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WATER QUALITY ENHANCEMENT BY AERATION OF THE RELEASE

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It is often desirable to enhance the water quality of releases from reservoirs by employing outlet works that aerate the flow. This is especially important if the water entering the outlet works is low in dissolved oxygen (DO), since many kinds of aquatic life cannot survive in a low DO environment.

Releases with low DO usually occur as a result of a low-level withdrawal from a density-stratified lake during late spring and summer. Density stratification restricts the vertical transport of DO from the oxygen-rich epilimnion to the hypolimnion. Typically, oxygen demands in the lower regions of the reservoir result in a gradual reduction in DO with depth. Thus, the concentration of DO in the release depends upon the depth from which water is withdrawn from the reservoir.

It is sometimes necessary to release from relatively deep in the reservoir to meet flood-control and/or cold water temperature objectives. In these cases, it may be necessary to employ outlet works that aerate and increase the DO in the release; however, these structures must be carefully designed. Enhancement is achieved only if aeration increases the DO level but does not significantly increase dissolved nitrogen (DN) concentrations. As a result, to design hydraulic structures that effectively reaerate releases, techniques are needed to predict the magnitude of gas transfer that occurs during flow through a structure.

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APPROACH

To develop predictive techniques, it is imperative to identify and analyze the dominant gas transfer mechanisms in various hydrodynamic flow regimes. If this is known, it will be possible to model, either physically or mathematically, the total gas transfer occurring during flow through a structure by superposition of the effects of the respective flow regimes. To achieve this objective, the dominant flow processes typically encountered in CE hydraulic structures are being investigated in hydraulic models and field studies under EWQOS Work Unit IIIA.

MODEL STUDIES

Free hydraulic jumps. The initial investigations addressed free hydraulic jumps since they occur in numerous hydraulic structures and since preliminary data indicated that this flow regime induces substantial reaeration. The gas transfer was related to the Froude number and unit discharge

Hydraulic jumps with unit discharges of 0.414, 0.331, and 0.261 cfs for a range of Froude numbers of flow between 1.8 and 9.3 have been investigated (Figure 1). The gas transfer for a particular unit discharge increases for the range of Froude numbers of flow investigated. Similarly, for a particular Froude number, the uptake increases with unit discharge. As the Froude number or unit discharge is increased holding all remaining variables constant, the energy dissipated in a hydraulic jump increases, resulting in greater gas transfer.

Flow visualization studies indicated that air entrainment predominantly occurs in the upper region of the hydraulic jump and is most prominent in the roller; only a few entrained air bubbles

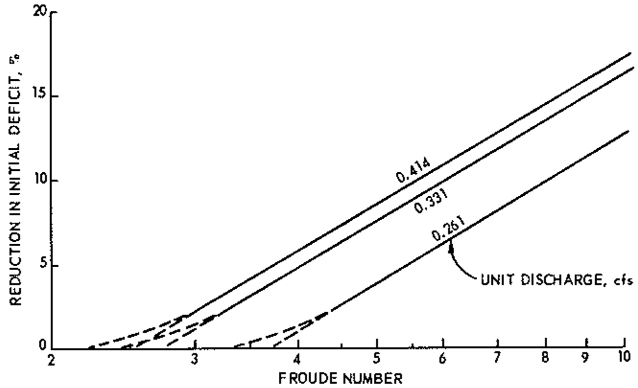


Figure 1. Gas transfer in free hydraulic jumps at various unit discharges

were visible at depth (Figure 2). As a result of the air-entrainment pattern, gas exchange in a well-designed hydraulic jump primarily occurs at or near the surface.

This implies that the dissolved gas concentrations during flow through a hydraulic jump will always approach saturation concentrations corresponding to surface conditions. The results are very significant with respect to the design and application of free hydraulic jump to improve water quality.

If the entering fluid is low in DO, an oxygen uptake will result. Conversely, if excessive DN concentrations exist in the forebay, a hydraulic jump may be used to reduce DN. Additionally, if both problems existed concurrently, free hydraulic jumps could be used to solve the problems.

The quantitative changes in dissolved gas concentration can only be determined after hydraulic jumps with larger unit discharges and higher Froude numbers are investigated. After these investigations are completed, modeling techniques can be developed to predict oxygen and nitrogen transfer. In the interim, the test results to date can be used for qualitative indication of the relative effectiveness of various free hydraulic jump conditions in increasing DO and/or reducing excessive DN concentrations.

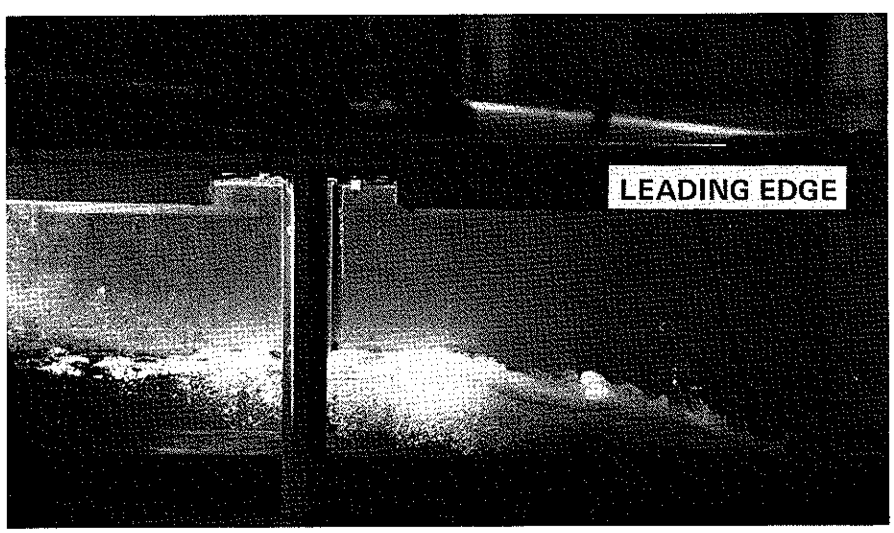
The test program indicated that the same approach would delineate the gas transfer characteristics of various flow regimes and that the relative oxygen uptake produced as a result of various structural modifications could be investigated in hydraulic models.

Effects of flip lips. Tests were conducted in a 1:20-scale model of Lower Monumental Spillway (Snake River) that reproduced a short portion of forebay and a single bay of the spillway section of the dam with the tainter gate for flow control. The stilling basin and a portion of the exit channel were included in the model. Spillway configurations with and without a flip lip on the spillway surface were investigated with a flow rate equivalent to 15,000 cfs in one bay of the prototype.

Flow visualization studies indicated a flow phenomenon analogous to prototype observations. Without the flip lip, a plunging flow (Figure 3) was observed with large quantities of entrained gas bubbles. The flip lip (Figure 4) deflected flow along and near the surface of the tailwater instead of allowing the water to plunge; bubble entrainment was much more localized and near the surface.

The flip lip increased the gas transfer by 37 percent in the model; however, this does not necessarily imply that a 37-percent increase in DO will occur in the prototype. The exact scaling relationship between the model and prototype is still under investigation. It does demonstrate that

Figure 2. Model study of free hydraulic jump



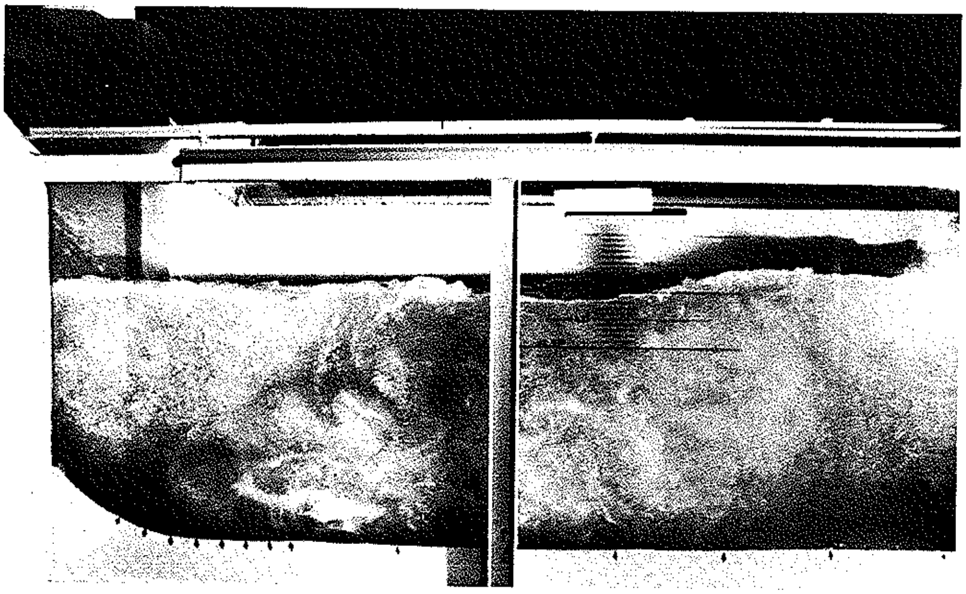


Figure 3. Plunging flow observed without flip lip in 1 : 20 scale physical model of Lower Monumental Spillway (Snake River)

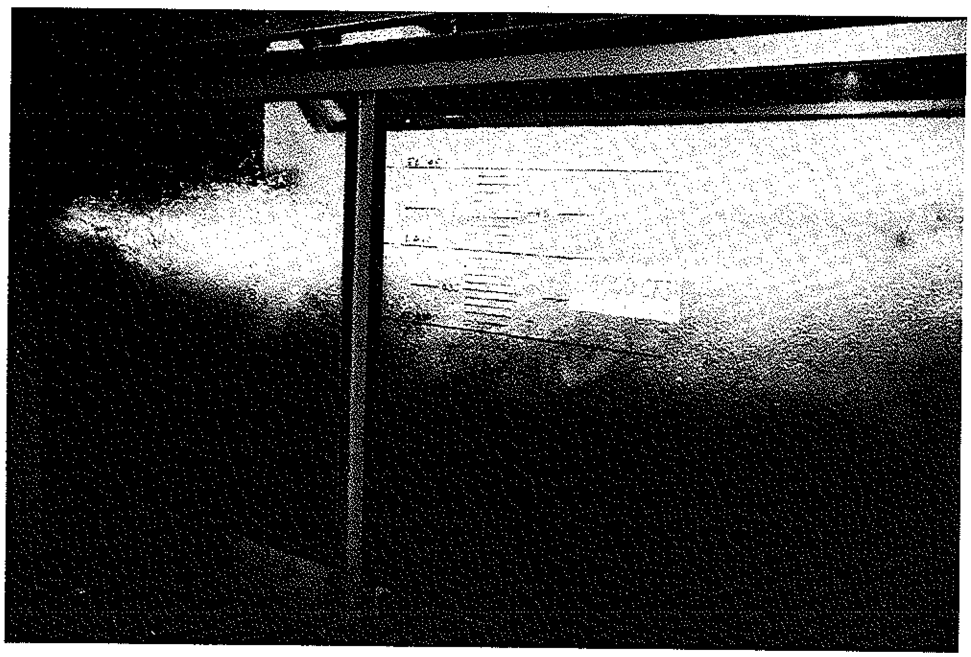


Figure 4. Surface flow observed with flip lip in 1 : 20 scale physical model of Lower Monumental Spillway (Snake River)

the flip lip will substantially increase the DO if a deficit exists.

Excessive nitrogen supersaturation does not occur with a properly designed flip lip because the gas is transferred from the released water near the surface to the atmosphere; consequently, nitrogen concentrations tend to be equilibrated relative to surface conditions. As a result, if nitrogen supersaturation exists in the forebay, degassing will occur, and if a nitrogen deficit exists, nitrogen concentration will approach the surface saturation concentration. Reduced nitrogen concentrations with a flip lip are not necessarily the result of less total gas transfer. This may or may not be the case, depending upon the respective operating conditions and geometrical configurations.

The Lower Monumental results clearly imply that the relative effectiveness of various structural modifications to improve gas transfer can be investigated in hydraulic models on a site-specific basis. Similarly, flow visualization studies can be effectively utilized to qualitatively investigate nitrogen supersaturation potential.

Conclusions. The released water quality can be improved by employing hydraulic structures that increase DO and/or decrease nitrogen saturation levels. Techniques have been developed by WES to assist in designing environmentally effective hydraulic structures. The approach utilizes a coupling of hydraulic modeling, flow visualization, and radioactive tracer techniques to determine the relative effectiveness of various outlet work designs and/or structural modifications. Implementation through various site-specific model studies will result in more cost-effective designs and should prevent ineffective structural modifications.

COMPARISON OF MODEL AND PROTOTYPE DATA

Research is also being conducted for comprehensive comparison of model and prototype data, thereby identifying generalized scaling relationships. At Enid Reservoir, field data have been obtained that quantify the gas transfer that occurred as the fluid traveled between specific points in the structure. Thus, the effects of the respective fluid flow processes can be independently determined at several operating conditions. Model data are currently being obtained for similar operating conditions from a 1:20-scale model of the Enid Outlet Works. This study coupled with the results from the other model investigations will facilitate identification of the dimensionless groupings required for quantitative scaling of reaeration occurring in various flow regimes common to reservoir outlet works.

BIOLOGICAL ASPECTS OF RESERVOIR WATER QUALITY MODELING

*Joseph L. Norton**

Predictive capabilities of reservoir water quality models depend primarily upon the degree of understanding of the many physical, chemical, and biological processes that influence water quality. The objective of EWQOS Task IB.1 is to increase the understanding of reservoir ecological processes and thereby improve the ability to describe and predict them.

TROPHIC STATE

Ecological processes in reservoirs are impacted by several factors including project operation, hydrodynamics, inflowing water quality, and meteorological conditions. The combination of these factors and processes determines the quality of water in the pool. This water quality is often expressed in terms of an arbitrary trophic-state scale ranging from oligotrophic (few nutrients present) to eutrophic (many nutrients present).

Because objectional manifestations of eutrophication constitute a large proportion of the day-to-day water quality problems of reservoir operation, a report discussing trophic state in lakes and reservoirs was prepared by the U. S. Environmental Protection Agency (EPA), Environmental Monitoring and Support Laboratory, Las Vegas, Nevada, through an Interagency Agreement with the WES.

The EPA report provides some insight into the rationale behind the concept of trophic state, presents several definitions of "eutrophication," and discusses several techniques of trophic classification. The report concludes that :

> Trophic classification should be placed in proper perspective and the need for appropriate application of classification techniques should be recognized. Consistent application of a specific trophic classification technique to a single lake or a group of lakes can reveal useful information concerning relative changes over time (trophic trend analysis). However, the limitations inherent in forcing lakes into categories with ill defined limits—particularly when the limits are based upon single parameters—must be recognized and discretion used in application of such techniques. A more practical approach to reservoir classification would place paramount consideration upon the potential beneficial uses of the lake and, possibly, the regional water quality characteristics required to meet those uses. From such analyses it would be readily apparent whether a reservoir can support such uses or whether it can be managed to bring important water quality parameters within acceptable ranges.

ZOOPLANKTON-BENTHOS

In addition to providing information on general ecological principles, Task IB.1 includes examining in detail some basic compartments of the reservoir ecosystem to enhance the predictive capabilities in those areas. The U. S. Fish and Wildlife Service, National Reservoir Research Program, Fayetteville, Arkansas, reviewed simulation modeling of zooplankton and benthos in reservoirs and provided recommendations for model constructs. This very thorough review and discussion also includes an extensive compilation of rate coefficients for grazing, assimilation, respiration, and mortality, both predatory and nonpredatory. These data have also been presented in histogram form to facilitate the

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stochastic modeling efforts under investigation in EWQOS Task IC.1 (One-Dimensional Reservoir Water Quality and Ecological Predictive Techniques). The algorithms proposed in this report have been incorporated into the CE one-dimensional reservoir water quality model (CE-QUAL-R1) and are currently under evaluation.

One recommended change involves the use of an Ivlev formulation for a grazing construct rather than the Michaelis-Menton formulations used previously. The feeding rates predicted as a function of increasing food concentration by the two equations are compared in Figure 1. At food concentrations below the half-saturation coefficient level k_s, the Ivlev formulation predicts feeding rates to be slightly less. Values predicted by the Michaelis-Menton formulations are lower at food concentrations greater than k_s. Although the overall form of the Ivlev equation is not appreciably different, preliminary results indicate substantially improved simulations.

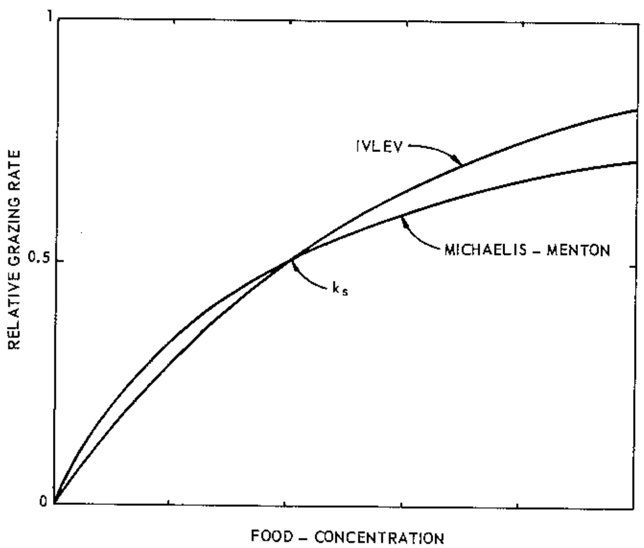

Figure 1. Comparison of the Ivlev and Michaelis-Menton functions with the same half-saturation value k_s.

PHYTOPLANKTON

Detailed studies for the CE-QUAL-R1 phytoplankton compartment are proceeding in a parallel fashion. Subsequent to an EWQOS workshop held at the Asilomar Conference Center, Monterey, California, April 1979, a two-volume contract report is being prepared by Tetra Tech, Inc., that discusses phytoplankton-environmental interactions in reservoirs. Volume I of this report, entitled "Phytoplankton-Environmental Interactions in Reservoirs," consists of a series of papers presented by leading phytoplankton researchers and provides a state-of-the-art review of phytoplankton dynamics. Volume II provides a thorough discussion of phytoplankton modeling and recommends several algorithms that are being evaluated in the CE-QUAL-R1 model.

A major change in the phytoplankton compartment that is being considered pertains to increasing the number of algal groups from two (currently modeled) to four. This extension will allow consideration of green algae, diatoms, nitrogen-fixing bluegreen algae, and nonnitrogen-fixing bluegreen algae as distinct functional groups. It is anticipated that this modification will improve the prediction of blooms and succession phenomena.

SUMMARY

Modeling of systems as complex as biota in reservoirs is a task that must be approached in an interdisciplinary fashion. The chemistry of the reservoir, for example, has profound effect on the biota. Efforts in other EWQOS work units have therefore been directed toward improving the understanding of (1) anaerobic situations to enable more accurate modeling and (2) the interactions between the dissolved and particulate portions of the aquatic system as they impact the availability of nutrients. This integrated approach coupled with extensive field data collection will yield improved water quality and ecological simulation models that can be applied to reservoir planning, design, and operation to attain environmental quality objectives.

DESCRIPTIONS OF RESERVOIR CHEMICAL PROCESSES

*Douglas Gunnison**

In many cases, impoundment of natural waters by CE reservoir projects has resulted in conditions wherein low concentrations of dissolved oxygen (DO) develop in reservoir hypolimnions and, subsequently, in the water discharged from projects with hypolimnetic withdrawal. Also, nutrients and metals are released from reservoir sediments when the hypolimnion becomes anoxic. Adverse impacts of these conditions include harmful effects on aquatic biota, loss of project benefits, increased operation and maintenance costs, potential conflicts with public health criteria, and increased costs to

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downstream water users. The present lack of knowledge of the many biological, chemical, and physical consequences of aerobic and anaerobic sediment/water interactions in reservoirs makes it difficult to predict the conditions that may occur and also to evaluate potential corrective measures should problems exist.

Descriptive methods that characterize reservoir water chemistry processes are required to provide both predictive and evaluative techniques to determine the occurrence of low DO levels and anoxic conditions and the effects on reservoir project purposes. Such descriptions are also needed to evaluate the effectiveness of various operational and/or structural alternatives in ameliorating these problems.

Particular emphasis is required on descriptions that characterize chemical changes associated with dissolved-particulate-matter interactions. Such descriptions are needed to provide accurate predictions and evaluations of nutrient and metal distributions between dissolved and particulate phases and the subsequent relative availability of these constituents in reservoirs.

Development and verification of descriptions of reservoir chemical processes are the objectives of laboratory and field investigations under EWQOS Task IB.2.

RESEARCH APPROACH

The development of new or improved descriptions of reservoir chemical processes requires several approaches to define and characterize the major biological, chemical, and physical interactions that must be considered. For both anaerobic and aerobic chemical processes, detailed literature reviews and technical workshops have been conducted to identify or develop descriptions of key interactions, verify the appropriateness of existing or proposed concepts, and suggest directions for laboratory and field efforts.

PREDICTING RESERVOIR WATER QUALITY

The initial efforts led to the development of a DO subroutine with anaerobic processes (DOSAP) that depicts the development of anoxic conditions in reservoirs. DOSAP consists of a seven-step procedure that tracks chemical processes proceeding from aerobic to anoxic conditions with a series of anaerobic product-generating steps, each of which is chemically more reducing (more intensely anaerobic) than the previous. The seven steps include:

- Dissolved oxygen depletion
- Dissolved oxygen exhaustion
- Ammonium accumulation
- Manganese accumulation
- Iron accumulation
- Sulfate reduction
- Methanogenesis

The theoretical basis for the development of DOSAP is presented in detail in a technical report entitled "Characterization of Anaerobic Chemical Processes in Reservoirs: Problem Description and Conceptual Model Formulation." This report is presently in publication.

Current efforts are focused on evaluating the most appropriate aerobic subroutine from those currently available for depicting dissolved-particulate chemical interactions. Once evaluations have been completed, the aerobic subroutine selected for use with DOSAP will be coupled to the Corps' reservoir one-dimensional water quality model, CE-QUAL-R1, for simulating the accumulation of anaerobic constitutents in an anoxic reservoir hypolimnion.

LABORATORY INVESTIGATIONS

Laboratory investigations were undertaken to quantify chemical process rate coefficients using sediments from existing CE reservoirs. Laboratory studies were also initiated to provide the chemical process rate coefficients for dissolved-particulate interactions.

Initial investigations of anaerobic sediment-water interactions were performed in small laboratory reaction vessels under intensively stirred conditions. Subsequently, it became evident that effective simulation of sediment-water interactions under natural conditions required devices that allowed interactions to occur under circumstances that permitted the sediment to remain settled while providing a large sediment-water contact area. It was also necessary to have a large volume of water from which to remove samples over prolonged periods of sediment-water exposure.

To meet these constraints, 250-litre sediment-water reaction chambers were constructed of plexiglass (Figure 1). The chambers can contain a sediment layer of 20-40 litres ($\approx$15 cm in depth) overlain with approximately 200 litres of water. To prevent stagnation, a circulation system was incorporated that provides a gentle but effective mixing of the entire water column. This enables a homogeneous, representative sample to be obtained anywhere in the water column.

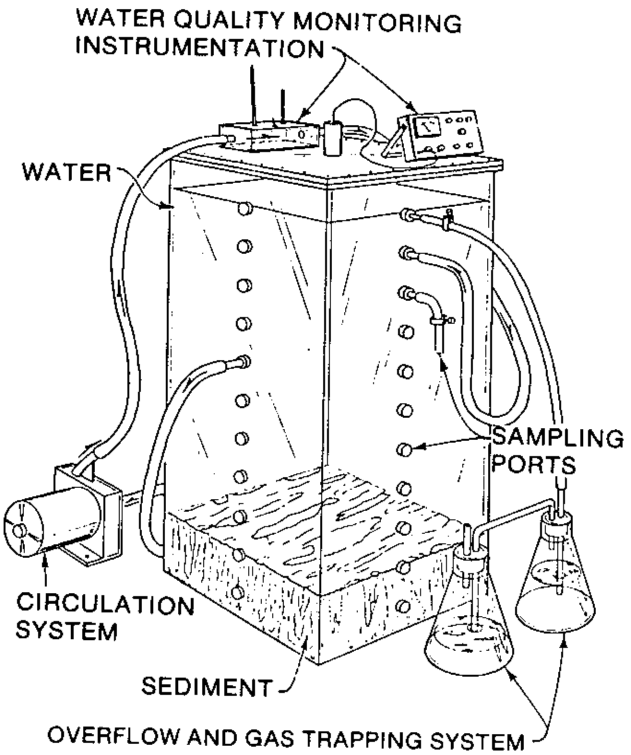

Figure 1. Sediment-water reaction chamber for studying anaerobic conditions in reservoirs

Since the initiation of investigations using these chambers, five sediments from different CE impoundments have been examined; an additional five impoundment sediments will be processed before the study is completed. Data being obtained in these investigations include information on the kinetics of nutrient and metal exchanges between sediment and water column under both aerobic and anaerobic conditions; values for the rate of dissolved oxygen depletion followed by changes in redox potential during the development of anaerobic conditions are also being obtained (Figure 2).

FUTURE ACTIVITIES

Field studies are being planned to provide verification of the chemical rates for anaerobic processes being obtained in laboratory investigations. Other future activities will be directed toward improving and verifying descriptive formulations depicting both aerobic and anaerobic processes.

SUMMARY

The approach of Task IB.2 is to convert conceptual descriptions for aerobic and anaerobic reservoir chemical processes into practical techniques for application to water quality management problems. In addition, the work unit will provide required data bases for evaluating interactive chemical processes that occur in CE reservoirs and influence water quality and authorized project purposes. The understanding and predictive capability provided by these techniques will form a sound technical base for developing engineering and operational solutions to difficult environmental quality problems.

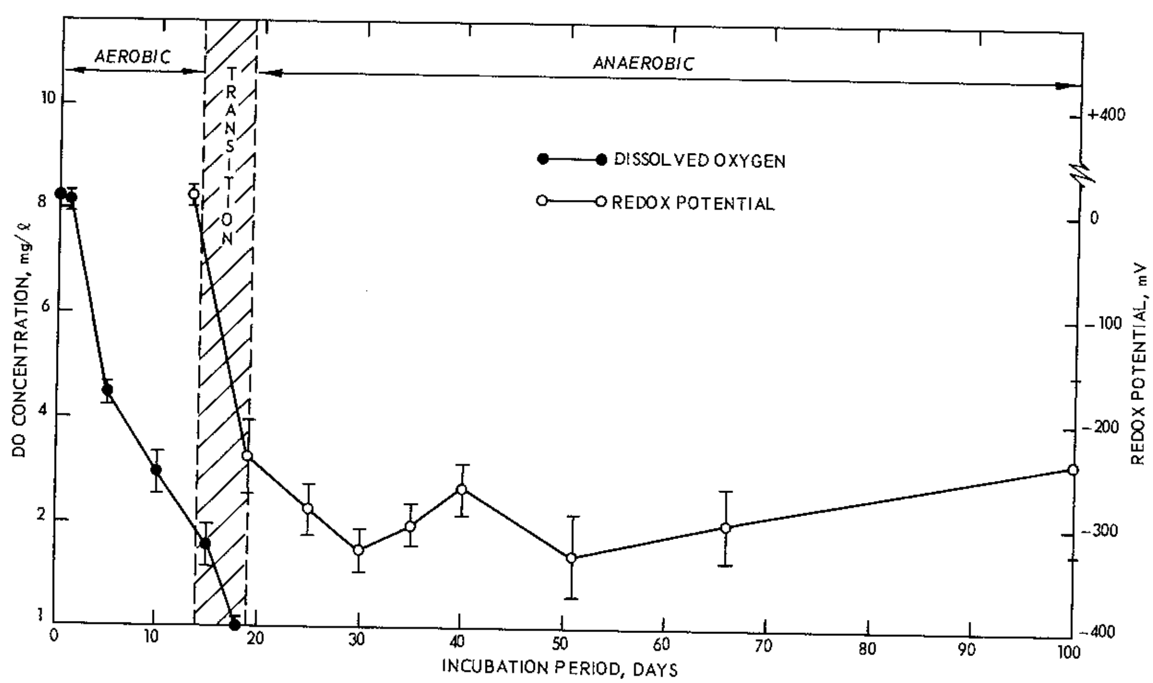

Figure 2. Rate of DO depletion followed by changes in redox potential during development of anaerobic conditions.

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