of the cofferdam (Option A), 90 percent less entrainment from the hypolimnion was measured in the physical model with the raised cofferdam. Depending upon the simulation year, anaerobic conditions developed in the hypolimnion in late June to mid-July. By the end of September, the thickness of the anaerobic zone had increased to between 65 and 80 ft depending upon the simulation year. As a result, this alternative is not considered viable.

In-Reservoir Temperature. Representative temperature profiles are presented in Figure 4. Temperature distributions produced in the reservoir by withdrawal over the cofferdam were colder than those predicted with the cofferdam removed. The withdrawal distribution is higher in the reservoir due to withdrawal over the cofferdam which results in the release of warmer water and the retention of colder water.

Released DO and Temperature

The predicted released DO concentration as a function of time for the 1966 and 1967 study years is presented in Figure 5. These results are similar to the results obtained for the 1955 and 1958 study years and are indicative of the general findings.

Qualitative Observations. Prior to June and after September (or October for conditions similar to 1955),

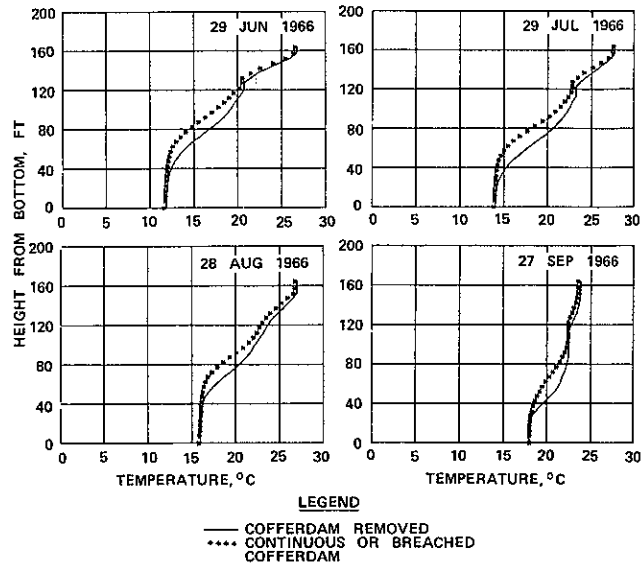

Figure 4. Predicted temperature distribution without the cofferdam and with the continous or breached cofferdam

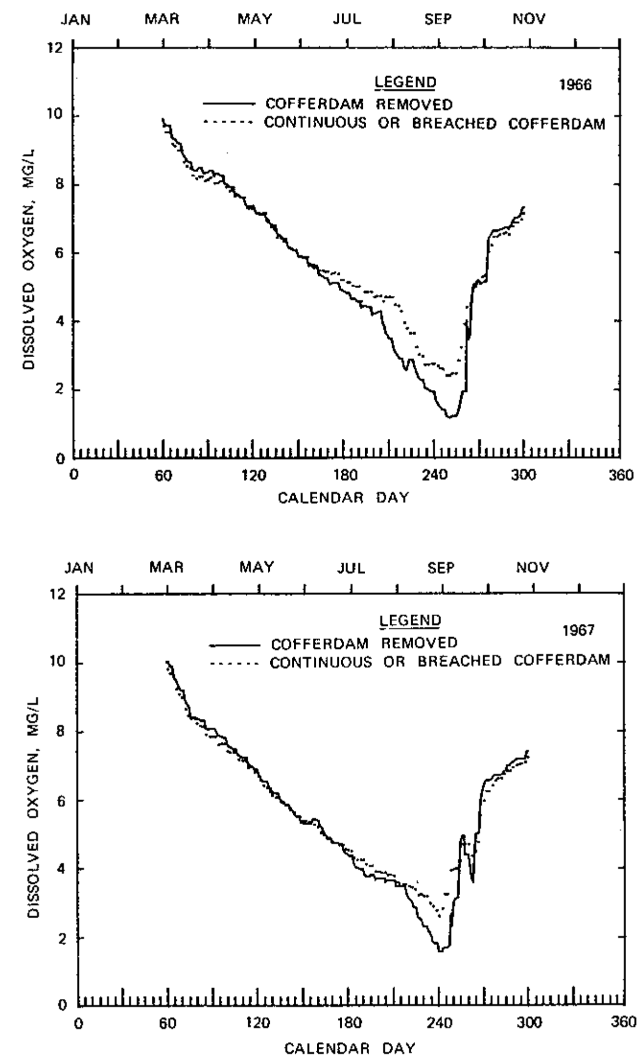

Figure 5. Predicted released DO

the predicted released DO concentrations with the respective cofferdam geometries were essentially equivalent. The difference in the released DO for the respective geometries during these periods was less than 0.25 mg/*l*. Thus, if the reservoir was unstratified or only weakly stratified, the in-reservoir geometry did not significantly impact the released DO.

The release DO concentration was more sensitive to the in-reservoir geometry during significant stratification. In general, the release DO concentration with the cofferdam either continuous or breached tended to be superior to those predicted with the cofferdam removed. These qualitative results are indicated in Figure 5. Essentially identical predictions were obtained for the breached (Option C) and continuous cofferdam (Option B) for the reasons indicated earlier.

Idealized Predictions Of Required Injection Oxygen. To withdraw water from the reservoir that has an average DO concentration of 6 mg/*l*, oxygen would have to be added to the withdrawal zone in the reservoir during periods in which the volumetrically weighted average DO concentration in the release is less than 6 mg/*l*. Typically, the predicted released DO was less than 6 mg/*l* between mid-May and October (Figure 5). The idealized daily average injection rate required to eradicate deficits below 6 mg/*l* was computed by multiplying the average daily release by the volumetrically weighted average DO below 6 mg/*l*. Predicted daily average injection rates for 1966 are presented in Figure 6. Although the predicted injection histories are unique for each study year, Figure 6 is representative of the results for all simulation years.

The temporal injection rate required over a simulation depends upon a large number of variables. However, at any particular time it is essentially dependent upon the vertical temperature and DO distributions, and the operational methodology. Both of these effects are apparent in Figure 6. During the expected maximum stratification, the least favorable DO distribution develops in the metalimnion and hypolimnion. The center line of the penstock is approximately 70 ft below the surface and thus significant quantities of water will be withdrawn from the metalimnion and hypolimnion. If large releases were made during periods of low DO, large injection rates would be required. Conversely, if small releases were made, smaller injection rates would be required. Thus, the predicted injection rates reflect the coupling between operations and the DO in the withdrawal zone. Further, DO in the withdrawal zone varies rather slowly whereas the hydropower operations are highly transient. As a result, erratic daily injection rates were computed.

The maximum daily injection rate (neglecting spikes created by the operational strategy) computed for each study year is presented below.

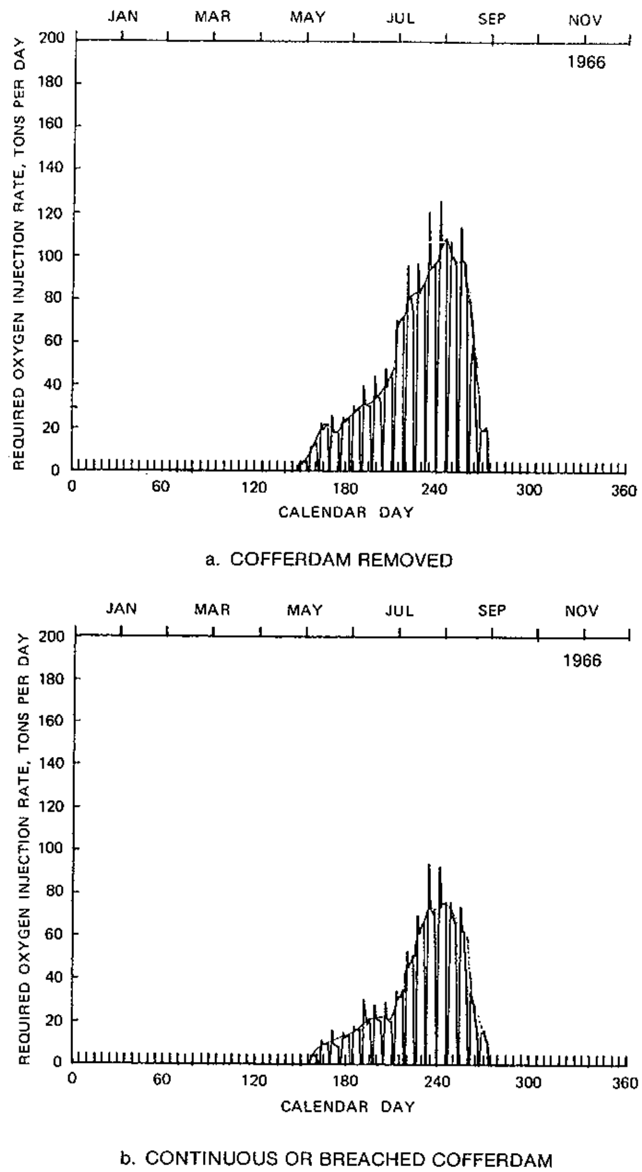

Figure 6. Daily deficit in released DO

	Computed Maximum Injection Rate in Tons Per Day		
Year	Cofferdam Removed	Continuous Cofferdam	Breached Cofferdam
1955	110	62	62
1958	97	55	55
1966	110	75	75
1967	95	70	70

Conclusions

The relative effectiveness and/or feasibility of four in-reservoir structural alternatives in enhancing reservoir and released water quality was predicted. Predicated upon this analysis, the alternatives were ranked in the following order:

Rank	Option
1	Removal of the cofferdam
2	Continuous cofferdam
3	Breached cofferdam
4	Raised cofferdam

The least favorable option is the raised cofferdam. Even though released DO is increased by raising the crest to el 400, substantially reduced water quality may result in the reservoir. Reasonable depletion rates will result in a rather large anaerobic region in the hypolimnion. This occurs because the high crest elevation minimizes advection and vertical mixing at the deeper elevations. This option is not recommended.

Although the predicted water quality (both in the reservoir and in the release) was basically the same for the continuous and breached cofferdams, the latter option is not recommended. The breach provides a flow path below the crest of the cofferdam. Between pumpback and generation, gravity flow through the breach could result in lower quality water between the cofferdam and dam. During the subsequent hydropower release, a pulse of water with relatively low DO concentrations could be released. This flow process was observed in the physical model but significant investigation of this flow was outside the scope of the numerical study.

The effect of the cofferdam (continuous or breached) on the performance of the proposed RBRR oxygen injection system is unknown because the injection system was developed from pilot studies at Clarks Hill Reservoir which did not have a submerged cofferdam. Results from the physical model indicated that the cofferdam significantly affects the hydrodynamics of both the selective withdrawal and pumpback processes. As a result, the presence of a cofferdam could have an adverse effect upon the projected efficiency of the injection system in enhancing the DO in the withdrawal zone.

Any horizontal obstruction in the reservoir which reduces the water withdrawn from the hypolimnion by withdrawal or pumpback (entrainment) has the effect of decreasing vertical mixing and advection. The decreased mixing and increased residence time can result in a degradation in the DO distribution (with time) in the lower layers if oxygen demands exist. The impact of a depletion rate of 0.1 mg/*l*/day upon the DO distribution during September of each study year is demonstrated in Figure 2. If severe loading exists in the hypolimnion, the impact could be more severe.

Removal of the cofferdam should complement the oxygen system. The proposed oxygen injection system is designed to enhance the DO distribution in the zone of withdrawal such that the flow weighted average DO is equal to or in excess of 6 mg/*l*. At any particular time, the desired increase in the DO distribution depends upon the deficit and velocity distribution within the withdrawal zone. It is difficult to design an optimum variable rate system that matches this objective at all times because the deficit distribution varies with time. Thus, the system has to be designed for the maximum anticipated deficit. However, it must also be capable of distributing the oxygen appropriately within the zone of withdrawal. The characteristics of the withdrawal zone (location of the limits and velocity distribution) vary with the hydrological and meteorological conditions. Removal of the cofferdam should reduce this problem. The enhanced vertical mixing which results from the pumpback process will tend to distribute the DO and make placement of oxygen within the withdrawal zone less critical.

The deeper withdrawal distribution that will result with the cofferdam removed will provide slightly cooler releases (1°C to 2°C) than with the other in-reservoir structural alternatives. During periods of relatively strong stratification, the release temperatures will be more favorable. If the temperature criterion is exceeded, this geometrical alternative will tend to reduce its duration and intensity. This should be beneficial in meeting the cold water temperature objective.

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