CE-QUAL-ICM THREE DIMENSIONAL SURFACE WATER QUALITY MODEL

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INTRODUCTION

Water quality encompasses the many chemical and physical features which determine the relative "health" of an aquatic system. The type and abundance of aquatic life forms and vegetation depend upon the water quality of the system. Systems adversely affected by anthropogenic loadings typically have degraded water quality as characterized by decreased dissolved oxygen (DO) levels and increased levels of nutrients and oxygen depleting substances. Degraded systems tend not to support the amount or variety of aquatic life that they did previously and are not as aesthetically pleasing to the people living and working near them.

The water quality of an aquatic system depends upon numerous items, some natural some anthropogenic. The complexity of the system and the processes involved require a comprehensive approach when addressing the issues of cause and effect when dealing with water quality. Both the physics of the system's circulation and the biological and chemical processes occurring within that system must be understood in order to describe the water quality and predict what impacts will occur as a result of changes to the existing system. The natural flow patterns and circulation within a system determine the residence time and mixing of water within that system and significantly affect the water quality of the system. Human activities such as dredging, channelization, creation of structures, and filling can result in changes in circulation. The degree to which circulation pattern modifications change the existing water quality is often not easily discernible.

In addition to the natural loadings, aquatic systems often are receptors of municipal and industrial wastewater discharges along with polluted rainfall runoff. These loadings can tax the assimilative capability of the system and result in a degradation of water quality which, in turn, can affect living resources such as fish, aquatic invertebrates, filter-feeders, and sub-aquatic vegetation. The degree to which degradation occurs or is due to pollution typically is not easy to determine without conducting a comprehensive study on the physical, biological, and chemical processes at work in the system.

The Environmental Laboratory (EL) of the U.S. Army Waterways Experiment Station has developed a tool for use in answering these and other questions dealing with surface water quality. CE-QUAL-ICM (ICM) is a multi-dimensional surface water quality model developed for the study of eutrophication and anoxia in Chesapeake Bay (Cerco and Cole 1994). Chesapeake Bay water quality has been degraded by municipal and industrial wastewater discharges along with agricultural and other non-point source (NPS) discharges occurring in its watershed. These discharges were blamed for seasonal anoxic conditions in the bottom of the mainstem of the bay, algae blooms, increased levels of nutrients, and a decrease in living resources. Because of the scope of the water quality problem and the number of state and local governments involved, the U.S. Army Corps of Engineers was selected to perform a water quality modeling study. In this study, ICM was calibrated for a three year period using an extensive data base of water quality observations. Once the model was calibrated, numerous scenarios were performed in which the long term effects of different wasteload reduction plans were determined. Based upon these results, federal and state governmental bodies and regulatory agencies are determining what remediation steps to undertake.

CE-QUAL-ICM FEATURES

CE-QUAL-ICM is a multi-dimensional (1,2, or 3-D) finite volume water quality model. Surface water systems are divided into boxes, or cells, and the concentrations of the constituent of interest within each of the cells computed. Exchange between a cell and its neighboring cells is accomplished via advective and dispersive transport processes across the flow face that connects one cell to another. The release version of ICM consists of 22 independently activated state variables (Table 1). ICM interfaces with a fully predictive sediment diagenesis submodel which receives settled material from the water column, decays that material, and in response to water column conditions, releases it back to the water column. In place of the sediment model, sediment fluxes can be specified at the user's discretion. ICM allows external loadings of constituents for simulation of point source and non-point source loads along with loadings due to atmospheric deposition. ICM has numerous forms of user controlled output including instantaneous and averaged (over time) concentrations for all constituents being modeled and mass balances of sources and sinks for constituents.

Hydrodynamic information required by ICM consists of cell lengths, cell volumes, cell surface areas, flow face areas, horizontal flows, vertical flows, and vertical diffusivities. Typically this information is generated using the Computational Hydrodynamic in 3 Dimensions (CH3D) finite difference model. CH3D uses a curvilinear grid to capture the physical features of a system. Inputs to CH3D consist of external flows at river boundaries, water surface elevations at tidal boundaries, bottom friction coefficients, salinity and temperature boundary conditions, and meteorological data. Hydrodynamic information for ICM is averaged, output from CH3D, and then stored in a file. Because of this arrangement, hydrodynamic information for ICM need only be generated once. Multiple ICM simulations can be performed using "stored" hydrodynamic information which decreases the computational requirements of a study and the run times of an individual simulation. This arrangement also allows ICM to utilize a stability based timestep computation feature which enables it to use longer timesteps than CH3D which further decreases total ICM simulation time.

In addition to the Chesapeake Bay, ICM has been used by WES to study 7 other surface water systems (Table 2). The reasons for these studies varied. In some instances it is necessary to determine beforehand the water quality impacts resulting from a proposed project which will alter circulation within the system. Examples of such projects are the creation of islands and fill areas, dredging of channels, and flood diversion projects. In many instances, permitting bodies require conclusive evidence that the proposed project will not degrade water quality. Another use for ICM is in analysis of a system and determination of the allowable wasteload for that system. Numerous wasteload load reduction scenarios can be performed quickly and easily prior to imposition of any new standards upon dischargers to the system. A third use for ICM is in the study of little understood systems in order to determine what are the key processes at work within the system. An example of this is the ICM study of an upland hardwood wetland in which it was determined that leaf litter contributed significantly to the nutrient loading of the system.

Studies conducted for investigation of water quality impacts due to circulation changes typically consist of weeks long simulations of a specific event, i.e., flood, with and without the project. Model output is generated often in these studies to capture any transient event. Because of this, output files from these studies can be very large even though a short period was. On the other hand, studies conducted for wasteload allocation or eutrophication purposes can consist of multi-year to multi-decade simulations. The reason for the simulation's long duration is to observe the long term response of the sediments to the changes in the overlying water column. Output from these studies may be generated on a monthly or quarterly time frame so that long term trends are observable.

Computational resources required for an ICM simulation are changing. When the model was developed, the only computers capable of performing simulations in a reasonable time frame were supercomputers such as the CRAY Y-MP. Today, ICM simulations are performed using workstations and top-end PCs. The specific computational requirements for an ICM application vary from study to study. The major factors affecting the decision on which machine to use for the simulation are the grid size and simulation duration. ICM computational memory requirement is directly linked to grid size and storage requirements are a function of grid size and simulation duration.

A recent application of ICM is presented below. This study was conducted for the New York District, Passaic River Division, for the purpose of determining what impacts might result from operation of a flood diversion tunnel discharging into upper Newark Bay.

Study Background

The Passaic River drains 935 square miles of northern New Jersey and southern New York and empties into Newark Bay which is part of the New York/New Jersey harbor system, (Figure 1). The Passaic, along with the Hackensack River, are the only freshwater flows into northern Newark Bay. The Passaic River basin is heavily developed and is susceptible to destructive flooding during storm events. A diversion tunnel has been proposed as a means of alleviating the flooding in the lower portion of the Passaic basin by diverting floodwaters from the upper basin directly to Newark Bay. Floodwaters would enter the tunnel at two locations in the upper basin and be discharged at an outlet structure located between the mouths of the Passaic and Hackensack Rivers. Total tunnel length would be 20.1 miles and the tunnel would have a diameter of 42 feet. Due to construction requirements, the proposed tunnel will have a profile of an inverted siphon with a volume of 2.65×10^6 m^3 below sea level. Under one set of operating conditions, this portion of the tunnel would remain filled with floodwaters after a flood event.

The objective of this study was to determine what impact operation of the Passaic River Flood Diversion Tunnel would have upon living resources in Newark Bay, specifically fin fish and shell fish. With the aid of the Marine Fisheries Service, the parameters impacting these living resources most were identified as temperature, dissolved oxygen, and salinity. Information on these parameters and the impact of tunnel operation upon them would be used by others to determine the effect upon living resources.

Models

The sigma version of CH3D was used for the hydrodynamic portion of the study and to generate hydrodynamic information for the water quality model CE-QUAL-ICM. Calibration and scenario hydrodynamic information was generated using a CRAY C-90 supercomputer. Water quality computations were conducted using a CRAY Y-MP supercomputer. Specific information of ICM kinetics for the Passaic River study can be found in Cerco and Bunch (1996).

Hydrodynamic and Water Quality Grids

The water quality grid for this study was a one-to-one overlay of a portion of the hydrodynamic grid. The region covered by the hydrodynamic grid extended from the Hudson River Fall line to the New York Bight. The size of this grid was necessitated by the availability of information for hydrodynamic boundary conditions and was far beyond the farthest extent of any impacts arising from tunnel operation. For computational efficiency and in order to decrease the amount of input data required, a smaller portion of this grid (Figure 2) was used for water quality simulations. Though smaller than the CH3D grid, the ICM grid was still extensive enough that the Hudson River boundary and the open ocean boundaries had negligible impact upon the tunnel outlet site and would therefore not bias the results. This was documented in numerous simulations run prior to locating the boundaries at these locations. The ICM grid, after moving the boundaries, had a total of 6815 cells in five layers of 1363 cells each. The total number of cells in the ICM grid was approximately 40% of the total in the CH3D grid.

State Variables

In this study, the question to be answered was what effect the tunnel operation would have upon water quality. In order to answer this question the following state variables were modeled: temperature, salinity, dissolved oxygen (DO), chemical oxygen demand (COD), and ultimate biochemical oxygen demand (BODu).

Temperature and salinity were modeled because of the short term changes in both, arising from tunnel operation, could be detrimental to living resources. Both parameters are already calculated in CH3D as part of its hydrodynamics computations and would have been adequate for determination of impacts from tunnel operation upon these two parameters. These variables were included in the ICM suite of state variables because of the effect that they have upon other variables. Both temperature and salinity affect dissolved oxygen solubility. Temperature is also modeled because of the important effect it has upon biochemical reactions. Computation of salinity in ICM allows for verification that ICM and CH3D are linked properly and transporting material in a like manner.

Dissolved oxygen was modeled because it is essential for higher order life forms. Transient effects upon DO could have serious impacts upon all aquatic life in the area. The extent of any impact upon dissolved oxygen arising from tunnel operations could be ascertained. DO also plays an important role in many chemical reactions and processes which can affect water quality. BODu and COD were included because of the effect that both have upon DO. BODu is a measure of the oxygen requirement to biologically decay all organics in water. In this study, COD was used to represent the oxygen demand required to oxidize reduced substances which might be generated by tunnel operation. COD can also be generated when DO levels in the water column are insufficient to satisfy benthic oxygen demands.

Model Applications

Application details of CH3D are covered in the hydrodynamic report and are beyond the scope of this paper. Application of ICM can be separated into three distinct operations: data collection and assembly, ICM calibration, and tunnel scenario testing. Each of these is covered below.

Data Collection and Assembly

WES contracted the field sampling program for this study to Stevens Institute of Technology. Stevens personnel made in situ measurements of temperature, salinity, and dissolved oxygen at thirty stations throughout the study area at monthly intervals during the period July to September 1994. During each sampling event, grab samples were collected at 25 of those stations and analyzed for five day BOD (BOD5) and BODu. Data collected by Stevens was augmented with dissolved oxygen and temperature measurements made by the National Marine Fisheries Service during the period May 1993 to May 1994 and with data obtained from New York Department of Environmental Protection.

Stevens also compiled a database of point source dischargers for the entire New York - New Jersey Harbor area. From this list, the most substantial dischargers in study area were identified and their discharge records for the year preceding the calibration period obtained from the New Jersey Department of the Environment. Information on point source dischargers obtained by Stevens was augmented with data contained in reports generated for EPA on waste loads to the New York-New Jersey harbor system (HydroQual 1991).

Combined Sewer Overflows (CSOs) generate a significant nonpoint source loading to this system. Loads due to CSOs were developed for each watershed discharging into the study area using daily precipitation records and information contained in the New York/New Jersey Section 208 report (Hazen and Sawyer 1978). Nonpoint source loads were applied as distributed loads to all edge of stream cells below the fall lines. Freshwater inflows representing point source and nonpoint source flows were included in CH3D because of the magnitude of the flows and the effect that they have upon circulation in certain areas of the system.

Ocean boundary conditions were set using data collected by Steven's Institute and the New York City Department of Environmental Protection. Fall line BODu boundary conditions were set using a relationship developed for each stream based upon flow and observed BOD. Fall line loadings were calculated as the product of the calculated fall line BOD and flow.

ICM Calibration

ICM was calibrated for the period July 1, 1994, through September 11, 1994. Loadings to the system and boundary conditions were generated as indicated above. Artificial initial conditions corresponding to July 1 were used for calibration. They were generated by looping the model with constant inputs until equilibrium was reached. ICM output was compared to data collected during the July to September field study using time series plots, longitudinal transect plots, and predicted/observed scatter plots. Time series plots of model output and observed data for mid-Newark Bay are shown in Figure 3. The solid line represents ICM daily depth-averaged concentrations and the shaded region indicated maximum and minimum daily ICM values. Circles represent mean observed concentrations and the vertical bar indicates the range of observations.

ICM predictions for the overall system were good. ICM performs well in Newark Bay below the proposed tunnel's outlet. It captures the minimum DO levels which is important for living resources impact determination. ICM does an excellent job on temperature predictions and the salinity predictions are within the range of daily observations.

ICM Scenarios

A matrix of scenarios were developed to assess impacts of tunnel operation. Scenarios consisted of three tunnel configurations: no tunnel, dry tunnel, wet tunnel. The no tunnel configuration simulated future conditions as if the tunnel were not constructed and served as a point of comparison for the other two configurations. In the dry tunnel configuration, the below-sea-level portion of the tunnel is pumped dry after each flood. In the wet tunnel configuration, the tunnel contains floodwater from the preceding flood which is forced out by the next flood. Since the tunnel was designed to operate on floods with periods of two years or greater, the water in the tunnel would have adequate time for extensive water quality degradation. Floodwater BODu levels in excess of DO levels could result in anoxic conditions leading to production of reduced substances and methane. It was feared that this situation would severely degrade DO levels in the receiving waters of Newark Bay when this water was discharged from the tunnel by the next flood.

The effects of prolonged storage on floodwaters was determined by incubating samples of Passaic River water for six months under conditions similar to those expected in the tunnel. DO levels were measured daily and samples were withdrawn periodically for determination of BOD. Gas production was monitored to observe if hydrogen sulfide or methane were generated by anaerobic decay. Experimental results indicated that biological decay continued until DO reached 1.5 mg/l, then ceased. BODu levels were slightly higher than DO levels at the end of the experiments and no gas production or immediate oxygen demand was observed. Based upon these results, it is reasonable to expect that DO and BOD in the tunnel eventually would, under worst case conditions, reach 0 mg/l.

The incubation results corroborated conclusions reached after comparing observed DO and BODu levels of the upper Passaic River. Historical observations indicated that mean fall-line DO and BODu levels are approximately equal.

Flood conditions resulting from three storm events were simulated for each tunnel configuration: 2 year storm, 25 year storm, 100 year storm. The 2 year storm flood is the minimum flood which will cause tunnel operation. All scenarios were run for February and July mean meteorological conditions. Newark Bay temperatures are coldest (1° C) in February and warmest (28° C) in July. These months provide worst case conditions for temperature shock to living resources resulting from a discharge of 12.7° C tunnel water. July also provides the lowest receiving water DO and less capability to handle anoxic tunnel discharges.

Scenarios had durations of 27 days. The first 13 days were model "spinup" which allowed the model to equilibrate with scenario loads and boundary conditions. Spinup was followed by a 14 day storm simulation.

Scenario Results

A total of 18 scenarios were run. Results from wet and dry tunnel simulations were compared to base (no tunnel) simulations for the same conditions. Any differences in the simulations with the tunnel and the base simulation were attributed to tunnel impact. DO results for four scenarios are shown in Figures 4 - 7. Solid lines indicate base (no tunnel) conditions and dashed lines indicate wet or dry tunnel conditions.

Results from the dry tunnel simulations indicated DO concentrations increased in upper Newark Bay with the tunnel in place. This occurred because the tunnel was placing oxygen saturated floodwaters directly into upper Newark Bay. Without the tunnel, the DO of these floodwaters would be decreased by CBOD and SOD as it traveled down the Passaic River.

In the wet tunnel scenarios a short term decrease in DO occurs near the tunnel outlet. For the 2 year, 25 year, and 100 year storms the minimum DO next to the tunnel outlet was approximately 2 mg/l. The minimum DO predicted at the tunnel outlet for the 2 year storm was only slightly lower than the minimum DO predicted without the tunnel. Results indicated that the duration of the DO decrease near the tunnel outlet for the 2 year flood was longer than that of the 25 year and 100 year floods. This is because a longer period is required to purge the tunnel with the 2 year flood. Once the tunnel has been purged of the 0 mg/l DO water, the tunnel conveyed DO saturated upper Passaic River water which resulted in an increase in DO concentrations near the outlet.

CONCLUSIONS

Scenario results indicated that DO impacts resulting from discharge of DO depleted water were limited in duration and extent. Dilution and reaeration combined to limit tunnel impacts. DO depleted tunnel water mixed quickly with the receiving waters of Newark Bay. Mixing was enhanced by DO saturated water from the tunnel and the flood flows on the Passaic and Hackensack Rivers. Reaeration, which is proportional to DO depletion, rapidly replenishes the deficit caused by the DO depleted tunnel waters.

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Table 1. CE-QUAL-ICM State Variables

Temperature	Refractory Particulate Organic Nitrogen
Salinity	Total Phosphorus
Suspended Solids	Dissolved Organic Phosphorus
Algae (3 forms)	Labile Particulate Organic Phosphorus
Dissolved Organic Carbon	Refractory Particulate Organic Phosphorus
Labile Particulate Organic Carbon	Chemical Oxygen Demand
Refractory Particulate Organic Carbon	Dissolved Oxygen
Ammonium	Dissolved Oxygen
Nitrate	Dissolved Silica
Dissolved Organic Nitrogen	Particulate Silica
Labile Particulate Organic Nitrogen	

Table 2. CE-QUAL-ICM Studies

Application	Citation (if applicable)
Chesapeake Bay Eutrophication Study	Cerco and Cole, 1994
Lower Green Bay, Wisconsin	Mark et. al., 1993
Indian River/Rehoboth Bay, Delaware	Cerco et.al., 1994
New York Bight	Hall and Dortch, 1994
Cache River, Arkansas	in publication
San Diego Bay, California	videotape
Passaic River/Newark Bay, New Jersey	Cerco and Bunch, 1996
Chesapeake Bay Tributaries	study in progress
San Juan Bay, Puerto Rico	study in progress

Figure 1. Passaic River study area showing diversion tunnel route

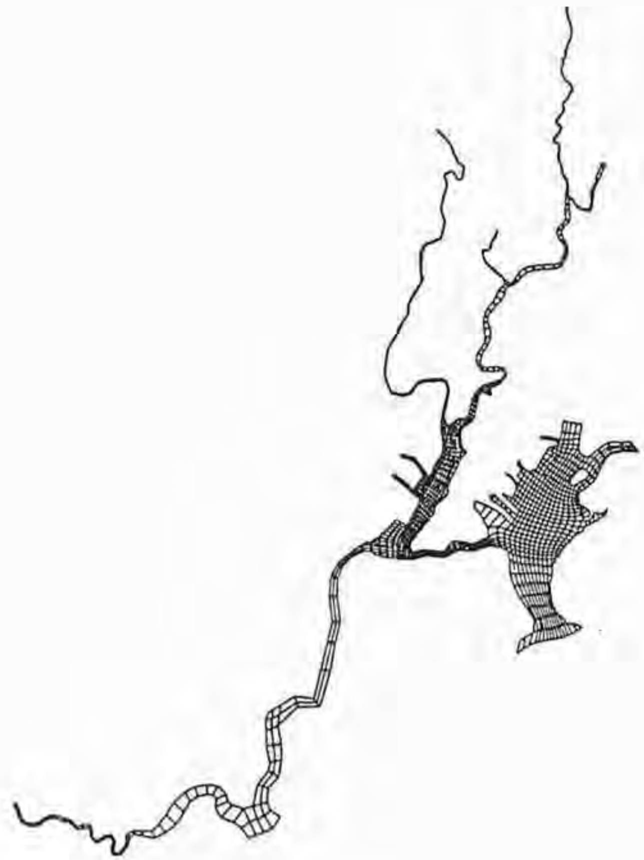

Figure 2. Water quality grid

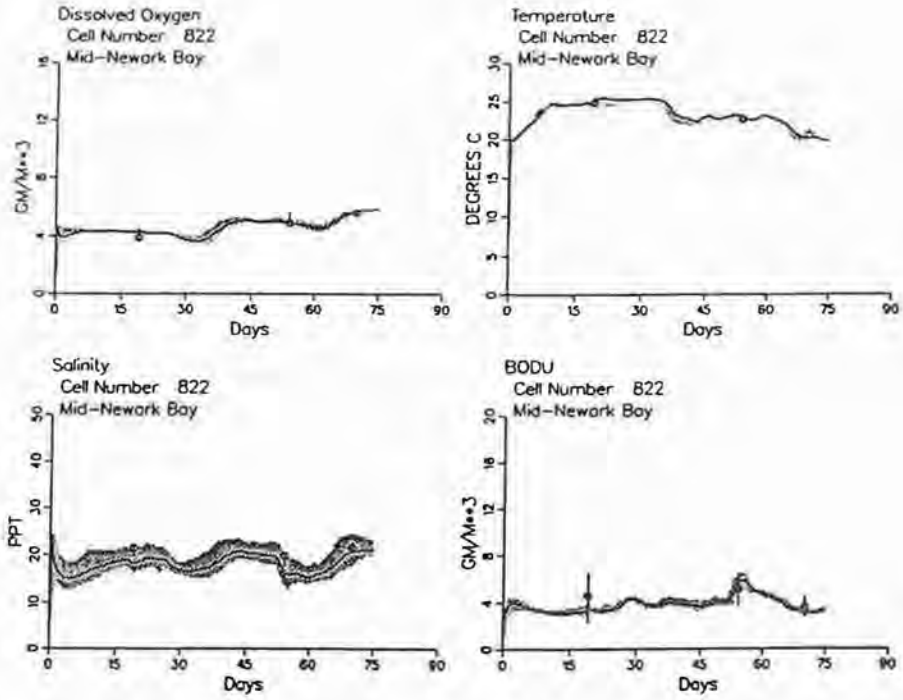

Figure 3. ICM calibration results

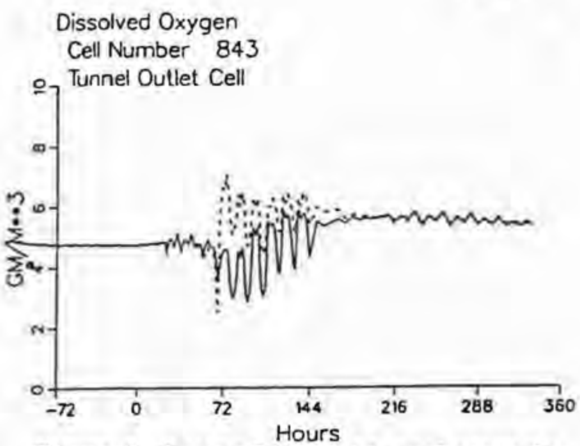

Figure 4. 2 year July wet tunnel scenario.

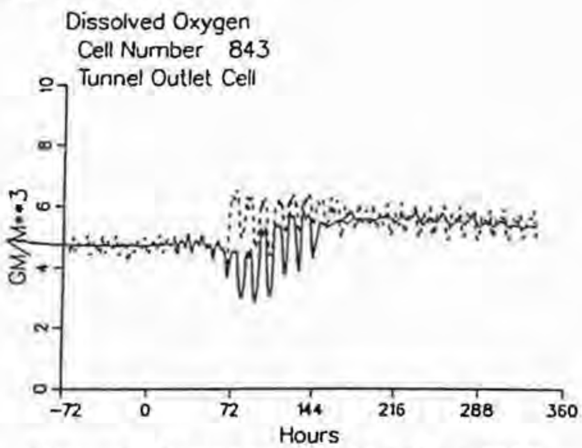

Figure 5. 2 year July dry tunnel scenario.

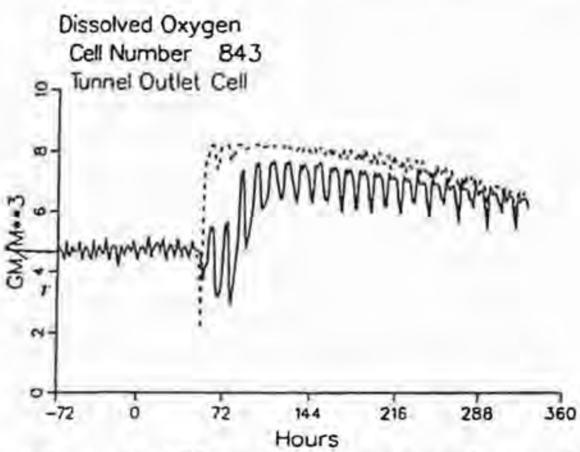

Figure 6. 100 year July wet tunnel scenario.

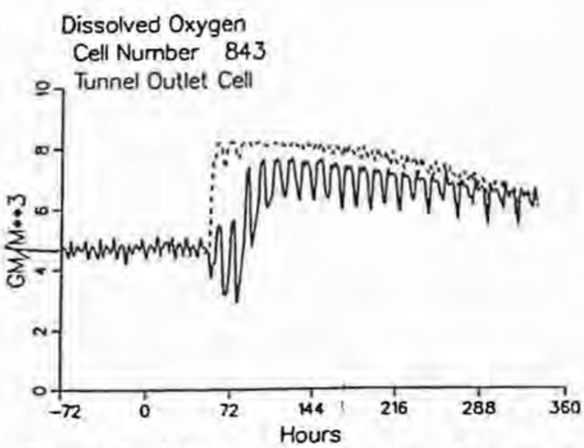

Figure 7. 100 year July dry tunnel scenario.