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Kentucky River Basin Water Quality Assessment Study

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WATER QUALITY ASSESSMENT STUDY

L. Ormsbee
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Prepared for:
The Kentucky River Authority

By:
The Kentucky Water Resources Research Institute
University of Kentucky, Lexington Kentucky

October 1998
KWRRI

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EXECUTIVE SUMMARY

This report documents the procedures and results of the KWRRI Kentucky River Water Quality Assessment Study. This study was authorized by the Kentucky River Authority in a contract to the Kentucky Water Resources Research Institute dated April 1, 1997. The major tasks of the study are outlined below:

Task 1:Develop Water Quality Model of the Kentucky River System

Task 2:Identify and Access Existing Sources of Data

Task 3:Characterize Biological Impacts during Low Flow Periods

Task 4:Test the Developed Water Quality Model with Existing Data

Task 5: Identify Additional Data Needs and Develop a Monitoring Network Proposal

This report summarizes the work associated with Tasks 1, 2, and 4. The work associated with Task 3 is summarized in a separate report entitled **A Review of Research on The Kentucky River Ecosystem: Biota and Human Impacts** by R.M. Waltman and R.J. Stevenson. The work associated with the last part of Task 5 is summarized in the report **Kentucky River Monitoring Network Proposal** (L. Ormsbee, L. Jarrett, and B. Perkins).

The current report summarizes the work associated with the construction, calibration, and application of the CE-QUAL-W2 (Cole and Buchak, 1994; Corps of Engineers, 1990) water quality model to the Kentucky River. In applying the model to the Kentucky River System, the primary objective was to assess the impact of the operation of low-level control valves on the water quality of the Kentucky River. This was accomplished by modeling the impact of the valves for low flow conditions associated with the 1930 drought of record along with projections for the year 2020. The results of this study indicate that for the modeled scenario, the proposed valves can be used to draw down the individual pools on the Kentucky River a maximum of 4 feet without causing significant chronic or acute impacts to the biota of the river.

CHAPTER 1

INTRODUCTION

1.0 Background

The Kentucky River Authority was first established by the General Assembly in 1986 to take over the operation of the Kentucky River Locks and Dams 5 through 14 from the U.S. Army Corps of Engineers. Following the drought of 1988, the Authority was given a mission to protect and improve the waters of the Kentucky River through environmental management of the entire watershed. As part of this mandate, the Authority is charged with developing comprehensive plans for the management of the Kentucky River Basin, including a long-range water supply plan and a drought response plan.

In April 1995, the Authority executed a contract with the University of Kentucky Water Resources Research Institute (KWRRI) to perform a water supply study of the river basin. Results of that study indicate that in the absence of any conservation and/or drought management plans, a water supply deficit of approximately 9.7 billion gallons could be expected to occur in 2020, if the 1930 drought of record were to re-occur under existing conditions. Of this amount, approximately 60% of the deficit can be attributable to satisfying current Division of Water low-flow requirements.

When minimum flow requirements are not being met, fish will die from lack of oxygen, and health and odor problems will occur, because there will not be enough dilution and dispersal of impurities. The regulatory standard for maintaining low flow is based on a statistical calculation of the lowest recorded flow in the river for seven straight days in any 10-year period (i.e., the 7Q10). When permitted withdrawals and the water in the river together do not add up to the 7Q10, the Division of Water is empowered to begin cutting back on the withdrawal permit limits. It should be recognized that the 7Q10 value represents a regulatory numerical standard that is not based on the point at which dissolved oxygen and waste dispersal actually become a problem. Actual minimum flow requirements can be estimated for a site-specific area that may in fact be either higher or lower than the current 7Q10 value.

Currently, low-level release valves have been installed in dams 11-14. Flows through dam 10 and dams 8-4 can be regulated using existing gate valves in the associated locks. A pump is needed to transfer flows past dam 9. As a result, the Kentucky River Authority now has the capacity to maintain the 7Q10 flows on the river through the operation of these valves and associated hydraulic structures. In addition, the Authority has considered the installation of temporary crest gates on dams 9 and/or 10. The optimal operation of these facilities will depend on the ability of the KRA to monitor and predict low flows on the river as well as to predict potential water quantity and water quality impacts. In addition to potential impacts on the river biota, the water quality can also directly impact the operational cost and efficiency of those water treatment facilities that use the Kentucky River as a water supply source.

To effectively manage such a system it is imperative that the authority have some method to predict the associated water quality impacts. The Kentucky Division of Water currently collects both ambient and compliance-based water quality data in the basin that provides some information for management purposes. In addition, the Kentucky River basin was a pilot study site for the USGS National Water Quality Assessment (NAWQA) program (1986) and some initial baseline information has been developed and documented. Unfortunately, such information is generally insufficient for evaluating the impacts of short-term or real-time management decisions. One way to circumvent this data deficiency is through mathematical modeling. The development of a water quality model of the Kentucky River will allow water resource managers and interested parties to evaluate a wide range of operational questions. These include the following:

- Can flows in the Kentucky River be reduced below the 7Q10 without violating the minimum dissolved oxygen requirements?
- Will release valves retrofitted to the dams along the Kentucky River improve water quality?
- What will be the magnitude of dissolved oxygen problems in the Kentucky River in the year 2020? Will the use of valves improve the situation?
- What withdrawal rates significantly reduce the residence time of water in a pool of the Kentucky River during extreme low-flows?
- Will reducing the residence time of water in the Upper Kentucky River Basin impact the Lower Kentucky River Basin algal growth problem?
- How much can the algal growth be reduced in different pools of the Kentucky River Basin by reducing treated wastewater effluents? .... Untreated?
- How much algae can the different pools of the Kentucky River sustain without violating water quality standards for oxygen?

1.1 Project Overview

This report provides the results of a water quality modeling study of the Kentucky River. This study was authorized by the Kentucky River Authority (KRA) in a contract with the Kentucky Water Resource Research Institute dated October 1, 1996. The CE-QUAL-W2 computer model was used in performing the study. The purpose of the study was to assess the potential water quality impacts of various management strategies (e.g., valve operations) for the 1930 drought of record for projected water demands for the year 2020. With the use of valves in the 1930 simulation, water consumption from the pools is allowed to continue to levels below dam crest level. This inherently effects the water quality of the pools. To predict the water quality impact associated with such operations, a mathematical model of the river has been developed. Prior to an evaluation of the impacts of the management strategies, the developed model was first calibrated using data associated with the 1988 drought.

This report is divided into six chapters. Chapter one provides an introduction to the study, as well as examining previous studies. Chapter two provides an overview of the general water quality of the Kentucky River. Chapter three provides an introduction to CE-QUAL-W2, while chapter four contains a discussion of the model calibration. Chapter five provides a summary of the results of the 1930/2020 simulations. Finally, chapter six contains a summary of the results of the study along with conclusions and recommendations.

1.2 Physical Description of Study Area

The Kentucky River Basin extends over much of the central and eastern portions of the state and is home to approximately 710,000 Kentuckians. The watershed includes all or part of 42 counties and drains over 7,000 square miles with a tributary network of more than 15,000 miles. A map of the watershed is shown in Figure 1.1. Three forks, the North, South, and Middle, form the headwaters of the Kentucky River. These forks combine near Heidelberg and drain over 1/3 of the basin. The river reach extending from the union of the three forks near Heidelberg downstream to the river's mouth at the Ohio River near Carrollton, Ky. is commonly referred to as the *main stem* of the river. The main stem is approximately 254 miles long and is divided into fourteen contiguous pools by a series of locks and dams. These locks and dams, originally established for navigation, now serve to impound the river for the 575,000 Kentucky residents that rely on the river as their primary water supply. The pools created by the lock and dams provide a year-round water supply to the surrounding municipalities, industries, and riparian farmers. A map of the lock and dam system is shown in Figure 1.2.

Four major impoundments exist in the basin that affect water supply. The Corps of Engineers owns and operates two flood-control reservoirs in the headwaters of the Kentucky River. The larger of the two reservoirs, Buckhorn Lake, has a total storage capacity of 54,783 million gallons (MG) and impounds approximately 10,500 MG at seasonal pool. The smaller reservoir, Carr Fork Lake, is roughly 2/7 the size of Buckhorn Lake, and impounds 7500 million gallons at seasonal pool. While Buckhorn and Carr Fork are not water supply reservoirs, they augment flows in the river during low flow periods. A third impoundment, Herrington Lake, exists on the Dix River, a major tributary located in the middle of the basin. Herrington Lake is owned and operated by Kentucky Utilities for hydropower generation and has no release obligation during drought periods. The fourth major impoundment in the basin is Jacobson Reservoir, a pump storage facility used exclusively for water supply. Water from the Kentucky River is pumped into Jacobson during wet periods and used to augment water supply during dry and peak periods. Jacobson is owned and operated by Kentucky American Water Company, the largest water supplier in the river basin.

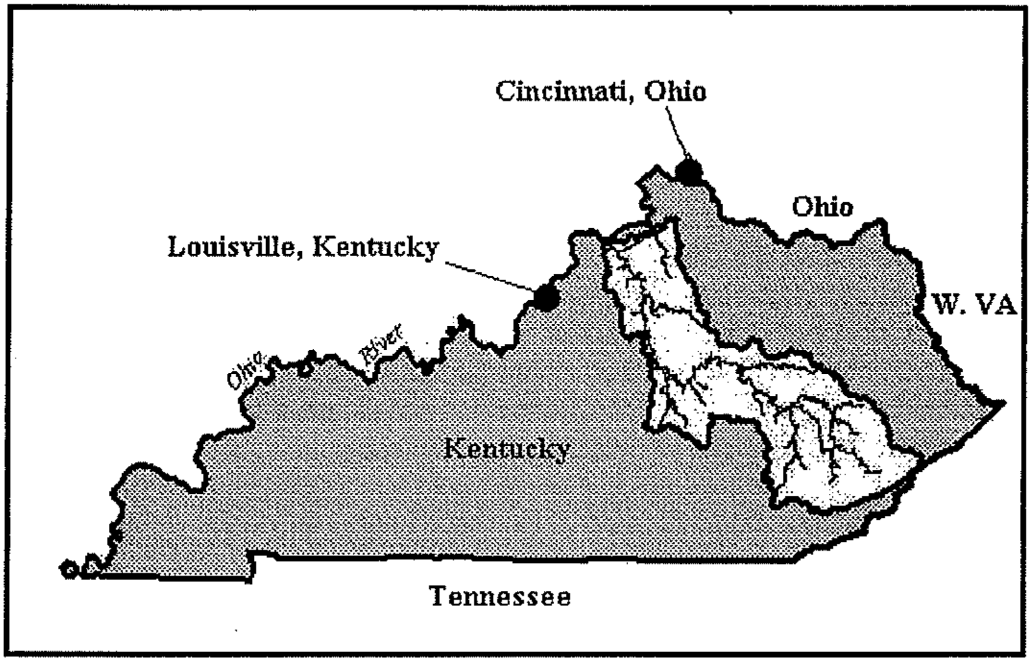

Figure 1.1 Map of the Kentucky River Basin

The climate of the basin is moderate and humid. The annual mean temperature is 56 degrees F, with a mean low of 25 degrees F (January) and mean high of 81 degrees (August). Average annual rainfall is 46 inches, with the northern part of the basin receiving slightly more rainfall than the southern part. The wettest month of the year is March, and October is typically the driest. On average, 28 percent of rainfall results in surface runoff, while nine percent recharges the ground water. Surface runoff is greater in the Eastern Coal Region and groundwater recharge is greater in the Bluegrass Regions due to Karst features. Stream flow varies greatly across the physiographic regions and with season. Karst features heavily influence these patterns. For example, stream flow in the Bluegrass Regions consists of flowing and dry (sinking creeks) stretches. The average annual flow for the streams across all physiographic regions is 1.4 cubic feet/second per square mile. However, during hydrologic extremes, flows vary greatly across the basin. Unit peak flow in the basin varied from 344 cubic feet per second per square mile to 18.3 cubic feet per second per square mile (Haag and Porter 1995). The 7-day, 10-year low-flow ranged from zero to 3.7 cubic feet per second. There are 15 man-made reservoirs in the basin. These reservoirs (total surface area of 6,530 acres and 286,000 acre-ft total volume) are operated for flow control and low flow augmentation. These operations tend to moderate pre-impoundment flow extremes. The main stem of the Kentucky River is also highly regulated, having a series of 14 locks and dams (Smoot et al., 1991, Haag and Porter 1995).

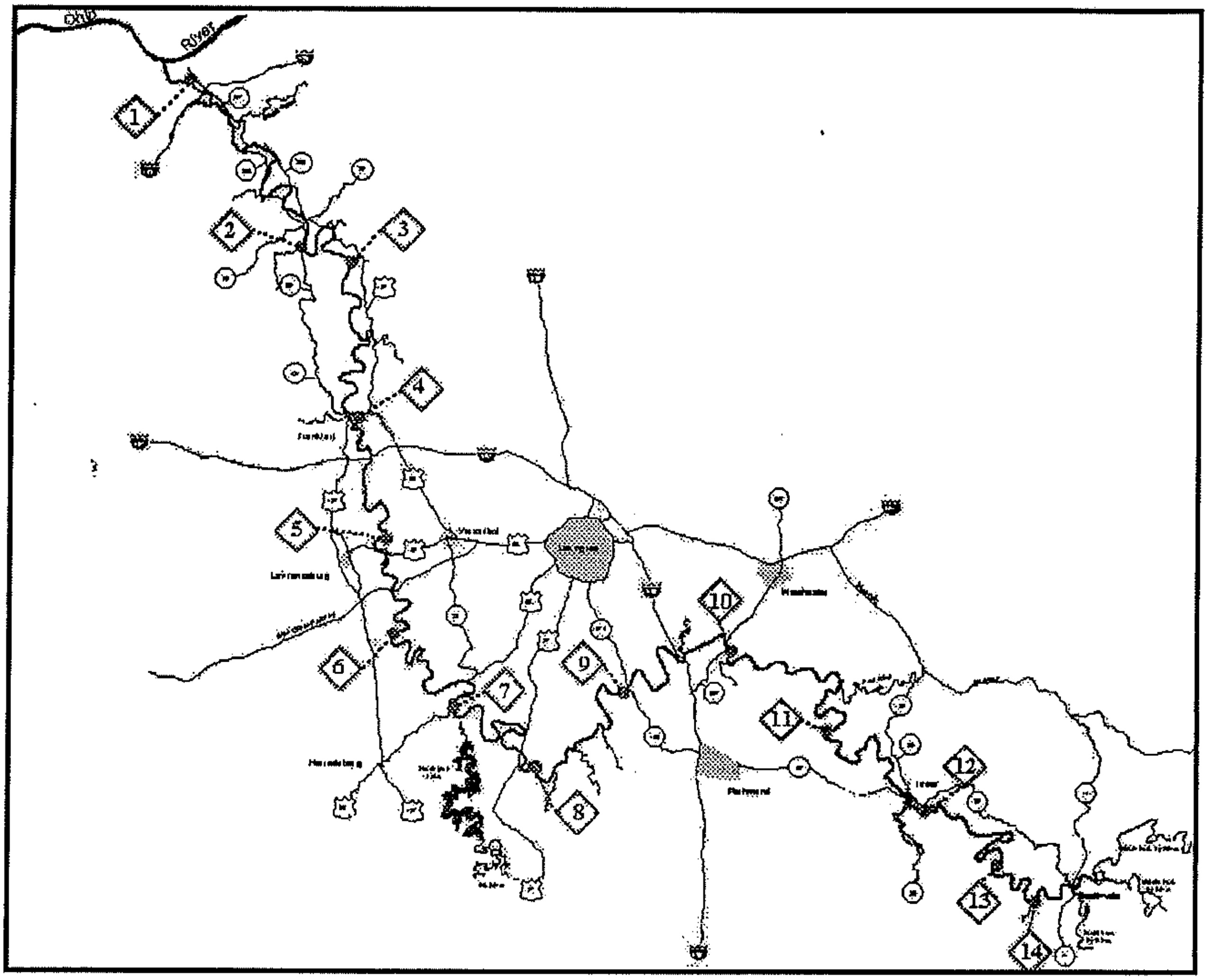

Figure 1.2 Map of the Kentucky River Lock and Dam System

Population and landuse vary in the Kentucky River Basin. Population is concentrated in a few counties (Fayette, Madison, Jessamine, Scott, Franklin, Clay and Perry). Lexington is the major urban center. Other centers include Carrollton, Frankfort, Georgetown, Danville, Richmond and Hazard. The 1990 Census estimated the Basin's population to be 649,260. Landuse in the basin varies from upstream to downstream in the river basin (Figure 1.1). The southern part of the basin is mostly forested, while the central area consists of agricultural and urban landuses. The northern part of the basin is a mixture of forested and agricultural landuses with interspersed urban areas. Basin wide, 50 percent of the land is forested (heavily concentrated in the Eastern Coal Field Region). Hardwoods (hickory and poplar) dominate the forests with about 10 percent pines and eastern red cedar, and 40 percent of the basin is devoted to agriculture (mostly the Inner and Outer Bluegrass Regions). Crops include corn, soybean, wheat and tobacco. Livestock includes horses, dairy and beef cattle, poultry, sheep and goats. About 25 percent of the State's coal is mined in the Eastern Coal Field Region. Limited oil and gas production occurs in the Knobs Region.

1.3 Summary of Previous Water Studies in the Kentucky River Basin

The following summarizes the previous studies performed on the main stem (or parts thereof) of the Kentucky River. These four studies led to the current water quality study.

1.3.1 Harza Deficit Study

In 1988, the Kentucky River Basin experienced a significant drought with water shortages (of varying intensity) realized in 35 counties, and a state water emergency was declared. The attention caused by the 1988 drought stimulated considerable public concern as to the availability of water in the basin during a severe drought. In response to growing public concern, a study was contracted with Harza Engineers to assist the Kentucky River Basin Steering Committee, a predecessor of the KRA, in adopting a long-range water supply plan. The purpose of the study was to quantify water-supply deficits occurring in the basin under several different droughts and for current and projected demand forecasts. A water-supply deficit was defined as the difference between the water demand and the water supply when the water supply was less than demand. Additionally, alternatives aimed at reducing or eliminating a design deficit were to be developed and evaluated. The results of Harza's deficit analysis were documented in a 1990 report entitled **Phase I Interim Report Water Demands and Water Supply Yield and Deficit** (Harza, 1990).

1.3.2 Harza Water Supply Study

Based on the results of the Phase I Report, Harza completed a second study that resulted in a report entitled **Preliminary Long-Range Water Supply Planning Study for the Kentucky River Basin** (Harza, 1991). The purpose of the study was to develop, evaluate and recommend a long-range plan to provide for the projected water-supply deficits for the various communities/utilities and individuals who depend on the Kentucky River for water supply. Twenty-seven alternative water-supply plans were developed and evaluated for the Phase II study. All of the plans would provide for the entire project deficit. Elements of the plans included:

1. Rehabilitation/reconfiguration of the Kentucky River Locks and Dams;
2. Small Upstream Reservoirs on Kentucky River tributaries; and
3. Pipelines from the Ohio River.

The Kentucky River plan included new dams at existing sites of Locks and Dams and at new sites. Raising of pool-water levels by up to 15 feet and lowering of existing water-supply intakes were considered. The Small Upstream Reservoir plan elements included dams of 50 feet to 150 feet in height with storage volumes of 1.2 to 7.0 billion gallons. Ohio River pipelines included pipelines from Maysville and Louisville with capacities of 40 million gallons per day (MGD) to 60 MGD and having lengths of 72 miles to 155 miles. The alternative long-range plans were developed by using single plan elements capable of meeting the entire deficit and by combing smaller elements.

The recommended long-range water-supply plan was to develop two or three new dams on the Kentucky River to store water for use during droughts. The new dams would replace existing locks and dams or would be constructed at new sites. The sites considered most favorable are existing Locks and Dams 10, 11 and 12, and two new sites identified in the report as 10A and 12A, which are in the pools of the existing Locks and Dams 10 and 12, respectively. Combinations of new facilities at these sites consistently scored higher than all other alternatives.

The recommended plan was not the most cost-effective alternative. Alternatives based on the Kentucky River were ranked higher than those based on Small Upstream Reservoirs because the Kentucky River alternatives were expected to result in fewer potential environmental, social and cultural impacts. On most other criteria, including legal, administrative, operation and water quality, the alternatives were generally equal.

1.3.3 ESE Kentucky River Aquatic Study

In 1990, the Kentucky-American Water Company (KAWC) contracted Environmental Science & Engineering, Inc. (ESE) to conduct a water quality/biota study of the Kentucky River Basin. The study area was the set of pools located between lock and dam # 10 and lock and dam # 4 (pools 9 through 4). This stretch is the most populated 111 miles of the main stem of the river. ESE focused on the effect low-flow scenarios (those below the 7Q10 flow) would have on water quantity, water quality, recreational users, downstream users, and aquatic life.

The ESE study implemented the use of a dynamic water quality model developed by the U.S. Army Corps of Engineers called the Water Quality for River-Reservoir Systems (WQRRS). Due to the lack of historical information, much of the data for the ESE study was manufactured, and calibration relied heavily on the recommended coefficients of the user manual. Of the data available, United States Geological Survey (USGS) river stage and flow were used for locks and dams 4, 6, and 10.

The ESE Kentucky River Aquatic Study provided three main recommendations. The first recommendation was that the water quality in pools 9 and 6 be monitored when the flowrates of pools 10 and 6 fall beneath 150 cfs. In particular, temperature and dissolved oxygen measurements should be collected. The second recommendation was that the stage at pool 9 should be continuously monitored, possibly through the installation of a gauging station at lock and dam # 9. Finally, the report recommended that a low-flow assessment on large aquatic animals be performed. The ESE water quality report concluded that KAWC withdrawal permit for pool 9 could be increased from 55 MGD to 62 MGD without significantly impacting the biota of the river during short-term, low-flow conditions (i.e., 7Q10 flows for less than 30 days).

1.3.4 KWRRI Water Supply Study

Based on the results of the 1990 ESE study, Kentucky-American Water Company applied for and was granted a variance on the minimum flow requirement for pool 9 from which it draws its water. Implementation of the variance could have directly impacted the results of the original design deficit of the Harza study and thus affect the recommendations of the Phase II report. In addition, the River Authority initiated several capital construction projects on the lock and dam system that also had potential impacts on the recommendations of the Phase II report. Because the need for additional capital construction to enhance the available water supply in the basin was to be based on the amount necessary to reduce the deficit, the Authority decided to initiate a reassessment of the basin deficit that took into consideration these and other factors not considered by Harza study. In April 1995, the Authority executed a contract with the University of Kentucky Water Resources Research Institute to perform such a study.

As part of the KWRRI study, a comprehensive computer model of the river, KYBASIN, was developed. Simulations of water movement and exchanges in the Kentucky River Basin were performed using this hydrologic routing model of the main stem of the Kentucky River to identify the location and magnitude of water shortages resulting from the imposition of two historical droughts. Simulations of the Kentucky River Basin under the existing water supply system were performed for 1930 and 1953 drought conditions using KYBASIN. Water supply deficits for existing demand conditions (i.e., 1994) and projected demands (i.e., 2000, 2010, and 2020) were predicted by the model. For the 1930 drought and 2020 demand conditions, a design deficit of 9.7 billion gallons was predicted.

In applying the model to the Kentucky River system, it was determined that a majority of the projected deficits (i.e., 6.7 billion gallons) could be eliminated through the installation of low-level release valves in dams 4-14. Installation of such valves allows for the 7Q10 requirement to be met even when flows over the in-river dams drop below the associate minimum flow requirement thereby allowing withdrawals from the upstream pools for water supply purposes. Currently, low-level release valves have been installed in dams 11-14. Flows through dam 10 and dams 8-4 can be regulated using existing gate valves in the associated locks. A pump is needed to transfer flows past dam 9. As a result, the Kentucky River Authority now has the capacity to maintain the 7Q10 flows on the river through the operation of these valves and associated hydraulic structures. In addition, the Authority has considered the installation of temporary crest gates on dams 9 and/or 10. The optimal operation of these facilities will be dependent the ability of the KRA to monitor and predict low flows on the river as well as to predict potential water quantity and water quality impacts. In addition to potential impacts on the river biota, the water quality can also directly impact the operational cost and efficiency of those water treatment facilities that use the Kentucky River as a water supply source.

Four primary water supply alternatives were evaluated for satisfying the remaining 3.0 billion-gallon deficit in pool 9. These included: 1) Installation of temporary crest gates on dams 9-14; 2) construction of a large dam on the Kentucky River, 3) construction of a smaller dam on a tributary to the Kentucky River, and 4) construction of a treated-water pipeline from Louisville to Lexington. Of the alternatives that were directly under control of its authority, the Kentucky River Authority decided to pursue the use of the low level control valves along with the use of temporary crest gates as the most viable and economically feasible alternative for augmenting water supply during a severe drought. In support of these objectives, the Kentucky Water Resources Research Institute (1997) was contracted to develop a water quality model (KYQUAL) and perform an associated water quality study for the river basin. The initial focus of the study was to identify possible water quality impacts associated with the operation of the low-level release valves during a time of severe drought.

CHAPTER 2

WATER QUALITY

2.0 Water Quality Problems

Water quality problems in the Kentucky River Basin affect fish and aquatic life but also affect human usage of the resource. As is true of many other waterways in the U.S., many factors are contributing to the ongoing degradation of this resource (Fortner and Schechter, 1996). Table 2.1 shows a list of water quality problems in the Kentucky River Basin along with potential sources of pollution. Water quality data was compiled from the USGS documents (Evaldi and Kipp 1991, Smoot et al., 1991, Carey 1992, Griffin et al., 1994, Haag et al., 1995, Haag and Porter 1995, Porter et al., 1995) on the Kentucky River Basin.

2.1 Sources of Water Quality Problems

The source of the water quality problems in the Kentucky River can be traced to inflows that have been modified due to historical activity in the basin. These sources include, but are not limited to:

1) High organic loading from storm water, treated and untreated waste, sediment oxygen demand, and groundwater;
2) Excessive algal nutrients, nitrogen and phosphorus from storm water, treated and untreated waste, groundwater, and loss of riparian filtering (Fogle et al. 1994);
3) Storm water inflows, as well as illicit sewer discharges;
4) Lack of shading and impounding water, lack of natural water level fluctuation; and
5) Unregulated and illegal discharges into the Kentucky River Basin, treated and untreated waste, storm water and CSO discharges (Adams et al., 1997) although few may exist in the Kentucky River basin, landfill leachate, oil and gas recovery, and coal mining.

2.1.1 Excessive Algae Growth

Excessive algal growth in aquatic systems often results in extreme variations in in dissolved oxygen concentration. These fluctuations may produce evening and early morning concentrations (less than 4 or 5 mg of dissolved oxygen per liter of water) inadequate to support the resident aquatic animals. Releases of various organic compounds by actively growing algal populations may be toxic to other aquatic or terrestrial life or may produce disagreeable tastes and odors if the water is used as a water supply (Desikachary, 1959). Senescing or decomposing algae can also impart unsavory characteristics to the water.

Nutrients are compounds, such as nitrogen (ammonia, NH_3-N, nitrate, NO_3-N) and phosphorus (orthophosphate, PO_4-P), that stimulate the growth of algae. Algae require a greater amount of nitrogen (16:1 ratio of N to P) than phosphorus (Chapra, 1997). However, nitrogen is usually more readily available that phosphorus so nitrogen rarely limits algal growth. Nitrogen is abundant in the atmosphere and may enter stream systems either through direct diffusion, atmospheric deposition or via geological sources. Nitrogen is highly soluble (Brezonik, 1994). As water flows over and through soils, dissolved nitrogen is carried with it and enters streams and rivers via watershed runoff. Phosphorus is less mobile and usually bound tightly to soil (colloidal) particles (Hill, 1981). Phosphorus enters stream systems in the particulate, less available, form. These watershed dynamics usually result in greater instream availability of nitrogen than of phosphorus.

However, human modifications of the landuse (e.g., urban, suburban, and agricultural activities) can alter the nutrient dynamics of a watershed by either altering the ratio of nitrogen to phosphorus and/or by increasing the total amount of available nutrients (Kirchner, 1975). Both of the conditions may result in excessive algal growths. Stormwater from human dwellings often carries large amounts of dissolved nutrients. Rainfall washes lawn chemicals and fertilizers that are high in nutrients into streams. Precipitation itself can be a source of considerable material loading including nutrients. However, few studies are available on Kentucky River Basin conditions. Studies around the country indicate the problem may be significant (Hendry and Brezonik, 1980; Lewis, 1981; Owe et al., 1982; Halverson et al., 1984; Moore and Nuckols, 1984). In addition, wastewater treatment plants, untreated wastes from straight pipes, and leaking septic systems also increase nutrient levels in streams. Groundwater inputs, particularly those that have been recharged from urban areas, often contribute additional nutrients to stream systems.

Excessive levels of nutrients in streams stimulate algal growth if adequate light is available. Human actions often result in disruption of riparian corridors. Streamside vegetation provides organic matter to stream organisms plus provides shading. Intact riparian corridors filter out between 50-95 percent of ambient sunlight. Algal growth is dependent on sunlight. Low light levels (as is characteristic of intact riparian corridors) limit algal growth. When riparian vegetation is removed, once heavily-shaded streams are transformed into streams that receive high levels of light. The combination of high light and high nutrients may produce unacceptable magnitudes of algal growth.

Low flow in the Kentucky River can increase algal concentrations, and the likelihood of experiencing the deleterious effects associated with them, by increasing water residence times, reducing deep mixing or mixing out of the photic one, reducing turbidity or light attenuation, and concentration nutrients. These conditions also coincide with reduced reaeration resulting from atmospheric diffusion and increased temperatures, which reduces the solubility of oxygen in water. Altogether, these scenarios can be environmentally difficult.

2.1.2 Low Dissolved Oxygen

Dissolved oxygen in the Kentucky River basin has been inadequately studied for the most part. If water quality impairments have occurred to a natural stream system, either as a result of human activity or natural processes (cultural and natural eutrophication), the daily dynamics of dissolved oxygen usually results in minimum dissolved oxygen values occurring in the early morning hours (before 6 a.m.). Most water quality sampling however occurs during working hours 7 a.m. to 5 p.m. Haag et al. (1995) reports that of 479 dissolved oxygen samples collected between 1987 and 1991 in the Kentucky River Basin, only 54 (11%) were less than 5 mg oxygen per liter of water. However, they also note that only 59% of all the dissolved oxygen samples collected were collected before 10 a.m. and that 78% of the low dissolved oxygen values were from that time interval. Smoot et al. (1991) in a review of historical dissolved oxygen data from the Kentucky River Basin (1976-1986) found that 12% of the 426 values collected were below 5.5 mg/l. The time of these sample collections was not available.

An evaluation of the dissolved oxygen data for the Kentucky River stored in the U.S. Environmental Protection Agencies STORET database indicated that six different state and federal agencies had made 975 collections of stream or river dissolved oxygen between 1991 and 1995. Less than 6% of the values were less than 5 mg/l, however, none of the samples had been collected before 7:45 a.m. There is considerable reason to believe that the low number of violations is more a function of biased data collection than of high quality water.

Most of the critical dissolved oxygen problems, low and high, in the Kentucky River occur in the middle and lower parts of the basin. Haag et al. (1995) also reported that all dissolved oxygen concentrations in excess of 105% dissolved oxygen saturation occurred in the mainstem of the river below Lock and Dam 7. The significance of saturation values in excess of 105% is related to algal primary productivity. Dissolved oxygen concentrations in natural waters do not exceed 100% saturation except during high rates of algal production. Haag and Porter (1991) present collaborating evidence for the high algal production rates finding that for the same time period the highest chlorophyll *a* were found in the same locations.

Low dissolved oxygen concentrations have been recorded in several tributaries to the Kentucky River basin during the summer. This was a result of stagnant water conditions when groundwater or wastewater may have been the sole or at least the dominant source of water. The decaying algae in the water cause low dissolved oxygen conditions. The dead algae settle into the sediment and decay. The bacteria and zooplankton consume algae and oxygen, thus depleting the water of oxygen for fish and other aquatic life.

In the winter, low dissolved oxygen has been recorded in the Kentucky River Basin system. The low dissolved oxygen is caused by the breakdown of biodegradable organic material or of ammonia compounds. Sources of these compounds are storm water, sediment accumulation from summer algae decomposition, urea (a de-icier applied to the airport and to roads and bridges during freezing conditions, this compound readily breaks down to ammonia). Deicing compounds such as ethylene and propylene glycols have an organic strength (when not diluted with water) over 10,000 times that of CSOs and storm water. The large majority of storm water runoff in the Kentucky River basin either infiltrates into the groundwater or runs off into the tributaries of the Kentucky River. During such wet weather periods, dissolved oxygen conditions in the winter were not below DOW minimum standards of 4 mg/l. During the summer, dissolved oxygen concentrations in many tributaries of the Kentucky River often dipped below 5 mg/l.

2.1.3 Bacteria

Bacterial loadings into the Kentucky River influence the sanitary quality of the water. Median concentrations of fecal coliform bacteria in the Kentucky River from the years 1980 to 1990 and between L&D 14 and L&D 2 ranged from 40 to 680 colonies per 100 milliliters of water (Haag et al., 1995).

During rain events, many sewage treatment plants in the basin cannot take all the water from sanitary and storm water, and some spills untreated into the Kentucky River and its many tributaries. The bacteria loading from this source is exacerbated by the discharge of untreated sewage from residential straight pipes, and runoff from confined domestic animals. These are the primary sources of pathogenic bacteria in the Kentucky River. In the Upper Kentucky River Basin, storm water and unknown sources contribute to coliform levels above the standard of 200 colonies/100 ml sample, but these violations are usually small compared to the CSOs, which contribute bacteria concentrations usually greater than 100,000 colonies per 100 ml sample. (Heaney and Huber, 1984).

2.1.4 Temperature

The optimum upper temperature for cold water fish such as trout is about 14°C (52.7°F), with an upper lethal temperature of 26°C (78.8°F). Pooling of water in the Upper Kentucky River Basin and removal of shade trees along the banks of the Kentucky River Basin system cause temperatures above the optimum range for trout. In the Upper Kentucky River Basin and Lower Kentucky River Basin, temperatures above 25°C (77°F) are common. Other fish species, such as warm water fish like crappie and bass, successfully tolerate the warmer waters.

2.1.5 Toxic Compounds

Toxic compounds have been found in some sediment locations in the Lower and Upper Kentucky River Basin, as well as in fish tissue. The source of these toxins is industrial discharges and storm water. These compounds can impact human health when:

- fish that have high concentrations of toxins in their tissue are eaten;
- sediments are ingested during swimming or by handling the sediments.

2.1.6 Biological Impacts

As part of the current water quality study, a general biological assessment of the river was performed. The results of this study have been provided in a separate report entitled **A Review of Research on the Kentucky River Ecosystem: Biota and Human Impacts (Waltman and Stevenson, 1998)**. The following general observations and conclusions were developed as part of this study:

1. The primary sources of pollution to the river are siltation from agricultural runoff and nutrient enrichment from wastewater treatment plant effluents and agricultural runoff. Other sources of pollution, including pesticides, metals contamination, and brine intrusion from oil and gas wells, combine to affect the organisms of the river ecosystem (Haag and Porter, 1995).

    1) During periods of low flow, the river is reduced to a series of pools that are subject to stratification and subsequent DO depletion and surface-water temperature elevation (ESE, 1991).

    2) The influx of toxic organic compounds such as atrazine and butylate herbecides and organochlorine insecticides to the river is of growing concern because of the bioacccumulation phenomenon that occurs in living organisms (Smoot et al., 1991). In areas where there were no detectable organic compound concentrations in the water column, tissue analysis from organisms such as fish and mussels contained significant levels of various organic compounds. Bottom dwelling organisms are especially susceptible to toxic organics adsorbed to sediments.

2. The macrobenthic invertebrate community has responded to alteration of water quality and physical habitat by changing composition to include mostly pollution tolerant species and by decreases in diversity, evenness, and abundance.

3. The most recent survey of mussels in the study area was completed in 1975.

    1) All species present are considered facultative; they can live in polluted waters.
    2) More recently, researchers have concluded that reduced velocities, increased sedimentation, and other water quality changes would eliminate all populations over time.

4. Studies dating back to 1954 indicate that the fish assemblage has been and still is dominated by species considered facultative. Facultative species are approximately 63.5% of the total species collected.

    1) Littoral fish species dominate the upstream samples where more near-shore structure exists. The lower pools that consist mostly of open water areas and less near-shore structure are dominated by benthic or pelagic fish species.
    2) Increased sedimentation, increased discharges from municipalities and industries, and increased organic and inorganic inputs to the river continue to significantly affect the population of fish on the river.

5. Pyhtoplankton densities and potential for nuisance algal growths in the river are positively correlated to nutrient enrichment. Diversity of phytoplankton decreases as nutrient concentrations increase.

6. Water temperature does not appear to present any threat to the organisms in the study area (ESE, 1990). However, according to water quality models, dissolved oxygen can be sufficiently low enough for extended periods of time that some organisms could be selectively eliminated from the river.

7. Recolonization of lost organisms from upstream sources is likely to occur during periods of high flow, but the continued stress on the ecosystem from low dissolved oxygen levels during periods of low flow will decrease the diversity and quantity of organisms present. As a result, the following general operational constraints are recommended for the three main groups of aquatic organisms:

    Invertebrates:

    Species of invertebrates found in the study area that are considered to be indicators of good water quality include *Stenacton interpunctatum, Cheumatopsysches, Hydropsyche, Neureclipsir,* and *Polycentroparflavomaculatur.* All of these species require a minimum dissolved oxygen concentration of 4.0 mg/l for survival. The state recommends a minimum dissolved oxygen concentration of 5.0 mg/l in river and streams for maintaining a healthy aquatic organism population.

    Mussels:

    Most mussels can tolerate a minimum dissolved oxygen concentration of approximately 4.0 mg/l for extended periods of time. It appears that the mussels found in the study area inhabit the mid depth region of the river immediately adjacent to the channel bottom where D.O. concentrations were 6.0 mg/l.

Fish:

The USEPA has set a minimum of *5.0* mg/l D.O. to maintain healthy fish populations in watercourses. Acute D.O. values for most adult fish range from 1.0-3.0 mg/l depending on exposure duration, species, age, and water temperature. The embryonic and larval stages of fish were even more sensitive than adults requiring a minimum D.O. range between 3.0-6.0 mg/l for survival.

8. It is recommended that a minimum D.O. concentration of 4.0-5.0 mg/l be maintained throughout the entire water column at all time to ensure a healthy, diverse, and sustainable biotic community. Intensive research will be required to determine if concentrations below this recommended value will have an effect on particular species in the river. The duration of exposure to low dissolved concentrations is another question that requires further investigation. Low dissolved oxygen concentrations are not only a threat to the survival fish, but can also impact behavior, reproduction success, and general fitness of the organism. Over time, chronic exposure to moderately low D.O. concentrations can be just as lethal as acute exposure to extremely low D.O. concentrations.

9. There are some headwater streams of the Kentucky River that have remained relatively pristine over time. It is vitally important to protect these resources for their biodiversity of organisms, which can provide a source for recolonization downstream. To protect these systems, the natural hydrological cycle should be preserved by safeguarding against upstream river development and damaging land uses that modify runoff and sediment supply to the river. Any additional significant alteration to the existing flow regime of the Kentucky River will continue to compound the negative impact on the biota of the system.

Water Quality Problem	Problem Sources	Environmental Impact
Algae levels above 15 ug/l chlorophyll a	Excessive algal nutrients, N and P from storm water, treated and untreated waste, and groundwater	High algae levels create high pH levels (see above) and create nuisance, aesthetic concerns by forming algal mats on the surface of the water, reducing water clarity (water looks muddy) and contributing to sediment oxygen demand by the settling of dead algal cells to the bottom muds, a summer problem
pH levels above 8.5	Excessive algal growth due to high nutrient levels of N and P; these nutrients could be coming from stormwater inflows, groundwater, and treated and untreated waste in the Kentucky River Basin	High pH levels create a poor environment for fish and aquatic life; a summer problem
Dissolved oxygen levels below 4 mg/l	High organic loading from storm water, treated and untreated waste, sediment oxygen demand, and groundwater	All fish and aerobic organisms require oxygen to live in the water environment, water deprived of oxygen will cause aerobic organisms to die or relocate
Coliform bacteria levels above 200 colonies/100 ml	Storm water inflows, as well as illicit sewer discharges	Coliform bacteria themselves are used to indicate that there may be fecal contamination in the water - either from human or animal waste, a summer and winter problem
High water temperature	Lack of shading and impounding water, lack of natural water level fluctuation	To support cold water fish such as trout, temperature of 14°C (52.7°F) are an optimal upper limit, this is only a summer issue
Toxic metals and organics in sediments, water column, and fish tissue	Unregulated and illegal discharges into the Kentucky River Basin, treated and untreated waste, storm water and CSO discharges, landfill leachate, oil and gas recovery, coal mining	Toxic compounds can be consumed by fish and other aquatic life that bioaccumulate the toxins in their tissue. This becomes a health hazard when humans consume the contaminated tissue and a health hazard to aquatic organisms.

Table 2.1 Water quality problems in the Kentucky River Basin

CHAPTER 3

MODEL DESCRIPTION

3.0 Overview

The CE-QUAL-W2 computer model (Cole and Buchak, 1994) was selected for use modeling the water quality of the main-stem of the Kentucky River. CE-QUAL-W2 is a two-dimensional, laterally-averaged, hydrodynamic and water quality model. Developed by the Army Corps of Engineers Waterways Experiment Station, its primary applicability lies in its ability to model estuaries, lakes, and reservoirs. The pools created by the lock and dams of the main stem of the Kentucky River are assumed to take on the properties of these waterbodies.

3.1 Model Selection

Many water quality models are commercially available. Available models include WQRRS (Hydrologic Engineering Center), WASP (US EPA Center for Exposure Assessment Modeling), CE-QUAL-R1 (Waterways Experiment Station), CE-QUAL-W2 (Cole and Buchak, 1994), and RMA-2 (Waterways Experiment Station). CE-QUAL-W2 was selected for a multitude of reasons. First, all relevant constituent demands could be modeled in this program. Second, the CE-QUAL-W2 uses the simplified Navier-Stokes Equation to compute the hydrodynamics of the system. Third, CE-QUAL-W2 is configured to model multiple branches and tributaries (of which the Kentucky River has many). Finally, this model has been used in three other studies in the State of Kentucky, those being Herrington Lake (Jarrett et al., 1998), Cave Run Lake (FTN Associates, Ltd., 1997), and Taylorsville Lake (FTN Associates, Ltd., 1998).

3.2 Model Structure

The CE-QUAL-W2 is a computer program, written in Fortran, which may be run in batch mode on a standard microcomputer. Use of the program requires the development of a series of ASCII data files, which contain the parameter values necessary for characterization of the physical system. Upon execution, the program generates a number of output files, which are then examined for interpretation of the model results. Execution of the program requires a two-step process. In the first step, a pre-processor program checks the control file to determine what is to be done, looks for the other necessary input files for existence and proper setup, and organizes the information for the main program. The main program then performs the hydrodynamic and water quality calculations and returns the results in a number of output files.

3.3 Data Files

CE-QUAL-W2 requires a number of input data files. The most important of these is the control file. The control file specifies what actions are to be performed by the program, certain physical aspects of the water body, and many of the water quality parameters for the model. In addition to the control file, the user must provide data describing the physical configuration of the water body, all hydrologic data for modeling the hydraulics of the system, all meteorological data necessary for modeling the thermodynamics of the system, and all water quality data for modeling the water chemistry of the system. A summary of the various program files is provided in Appendix A.

3.4 Hydrological Configuration and Bathymetry

The physical attributes of each of the pools are very important to the calculations of the CE-QUAL-W2 model. The actual size and shape of each of the pools, how the geometry is subdivided (bathymetry), and the inflow and outflow balances are crucial to the validity of the model.

3.4.1 Physical Configuration

CE-QUAL-W2 conceptually represents a water body as a 2-D array of cells with each cell extending across the width of the water body. This "grid" of cells is determined by the longitudinal segment lengths (DX) and layer thickness (DZ) specified by the user. In applying CE-QUAL-W2 to the Kentucky River, a separate model was developed for each pool (e.g., pools 14-2). This resulted in 13 separate models. For each model, the associated pool was divided into a series of longitudinal cells, which were then divided vertically into a series of vertical cells. This resulted in a two-dimensional computational grid for each pool. Each longitudinal cell was proportioned to be a mile in length. Each vertical cell was proportioned to be 0.9 meters in height. Figures of the computational grids associated with each pool (model) are shown in Appendix B. Data from the USGS and the Army Corps of Engineers were used in the generating the bathymetry files for each pool. The HEC-2 river data and the GEDA program from the Army Corps of Engineers were used in generating the bathymetry files for each pool. The USGS quad maps provided each segment orientation.

3.4.2 Cell Width

The user must specify an average width for each cell in the grid. The average cell width will be used with segment length and layer height for model estimation of individual cell volume. Average cells widths for each pool in the Kentucky River were estimated using U. S. Army Corps of Engineers physical survey data of the river. The U. S. Army Corps of Engineers had surveyed the river for use in their HEC-2 hydraulic model. This data was transformed to the format of the CE-QUAL-W2 model.

Once initial estimates of cell widths were obtained, the model was run and the cell widths were then adjusted (1) to prevent numerical instabilities in the CE-QUAL-W2 model; and (2) to replicate the Corps of Engineers elevation-volume curves for each pool.

3.4.3 Outlet Configurations

Total discharge from each pool is subdivided into three different components (dam leakage, controlled releases through the low-level release valves, and uncontrolled release over the dam crest). Each discharge is modeled by specifying a separate discharge for each particular cell associated with the most downstream river segment. The location of each release point is shown on the associated pool grids in Appendix B. The flows assigned to each discharge point were obtained from the hydrologic results of the KYBASIN for the modeled scenarios.

3.5 Boundary Conditions

To apply the CE-QUAL-W2 model to a particular water body, the physical boundary conditions associated with the system must be specified. The physical boundary conditions necessary to model the system include 1) hydrologic boundary conditions, 2) thermodynamic boundary conditions, and 3) water quality boundary conditions. Each of these boundary conditions are discussed in the following sections:

3.5.1 Hydrologic Boundary Conditions

Hydrologic boundary conditions for each pool were obtained for two different flow scenarios: the 1998 drought and the 1930 drought. The 1998 flow scenario was used in calibrating the model, while the 1930 flow scenario was used to evaluate the water quality associated with the operation of the low-level control valves. In each case, upstream inflows as well as tributary inflows were obtained using the input data files previously prepared for the KYBASIN simulations for each flow scenario. A detailed discussion of the derivation methodology for both sets of flows is provided in **Kentucky River Basin Water Supply Assessment Study: Task III Report – Deficit Analysis** (Ormsbee and Herman, 1996). Utilization of the KYBASIN tributary flows in the CE-QUAL-W2 model required that the aggregate tributary flows to each pool be disagreggated and then assigned to the individual cells in the computational grid. This was accomplished by determining the proportional area associated with each tributary and then by multiplying the aggregate tributary flow by the associated percentage. The location of each tributary relative to the computational grid of each pool is provided in Appendix B.

Water withdrawal boundary conditions for each pool were obtained for two different demand scenarios: 1988 and 2020. In each case, the aggregate demands in each pool were obtained using the input data files previously prepared for the KYBASIN simulations for each flow scenario. A detailed discussion of the derivation methodology for these demand estimates is provided in **Kentucky River Basin Supply Assessment**

Study: Task III Report – Demand Forecasts (Blomquist and Hoyt, 1996). Application of the KYBASIN pool demands in the CE-QUAL-W2 model required that the aggregate demands to each pool be disaggreggated and then assigned to the individual cells in the computational grid. This was accomplished by identifying the location of each demand and then assigning it to the associated computational cell. The location of each demand point relative the computational grid of each pool is provided in Appendix B.

3.5.2 Thermodynamic Boundary Conditions

Thermodynamic processes in CE-QUAL-W2 are dependent upon the following boundary condition data:

1) Initial pool temperature data
2) Inflow temperatures for the simulation period
3) Meteorological data for the simulation period

3.5.2.1 Initial Temperature Values

The initial water temperature values in the Kentucky River model were estimated from a relationship between air temperature and water temperature developed for tributaries to Herrington Lake CE-QUAL-W2 model (USGS, 1998). Herrington Lake is on the Dix River a tributary to the Kentucky River, which made it reasonable to assume these relations would be adequate to estimate initial values, pool 14, for the Kentucky River and the tributaries.

3.5.2.2 Inflow Temperature Data

Inflow temperature data is important for simulating the proper vertical placement of inflows in each pool. Although any time interval may be used for specifying inflow temperatures, the use of daily observations is recommended. Daily-observed water temperatures were not available for the various pools, and thus simulated daily water temperatures were used.

Because stream temperatures fluctuate in response to meteorological forces such as solar radiation, wind, and air temperature, it is possible to estimate daily inflow temperatures using regression analyses based on variations in daily air temperatures and streamflow. Regression equations were developed for five stream systems within the Kentucky River basin where periodic water temperature measurements were made (16 times per year for two years). Water temperature served as the dependent variable and air temperature and streamflow served as the independent variables. The five selected basins ranged in flow from 0.01 to 6.05 cubic meters per second (cms). The daily air temperatures were smoothed using a three-day lagged moving average. The final equation (shown below) had an adjusted $R^2 = 0.78$ and a standard error of the estimate (SEE) = 2.33.

$$W_t = 8.92 + (0.638 * A_t) + (-0.97 * Q) \tag{1}$$

Where W_t = water temperature (degrees Celsius)
A_t = air temperature (degrees Celsius)
Q = streamflow (cms)

3.5.2.3 Evaporation Data

The CE-QUAL-W2 model does not contain a separate evaporation file, however the model does internally calculate evaporation if desired. Once all files necessary for hydrodynamic analysis were created, the model was run with evaporation in to back-out evaporation data. This new evaporation information was then added into the net lateral flow data into each pool scenario and all lateral files were then recalculated and recast into CE-QUAL-W2 format. The final step then was to re-run the CE-QUAL-W2 model and adjust the hydrodynamic files so that water budget and pool elevations balanced with observed data.

The meteorological file used for calculating evaporation was constructed by compiling data from the National Oceanic and Atmospheric Administration (NOAA) Local Climatalogical Data Sheets. There are a series of publications available on a monthly basis that contain all various weather data for a given Weather Service Office (WSO) on three-hour intervals. The data used in this study came from the Lexington Blue Grass Airport WSO and the Jackson, KY WSO. The meteorological data for 1930 came from historical data from the Lexington Blue Grass Airport WSO. Data from 1930 was available in daily intervals, and three-hour information was synthetically generated using trend models and Fourier series models. All inflow temperature files were created using a trend model that incorporates the air temperature trend and the flow trend for a particular inflow.

3.5.3 Water Quality Boundary Conditions

To construct the basic framework of a water quality management tool, it was necessary to make some simplifying assumptions about non-point source water quality behavior within the Kentucky River basin. These assumptions were used to produce a priori (Bayesian) probability distributions of the constituents of interests (Reckhow and Chapra, 1983). Information (data) was available for only a fraction of the 85 tributaries where non-point source loads were significant. Consequently, it was necessary to extrapolate the available information to the basins where we were uninformed.

A basic statistical approach was selected to accomplish this. This approach started by partitioning the variability of the basin and producing less variable and ostensibly more homogeneous subsets of basins to work with (Bierman et al., 1981; Haith and Tubbs, 1981). The partitioning was first performed with respect to the sub-basins to be simulated or the 85 model tributaries. These basins were characterized by landuse based on the Anderson I landuse coverages supplied by the USGS and the KRA. Secondly the basins were stratified by flow.

Many agencies and universities collected water quality data from the Kentucky River basin during the model calibration period of 1988. For the purposes of this study, all available data from the Kentucky River basin were compiled and screened for the periods from 1987 to 1990. This data was collected for diverse reasons and analyzed using disparate techniques. To minimize the noise associated with the collection and analytical problems all the data were screened for three criteria:

1. Only stream or river data tributary to the Kentucky River was used (this included the North, South, and Middle Forks of the Kentucky River).
2. The data was collected between 1987 and 1990.
3. The highest and lowest 3 values for each variable were discarded.

The majority of data sets from these periods were obtained as part of the National Water Quality Assessment (NAWQA) program of the U.S. Geological Survey (USGS). The locations of the 75 sample stations associated with this synoptic study are provided in Figure 3.1.

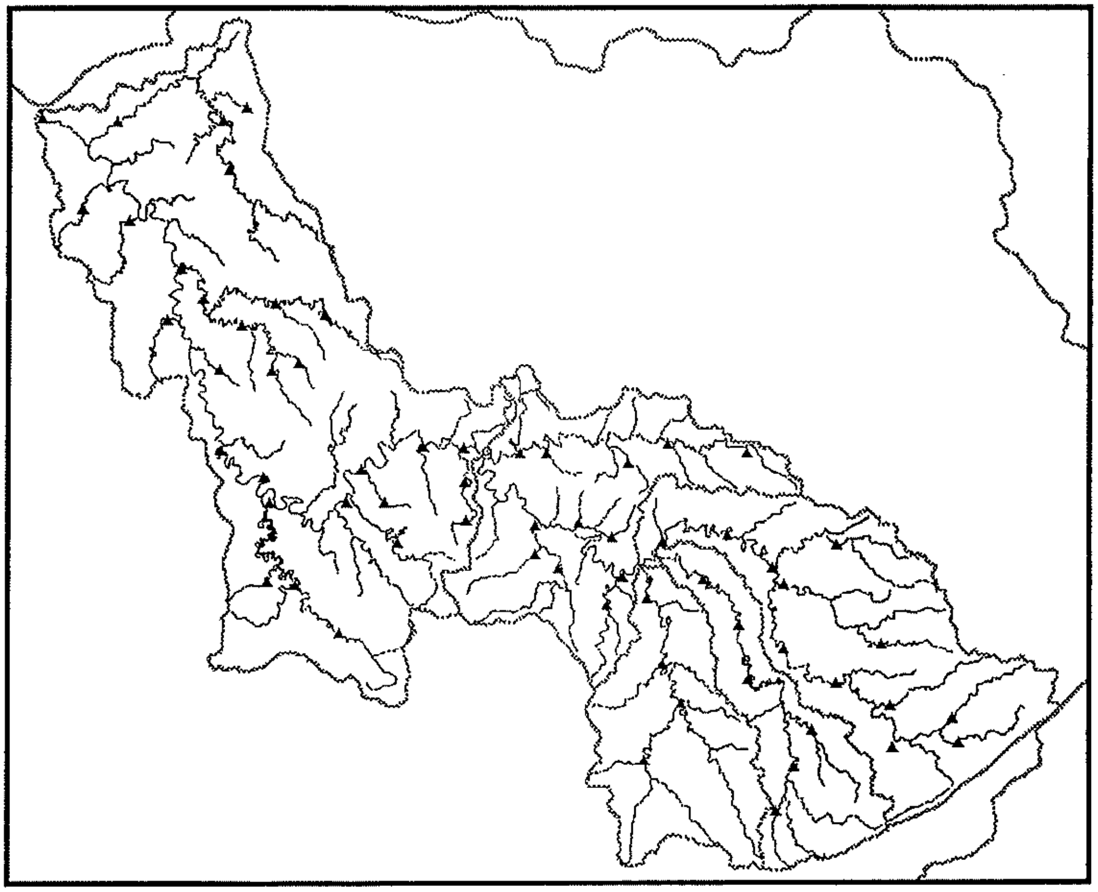

Figure 3.1 Water Quality Stations

Over 500 values of six different constituents were used to estimate daily concentrations for 85 tributaries to the Kentucky River. The six constituents were total dissolved solids, labile dissolved organic matter, soluble reactive phosphorus, ammonia nitrogen, nitrate nitrogen, and dissolved oxygen. Relations between each constituent and discharge were evaluated both in state space and logarithmic space. Relations between each constituent and temperature were also evaluated. All evaluations included reviewing the data as a whole and as reasonable subsets.

Subsets of the data included spatial subsets such as basin size, and basin landuse. Temporal subsets were also used. The strongest relation observed was between nitrate nitrogen and time of year within the basins that had a predominantly forested landuse. However, the r^2 value for this relation, with over 250 degrees of freedom, was less than 0.25, indicating that time of year explained less than 25% of the observed variability in the nitrate nitrogen data. Multiple regression models fared no better.

Despite those results, there is no denying that patterns of concentrations exist for these constituents. As a result, a conservative stratified approach was finally selected. This approach considered the role that landuse, time of year, and discharge played in influencing the concentrations of each constituent. The Kentucky River Basin was divided into two distinct types of landuses: forested and agriculture. K-means cluster analysis (Hartigan, 1975) and land-use data for the drainage area upstream of the U.S. Geological Survey's (USGS) National Water Quality Assessment (NAWQA) program tributary synoptic sites was used to produce two distinct groups (Haag et al. 1995). The groups were characterized by being internally more similar with respect to the percentages of the landuse classifications than they were externally. Each of the 85 tributaries was assigned to one or the other classes based on the predominant landuse in the drainage basin. The basins were further subdivided based on the mean and maximum flows of the tributary data, again using K-means analysis, to produce three flow classes of basins within each landuses type. Finally, the monthly mean and median were calculated for each of the six classes. Daily inputs were equal to these monthly values.

Two multiple-regression models were fitted to the Kentucky River Basin DO data: a forest model (Eq. 2) and an agricultural model (Eq. 3). The forest model indicates that variability in DO concentrations associated with this land use can be adequately modeled (predicted) using three independent variables: temperature (TEMP - C^o), pH, and the natural logarithm of instantaneous streamflow (LQIN - CMS). These three factors explain 73 percent of the variation in DO concentrations in drainage basins fitting the land-use description above. Most of the variability in the model was explained by temperature (72 percent), followed by streamflow (19 percent) and pH (9 percent).

$$DO_{conc} = 4.057 - 0.218*TEMP + 0.907*pH + 0.541*LQIN \qquad (2)$$

Where DO_{conc} = dissolved oxygen concentration
TEMP = air temperature (degrees Celsius)
pH = the pH level of the water
LQIN = the logarithm of the inflow

The agricultural model is generally applicable to drainage basins with a minimum of 66 percent agricultural land and a maximum of 24 percent forested land. The amount of urban land is also important for this model and should range from 8 to 18 percent. The model can be expressed as:

$$DO_{conc} = -1.924 - 0.147*TEMP + 1.183*pH + 0.003*TIME - 0.125*TOC + 0.516*LQIN \qquad (3)$$

Where DO_{conc} = dissolved oxygen concentration
TEMP = air temperature (degrees Celsius)
pH = the pH level of the water
LQIN = the logarithm of the inflow
TOC = Total Organic Carbon (mg/L)
Time = Time of day (1-24)

These models were used to model the non-point source component of the flux of material to each pool of the Kentucky River basin but not point source. Point-source contributions were calculated using data from the Kentucky Division of Water KPDES permits and monitoring files. Sixteen significant wastewater treatment plants were considered in the model. Data on the discharge rate and the constituent concentration were used to determine daily loads from each of the plants. When monthly monitoring data was available it was used to assign a daily concentration value for the constituents available, usually biological oxygen demand, ammonia nitrogen, dissolved oxygen, and total suspended solids. Loads were calculated as milligrams of constituent per day. For tributaries where these wastewater treatment plants' (WWTP) discharged, the loads of point source and non-point source (in milligrams of constituent per day) were combined and then divided by the combined discharge as liters per day. This produced a flow-weighted estimate of the daily concentrations.

The resulting models were developed to define the mass inputs or loads (Wt) of each contributing inflow to the river model. Load is defined as MT^{-1} and, as such, is time dependent. To account for the time dependency a transfer function was developed using collection stations, where daily streamflow data was also available. Relations between discrete monthly concentration data and daily streamflow data were used to interpolate concentration data to produce daily values. For simplicity, all forested drainage water quality was assumed to behave the same and all agricultural the same.

3.6 Model Processes

The constituent processes modeled by CE-QUAL-W2 are shown in Figure 3.2. For a detailed description of each process, the reader should refer to the CE-QUAL-W2 user's manual (Cole, 1995).

3.7 Model Assumptions

As with all mathematical models of physical systems, several basic model assumptions are required to be able to approximate the hydraulics and water quality associated with the Kentucky River system. In applying CE-QUAL-W2 to the Kentucky River, the following assumptions have been made:

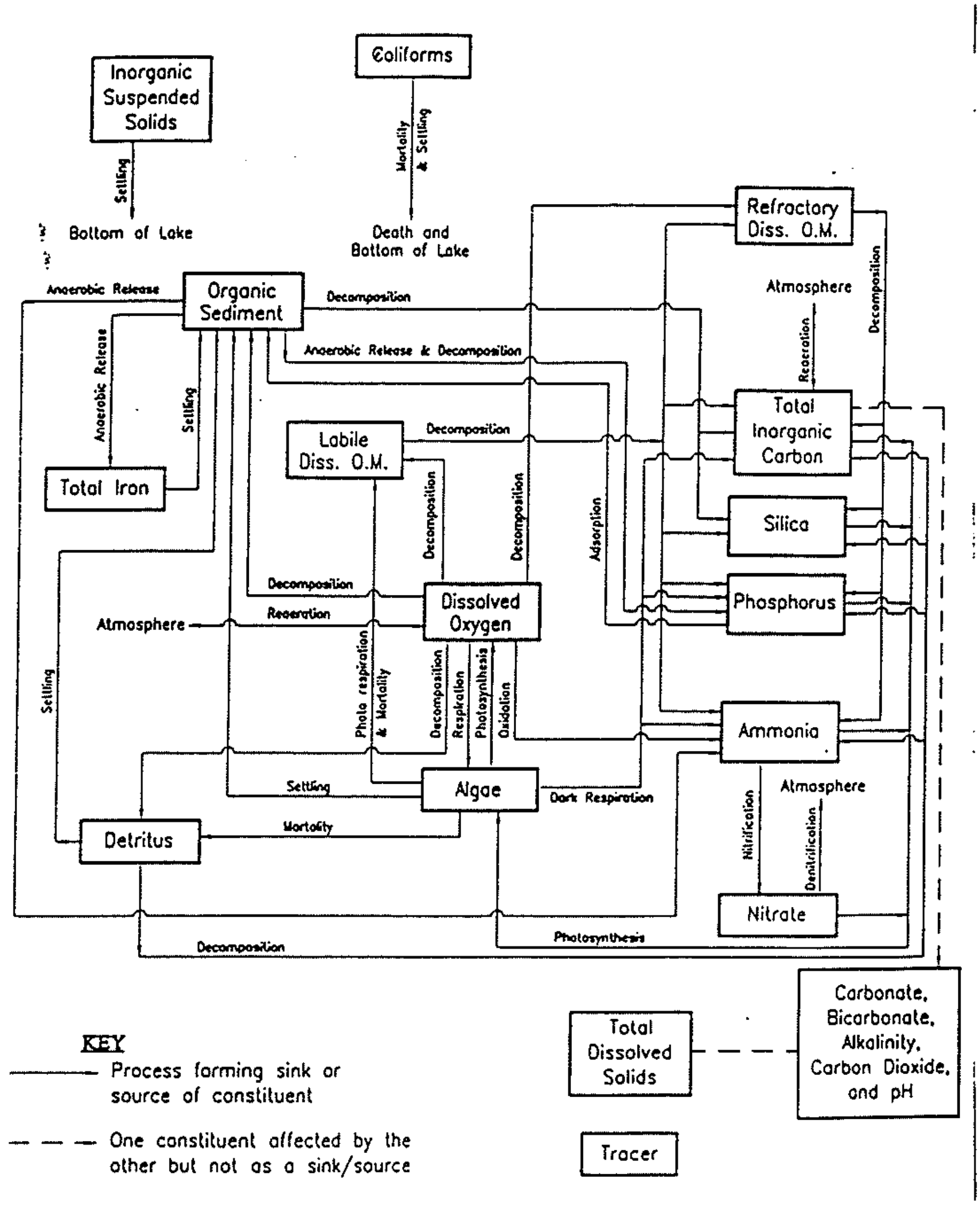

Figure 3.2 Constituent Processes

3.7.1 Hydrodynamics and Transport

CE-QUAL-W2 models the hydrodynamics of the Kentucky River using the two-dimensional form of the Navier-Stokes equations written in conservative form (momentum is conserved) with the Boussinesq and hydrostatic approximations. As a result, the governing equations are laterally averaged assuming there are negligible lateral variations in velocities, temperatures, and water quality constituents. With these approximations, turbulence is modeled through the use of eddy coefficients rather than the complete vertical momentum equation. These approximations are normally used in hydrodynamic models, so that the governing equations (which are analytical equations) can be solved numerically on a computer without creating unreasonable computational burdens. The vertical momentum equation takes into account the generation of significant vertical velocities in deeper segments bordered by relatively shallow segments.

3.7.2 Water Quality

3.7.2.1 Algal Limiting Factors

The CE-QUAL-W2 model takes into account algal growth limitation by soluble phosphorus, nitrogen, silica, and light. Growth is limited by only one factor (the factor in minimum amount compared to the algal growth requirements) in each time step. Recent literature indicates there can be co-limitations by nitrogen and phosphorus (Auer et al., 1986; Axler et al., Elser et al., 1990). Carbon limitation also is not included in the model and cannot be simulated. Although many species of blue-green bacteria (Desikachary, 1959) are capable of using atmospheric nitrogen by way of nitrogen fixation, the process is not included in CE-QUAL-W2.

3.7.2.2 Zooplankton/Biotic Web Interactions

The model does not take into account food web interactions involving zooplankton, fish, etc. Any effects that food web dynamics may have on water quality in terms of algae nutrient cycling are not considered.

3.7.2.3 Sediment Oxygen Demand

The sediment compartment in the model does not rigorously address chemical kinetics in the sediment or at the sediment/water interface (e.g., sulfate reduction, carbon diagenesis). Sediment oxygen demand (SOD) can be modeled either as a zero order process (i.e., oxygen demand is a constant value per unit of bottom surface area) or as a first order process (i.e., oxygen is consumed as accumulated organic sediment decays, which is assumed to follow a first-order decay process). Through model calibration of SOD and hydrodynamics, the model can reasonably reproduce anoxic conditions in the water column during stratified periods. However, the model does not rigorously simulate anaerobic processes and does not simulate oxidation and reduction reactions at all.

3.7.2.4 Reaeration

For the purposes of this study, reaeration of flows as they pass over the dams or through the control valves was ignored. This represents a conservative assumption. According to the ESE report (ESE 1991), historic data and data collected by ESE during the summer of 1990 indicate that water is typically reaerated with 1 to 2 ppm of dissolved oxygen as it passes over the dams. No data is currently available for reaeration rates through the installed valves in dams 10-14 or the gate valves in pool 9. As a result, these values were assumed to be negligible.

3.8 Numerical Limitations

CE-QUAL-W2 provides two different schemes for solving the hydrodynamic and constituent transport equations: (1) an upwind differencing scheme and (2) the higher order QUICKEST method (Leonard, 1979). The QUICKEST scheme was used in this study, because it produces less numerical dispersion than upwind differencing. A limitation of all numerical solution schemes, including QUICKEST, is that the solution is an approximation. Approximations are usually necessary to simplify the governing equations, so that they can be solved numerically. Also, the scheme is used to solve for parameters at discrete intervals of time and space, even though the system being modeled is continuous in time and space. Though smaller intervals (i.e., shorter times steps and smaller cells) decrease the number of errors due to discretization, they increase computational burdens. A compromise is thus required between discretization errors and computational burdens (FTN & Associates, 1998).

3.9 Model Results

The CE-QUAL-W2 model requires a fairly large amount of data. The water quality and hydrodynamic parameters, shown in Table 3.1, are generated as a function of time and a vertical and longitudinal location. Table 3.1 also provides a brief description of the importance that each variable has on the predictions of water quality in the pools.

Table 3.1 Water Quality Variables Simulated in the Kentucky River Model

Water quality or hydraulic variable simulated in the Kentucky River model	Importance of variable in assessing water quality conditions
Water surface elevation	Affects direction of water movement
Water velocity	Water movement or water velocity tells us where the water moves and how fast
Temperature	Important for fish survival and affects all biological and chemical processes, affected by meteorological conditions (including shading)
Algae concentration	The model predicts algae bio-mass concentrations, telling us where the algae growth problems are and at what concentration nuisance conditions are encountered
Bacteria	Coliform bacteria are modeled in the Kentucky River Basin, these are indicators of pathogenic organisms
pH	If pH is below 6.5 or above 8.5 fish and aquatic life could be impaired
Dissolved organic matter (soluble)	A measure of the amount of biodegradable organics in the water; as bacteria consume this organic matter, oxygen is consumed; this is comparable to BOD (biochemical oxygen demand, which is a measure of the amount of oxygen required to biodegrade an organic waste)
Refractory organic matter (soluble)	Same as dissolved organic matter except that the rate of decay of these organics is very slow
Sediment organic matter	Determines the rate of oxygen consumption by particulate matter settled to the bottom of the Kentucky River Basin - typically dead algae and particulate organics coming into the Kentucky River Basin
Detritus (particulate organic matter)	Particulate organic matter that decays as bacteria consume detritus as food, an oxygen sink
Total inorganic carbon	This is all the non-biological (inorganic) carbon in the system, these components are affected by algae growth and gas transfer across the air water interface, these components affect pH
Alkalinity	A measure of the water's ability to neutralize acids, affects pH
Dissolved oxygen	Amount of oxygen in the water; important for fish and aquatic life
Soluble phosphate	Amount of dissolved phosphorus in the water; an algae nutrient
Nitrate-nitrogen	Amount of dissolved nitrate in the water; an algae nutrient
Ammonia-nitrogen	Amount of dissolved ammonia in the water; an algae nutrient and a chemical that consumes oxygen
Conservative tracer	Amount of a conservative, or non-biodegradable, material in the water

CHAPTER 4

MODEL CALIBRATION

4.0 Overview

The purpose of model calibration is to refine estimates of certain coefficients and parameters so that the model can reproduce observed data over a wide range of environmental conditions. When calibrating a water quality model such as CE-QUAL-W2, the emphasis is to ensure that temporal and spatial trends in such processes as temperature and nutrient cycling, dissolved oxygen levels, and algal growth are adequately represented rather than trying to match individual data points (FTN & Associates, 1998).

4.1 Calibration Year

As discussed previously, the CE-QUAL-W2 was calibrated to replicate the water quality in the river for 1988. This year was selected for calibration for several reasons: 1) This represents the most recent significant drought year and thus should reflect model process behavior during a drought, and 2) Selected temperature, dissolved oxygen, and nutrient data were collected for this year in pools 10, 4, and 2.

4.2 Calibration Methodology

In calibrating CE-QUAL-W2 for each pool of the Kentucky River, a calibration process similar to that recommended in the CE-QUAL-W2 Users' Manual was employed (Cole and Buchak, 1994). Figure 4.1 shows the general pattern of calibration for the critical quality components of the CE-QUAL-W2 model. Table 4.1 provides a list of the general parameter categories for purposes of model calibration. Italicized coefficients have been observed to be the most sensitive parameters (Cole personal comm.; Jarrett, 1998; Martin, 1987). As can be seen from the figure, the hydrodynamic parameters of the model were calibrated first followed by the thermodynamic parameters and the water quality parameters.

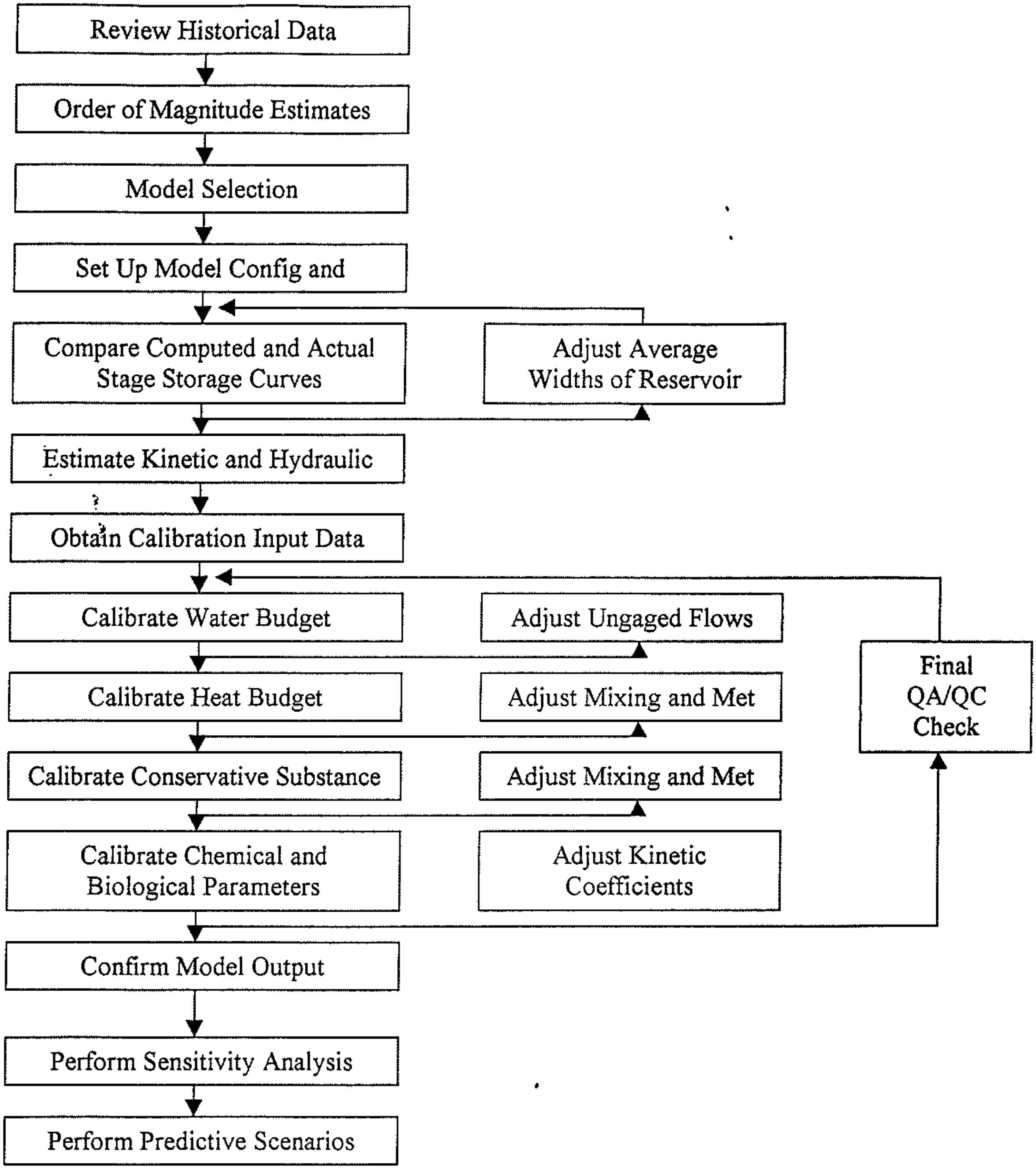

Figure 4.1 Calibration Flowchart

4.2.1 Hydrodynamic Calibration

Calibrating the hydrodynamics of the model is an iterative process. In the calibration process, both the inflow boundary conditions and the channel bathymetry were adjusted so as to match observed or predicted water surface elevations in the various pool segments. In calibrating CE-QUAL-W2 for 1988, model parameters were adjusted so as to match the water surface profiles generated by KYBASIN, which were in turn calibrated to match observed discharges at selected USGS gauging stations. The first step in calibrating the hydrodynamics involves developing the associated input flows to each river segment as well as the outflows at the downstream boundary condition. In applying CE-QUAL-W2, these inflows were obtained from the KYBASIN model. Once these data files were developed, CE-QUAL-W2 was run and the resulting water surface profiles were compared to those predicted using KYBASINS. In the event of discrepancies, the bathymetry files were then adjusted so as to minimize the associated deviations. Plots of the predicted and observed water surface levels for the 1988-calibration period are shown in Appendix C. As can be seen by the figures, the predicted and "observed" water surface levels are in very close agreement. Plots of the final calibrated stage-storage curve for each pool are shown in Appendix D. To insure the absence of any temporal biases in the resulting calibration process, the residual errors for each day were plotted as a function of time for each pool. Where temporal biases was identified, it was corrected by minor adjustments to the inflow values.

4.2.2 Thermodynamic Calibration

In calibrating the thermodynamic parameters of CE-QUAL-W2, predicted temperature values were compared to observed temperature profiles for pools 10, 4, and 2 using temperature data collected as part of the 1988 USGS NAQWA study (Haag, et al., 1995). Calibrated temperature profiles for these pools are shown in Appendix E. The final CE-QUAL-W2 coefficients used to calibrate the temperature algorithms are shown in Table 4.2 Parameters AX and DX are the horizontal dispersion coefficients for momentum and temperature/coefficients, respectively. The CHEZY coefficient is used in calculating boundary friction. The values used for AX, DX, and CHEZY were model default values and were not changed during calibration.

4.2.3 Water Quality Calibration

Water quality constituents of interest for this modeling effort were nutrients, algae, and dissolved oxygen (DO). The approach for calibrating each pool was to match such data against the 1988 observed data of the NAWQA study. The water quality coefficients for the model can be subdivided into four groups:

Biological coefficients (e.g., algal growth rates)
Chemical coefficients (e.g., nitrification rates, SOD, etc)
Rate modifiers (e.g., temperature factors, Q10 factors, etc) and
Stoichometric Constants (e.g., O_2 required to oxidize 1 mole of NH_3 to 1 mole of NO_3)

Coefficient values were compiled from the literature. The initial coefficient values used to initiate model calibration were taken from these coefficient compilations.

If necessary, initial coefficient rates were then modified to reduce the deviation between observed and predicted values during calibration. The coefficients, rate modifying parameters, and stoichometric constants for the water quality variables used in this study are shown in Table 4.3.

4.3 Calibration Results

Outflow data from pools 10, 4, and 2 were evaluated with respect to five water quality characteristics: temperature, dissolved oxygen, total phosphorus, nitrate-nitrogen, and ammonium-nitrogen. For the purpose of calibrating the CE-QUAL-W2 model, dissolved oxygen was selected as the primary model predictor, since the other model parameters directly affect dissolved oxygen. Appendix E contains the time-series plots for the dissolved oxygen results at each of the three pools. As can be seen from the figures, the predicted and observed values are in fairly good agreement indicating that the final model parameters are able to replicate the assumed natural process with a reasonable degree of accuracy. In particular, the model results tend to slightly underestimate the observed oxygen levels. With any modeling study, model performance is, in large part, a function of the data that is available to calibrate or to confirm the model assumptions.

4.4 Observations

The gathering and input of quality data is vital in any modeling scheme. This also holds true to the CE-QUAL-W2 model. The greatest problems with the input data for this model come from the model's sensitivity, thus requiring a great deal of data at very small time intervals. In addition, CE-QUAL-W2 requires that all data be in a format that it may readily read.

Limited data was available to fit model coefficients and to evaluate the reliability of the model fit (calibration and confirmation process). The available data was used to ensure that the relations between processes in the model were reasonable and and the time dependency of those processes were within certain bounds. Visual cues were used to evaluate model fits because of the lack of adequate data to perform statistical evaluation (James and Burges 1982; Nash and Sutcliffe, 1970).

The original modeling assumption is that CE-QUAL-W2 is capable of representing the salient features and processes of the Kentucky River Basin. Future data collection programs in the Kentucky River Basin should conform to the needs of falsifying these modeling assumptions (Beck, 1987; Oreskes, et al., 1994). Recommendations for additional water quality stations for use in improving the calibration of the model are provided in the companion report: **Kentucky River Modeling and Monitoring Needs Assessment** (Ormsbee, et. al., 1998).

Table 4.1 Model Calibration Parameters

BATHYMETRY
Cell Widths
Stage Storage Curves
Pool Surface Elevations
TEMPERATURE CALIBRATION
Wind sheltering coefficient
Longitudinal dispersion coefficient
Modify bathymetry
Depth location of outlets
Radiation absorbed in surface layer
Light attenuation coefficient
Attenuation coefficient for organic and Inorganic suspended solids
Suspended solids settling rates
PHYTOPLANKTON
Maximum growth rate
Settling rate
Half-saturation constants for
Phosphorus
Nitrogen
Saturation light intensity
Mortality rate
Dark respiration rate
Photo-respiration rate
NITROGEN AND PHOSPHORUS
Ammonia decay rate
Nitrate reduction rate
Sediment release rates
Partition coefficients
DISSOLVED OXYGEN
Sediment oxygen demand
STOICHIOMETRIC COEFICIENTS
Phosphorus
Nitrogen
Carbon
Oxygen
Ammonia
Algal respiration
Photosynthesis

Table 4.2 Thermodynamics Calibration Parameters

PARAMETER	PARAMETER DESCRIPTION	VALUE
AX	Longitudinal eddy viscosity	1.0
DX	Longitudinal eddy diffusivity	1.0
CHEZY	Chezy coefficient	72.0
WSC	Wind sheltering coefficient	0.85 – 0.95
BETA	Fraction of solar radiation absorbed	0.75
EXH20	Extinction coefficient for pure water	0.95
EXSS	Extinction coefficient for inorganic solids	0.1
EXOM	Extinction coefficient for organic solids	0.65
CBHE	Coefficient of bottom heat exchange	7.0E-8
TSED	Sediment temperature	12.5

Table 4.3 Water Quality Calibration Parameters

PARAMETER	PARAMETER DESCRIPTION	VALUE
C2I(1)	Tracer Initial Concentration	0.10
C2I(2)	Inorganic Suspended Solids Initial Concentration	2.0
C2I(3)	Coliform Initial Concentration	10.0
C2I(4)	Total Dissolved Solids Initial Concentration	51.0
C2I(5)	Labile DOM Initial Concentration	0.70
C2I(6)	Refractory DOM Initial Concentration	2.022
C2I(7)	Algae Initial Concentration	0.10
C2I(8)	Detritus Initial Concentration	0.10
C2I(9)	Phosphate Initial Concentration	0.50
C2I(10)	Ammonium Initial Concentration	0.05
C2I(11)	Nitrate-Nitrite Initial Concentration	0.84
C2I(12)	Dissolved Oxygen Initial Concentration	8.0
C2I(14)	Total Inorganic Carbon Initial Concentration	11.91
C2I(15)	Alkalinity Initial Concentration	31.0
C2I(20)	Iron Initial Concentration	0.10
COLQ10	Coliform Q10 Coefficient	1.04
COLDK	Coliform Decay Rate	1.40
SSS	Suspended Solids Settling Rate	1.40
AG	Algal Growth Rate	0.51
AM	Algal Mortality Rate	0.01
AE	Algal Excretion Rate	0.01
AR	Algal Dark Respiration Rate	0.02
AS	Algal Settling Rate	0.14
ASAT	Saturation Intensity at Maximum Photosynthetic Rate	190.0
APOM	Fraction of Algal Biomass Lost by Mortality to Detritus	0.70
AT1	Lower Temperature for Algal Growth	10.0
AT2	Lower Temperature for Max Algal Growth	33.0
AT3	Upper Temperature for Max Algal Growth	36.0

AT4	Upper Temperature for Algal Growth	38.0
AK1	Fraction of Algal Growth Rate at ALGT1	0.06
AK2	Fraction of Algal Growth Rate at ALGT2	0.80
AK3	Fraction of Algal Growth Rate at ALGT3	0.80
AK4	Fraction of Algal Growth Rate at ALGT4	0.07
LDOMDK	Labile DOM Decay Rate	0.12
LRDDK	Labile to Refractory DOM Decay Rate	0.002
RDOMDK	Max Refractory DOM Decay Rate	0.001
LPOMDK	Detritus Decay Rate	0.06
POMS	Detritus Settling Rate	0.35
OMT1	Lower Temperature for Organic Matter Decay	5.0
OMT2	Lower Temperature for Max Organic Matter Decay	22.0
OMK1	Fraction of Organic Matter Decay Rate at OMT1	0.1
OMK2	Fraction of Organic Matter Decay Rate at OMT2	0.99
SDK	Sediment Decay Rate	0.04
FSOD	Fraction of SOD	0.80
SOD	Range of Sediment Oxygen Demand for Segments	0.40 – 0.90
KBOD	5 Day Decay Rate @ 20 C	0.25
TBOD	Temperature Coefficient	1.0147
RBOD	Ratio of BOD5 to Ultimate BOD	1.85
PO4R	Sediment Release Rate of Phosphorous	0.013
PARTP	Phosphorous Partitioning Coefficient for Suspended Solids	1.40
AHSP	Algal Half-Saturation Constant for Phosphorous	0.001
NH4R	Sediment Release Rate of Ammonia	0.08
NH4DK	Ammonia Decay Rate	0.12
PARTN	Ammonia Partitioning Coefficient for Suspended Solids	1.0
AHSN	Algal Half-Saturation Constant for Ammonia	0.008
NH4T1	Lower Temperature for Ammonia Decay	5.0
NH4T2	Lower Temperature for Max Ammonia Decay	22.0
NH4K1	Fraction of Nitrification Rate at NH4T1	0.1
NH4K2	Fraction of Nitrification Rate at NH4T2	0.99
NO3DK	Nitrate Decay Rate	0.102
NO3T1	Lower Temperature for Nitrate Decay	5.0
NO3T2	Lower Temperature for Max Nitrate Decay	21.0
NO3K1	Fraction of Denitrification Rate at NO3T1	0.1
NO3K2	Fraction of Denitrification Rate at NO3T2	0.98
CO2R	Sediment Carbon Dioxide Release Rate	0.1
FER	Iron Sediment Release Rate	0.5
FES	Iron Settling Rate	2.0
O2NH4	Oxygen Stoichometric Equivalent for Ammonia Decay	4.57
O2OM	Oxygen Stoichometric Equivalent for Organic Matter Decay	1.40
O2AR	Oxygen Stoichometric Equivalent for Algal Dark Respiration	1.40
O2AG	Oxygen Stoichometric Equivalent for Algal Growth	1.40
BIOP	Stoichometric Equivalent Between Organic Matter and Phosphorous	0.011
BION	Stoichometric Equivalent Between Organic Matter and Nitrogen	0.08
BIOC	Stoichometric Equivalent Between Organic Matter and Carbon	0.45
O2LIM	Dissolved Oxygen Concentration at which Anaerobic Processes Begin	0.20

Table 4.4 Other Model Calibration Parameters

PARAMETER	PARAMETER DESCRIPTION	VALUE
DLTMIN	Minimum Timestep	1
DLTMAX	Maximum Timestep	6000
DLTF	Fraction of Timestep	0.9
T2I	Initial Temperature	19.0
ICETHI	Initial Ice Thickness	0.0
WTYPEC	Waterbody Type	FRESH
SLTRC	Transport Solution Scheme	QUICKEST
THETA	Time-weighting for Vertical Advection Scheme	0.55
NWSC	Number of Time Intervals the Wind Sheltering Coef Varies	6

CHAPTER 5

MODEL APPLICATION

5.0 Overview

Once CE-QUAL-W2 was calibrated using the observed data for the drought of 1988, the model was used to evaluate the impact of operating the low-level valves for the 1930 drought of record along with forecasted demands for the year 2020. This was accomplished by simulating the river for two different scenarios, 1) without valves, and 2) with valves. The simulation methodology and results associated with this application are presented in this chapter.

5.1 Simulation Period

In applying CE-QUAL-W2 to the 1930/2020-flow/demand scenario, the period from 5/27 to 9/30 was selected as the critical flow period.

5.2 Boundary Conditions

Both upstream and tributary flows for the selected simulations were obtained from an application of KYBASIN for the 1930/2020-flow/demand scenario. The hydrologic data and associated results for this flow scenario are discussed in detail in the report: **Kentucky River Basin Water Supply Assessment Study: Task V Report – Development and Evaluation of Water Supply Alternatives** (Ormsbee and Herman, 1996). Water quality loadings for the 1930/2020 scenario were generated using the previously described regression models (see Section 3.5.3) along with 1930 tributary flows and the forecasted 2020 return flows from the various point sources.

5.3 Initial Conditions

Initial hydrologic conditions for the model simulation were based on the results from the KYBASIN model for the simulation start date (i.e., 5/28). Initial conditions for the water quality parameters were obtained by starting CE-QUAL-W2 at the beginning of the year along with calibrated parameter values obtained from the 1988 simulations and then letting the model run until the beginning of the simulation period (i.e., 5/28). This initial simulation period was used to dampen the oscillatory affects associated with any initial parameter errors so that a relative parameter equilibrium could be obtained.

5.4 Hydrologic Confirmation

In an attempt to confirm the validity of the calibrated hydrodynamic parameters that were obtained using the 1988 simulation, the water surface profiles generated using CE-QUAL-W2 for both 1930/2020 scenarios were compared to those obtained from KYBASINS for the same scenarios. These results are shown in Appendix F. As is evident from the results, the water surface profiles were in very close agreement indicating that the bathymetry files used in CE-QUAL-W2 were able to reproduce the hydromechanics modeled in KYBASIN for the same period.

5.5 Simulation Results

Once the CE-QUAL-W2 data files for 1930/2020 scenario were completed and the hydrodynamic parameters were confirmed using the results from KYBASIN, CE-QUAL-W2 was used to predict a set of eight water quality parameters for each mile segment of the Kentucky River. The modeled water quality parameters include: temperature, dissolved oxygen (DO), algae, nitrate nitrogen (NO3), ammonium nitrogen (NH4), total phosphorus (TP), total suspended solids (TSS), total dissolved solids (TDS), labile dissolved organic matter (LDOM), and refractive dissolved organic matter (RDOM). For purposes of illustration, time series plots for the most downstream mile segment for each pool are presented in Appendix G.

As can be seen from Appendix G, predicted DO levels for all pools for both scenarios remained above the minimum value of 5 mg/L with the exception of pools 14 and 3. In general, the DO profiles associated with the valve scenario were only slightly lower than the without valve scenario, indicating that the valve scenario can be expected to produce a minimum impact on the dissolved oxygen in the river.

The low DO levels in pool 3 are directly related to the wide fluctuations in pool temperature and are concluded to be due to numerical instabilities in the water quality algorithm as affected by the irregularities in the bathymetry data. Attempts to eliminate these instabilities through adjustment of the bathymetry files proved to be unsuccessful.

The low DO levels in pool 14 are assumed to be associated with impacts of the upstream boundary conditions (i.e., the inflow loadings associated with the North, Middle, and South Forks of the Kentucky River). Improved DO levels for pool 14 will require more aggressive source water protection strategies in the upstream tributary basins, and in particular the North Fork of the Kentucky River. The DO levels for pool 14 show a significant drop for the valve scenario, which is assumed to be attributed to the small volume of the pool, and the associated decrease in the pool volume associated with operation of the valves for pool 14. These results would suggest that pool 14 be mined last in the event that additional river volumes are needed to offset severe drought conditions in the lower part of the basin.

Finally, an examination of the pool profiles indicate that dissolved oxygen concentrations for each pool and each scenario are all restricted to the lower sections of the river profile thus allowing for the migration of fish to more acceptable regions. Based on the observed locations of the dominant mussel bed, it appears that the reduced zones of oxygen will have minimum impacts on the resident mussel populations as well.

CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.0 Summary

The current report summarizes the work associated with the construction, calibration, and application of the CE-QUAL-W2 (Cole and Buchak, 1994; Corps of Engineers, 1990) water quality model to the Kentucky River. In applying the model to the Kentucky River System, the primary objective was to assess the impact of the operation of low-level control valves on the water quality of the Kentucky River. The results of this study indicate that for the modeled scenario, the proposed valves can be used to draw down the individual pools on the Kentucky River a maximum of four feet without causing significant chronic or acute impacts to the biota of the river. The one possible exception to this condition is pool 14. These results were obtained by modeling the impact of the valves for low flow conditions associated with the 1930 drought of record along with projections for the year 2020.

6.1 Conclusions

As pointed out in other in previous applications of the CE-QUAL-W2 model by FTN & Associates (1998), "While there are assumptions and limitations inherent in any modeling study, model simulations are essential in evaluating the direction of change and the relative magnitude of change for different management strategies. Without model simulations, the only alternatives for evaluating management strategies are to implement them and assess the response or to rely on best professional judgment. Prediction of absolute concentration and values for any constituent, however, is uncertain. All models are abstractions of the actual physical, chemical, and biological processes and interactions that are occurring in the actual physical system. The model algorithms do not, and cannot, incorporate all the pathways or forcing functions affecting stream or reservoir water quality. Therefore, there will be uncertainty in the estimates".

Despite the inherent limitations of model results, model simulations are extremely useful in comparing and evaluating the relative differences among management alternatives, but not necessarily for projecting exactly what the concentration of a certain constituent will be under the scenario being simulated. For example, if the model predicts a DO concentration of 5.1 mg/L for a certain time and place for a certain scenario, that does not necessarily mean that a state water quality standard of 5.0 mg/L will be maintained. However, simulations of different management scenarios can be compared so that the scenario that yielded the better water quality (e.g., higher DO concentration, lower algae concentration, etc.) can receive greater attention for additional study or refinement. In the context of the current study, two main scenarios were investigated: 1) operation of the river without valves – and subsequent enforcement of the state minimum-flow restrictions by reducing withdrawals, and 2) operation of the river with the valves – and subsequent enforcement of the minimum-flow regulations through the valves and thus allowing for additional withdrawals.

Application of CE-QUAL-W2 to the Kentucky River for both scenarios has revealed that the use of the operational valves to satisfy the minimum-flow requirements will have a minimum water quality impact as measured against the results associated with the no-valve scenario. The valve scenario has added the benefit of reducing the projected water supply deficit from 9.7 billion gallons to 3.0 billion gallons (for the 1930 drought/2020 demand conditions).

6.2 Recommendations

Based on the results of this study, it is recommended that the Authority give serious consideration to the use of the excess volumes in pools 9 – 14 during severe drought conditions. Since the greatest difference in water quality impacts between the valve and no-valve scenarios appears to be associated with pool 14, it is recommended that pool 14 be mined for additional downstream use only after pools 9 – 13 have been fully utilized.

While the comparative results of the two modeled scenarios indicate that the use of the low-level release valves will not significantly decrease the water quality levels beyond those associated with the no-valve scenario, the results do not provide guarantees with regard to the absolute predicted values. As with any modeling study, the accuracy of the results will be dependent upon the accuracy of the input data. In the present modeling study, the CE-QUAL-W2 model was calibrated using limited water quality data obtained from pools 2, 4, and 10. Improved assurances about the range or variance of the absolute predictions can be obtained by subsequent collection and utilization of additional data from these and other sites. As a result, it is recommended that the Authority consider developing a water quality monitoring network for the basin in support of this and other operational objectives.

Secondly, although the predicted comparisons provide some assurances with regard to relative impacts of the 1930/2020 model scenario, they do not necessarily provide assurances with regard to other flow scenarios although this may be inferred given the severe nature of the 1930/2020 scenario. Given the operational responsibilities associated with the Kentucky River Authority, it would seem highly beneficial to have the capability to predict absolute water quality impacts on the river in response to real-time operational decisions. Such a capability will require two additional technologies: 1) a real-time hydrologic/water quality operational model, and 2) a sufficient hydrologic/water quality monitoring network to support such a model. Even in the absence of a real-time model, additional hydrologic and water quality monitoring stations are beneficial to support general operations.

It is anticipated that a real-time hydrologic/water quality operational model may be readily developed out of a synthesis of the two previously developed planning models (i.e., KYBASIN and KYQUAL) with minimal additional effort. As a consequence, it is recommended that the Kentucky River Authority seriously consider development of such model. Once developed, the model could be used by the Kentucky River Authority personnel to predict anticipated pool levels and average water quality conditions in response to real-time hydrologic conditions and selected operational decisions (e.g., valve releases). While general hydrologic impacts could be predicted by using such a model along with existing real-time rainfall and streamflow gaging stations, it is unlikely that the existing stations would provide sufficient data on which to base river-wide operational decisions during extreme low-flow conditions. In addition, there exists no current real-time water quality network for the Kentucky River. To adequately predict water quality impacts in a real-time environment, it is obvious that additional water quality data be available. As a result, it is recommended that the Kentucky River Authority consider expanding the existing water quantity and water quality monitoring network of the Kentucky River to provide the basis for making such real-time operational decisions. In support of this recommendation, a companion report, **Kentucky River Modeling and Monitoring Needs Assessment**, has been prepared to provide some general recommendations on the need, the type, the location, and the priorities associated with individual gaging stations to be developed in support of such a network.

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Appendix A

Summary of Input and Output Files for CE-QUAL-W2

INPUT FILES

GENERAL FILES

Control (W2_CON)

This file dictates to the program what simulations are to be run, what files are to be included, and how/what output is to be displayed.

Bathymetry (BTH)

This file sets up the size and shape of the basin for the model into grid system. Data required includes segment lengths, layer heights, segment orientations, and cross-section data in top-width format.

Meteorological (MET)

This file tells the program the weather conditions for the duration of the model simulation. Data required includes temperature, dew point temperature, wind speed, wind direction, and solar exposure. Data should be input at a minimum of 8 hour intervals.

BRANCH FILES

This group of files contains information for the main branches of the modeled basin.

Branch Inflow (QIN)

This file inputs the incoming flowrate at the upstream end of the branch. Data should be at a minimum of 8-hour intervals.

Branch Inflow Temperature (TIN)

This file inputs the temperature of the incoming flow at the upstream end of the branch. Data should be at a minimum of 8 hour intervals.

Branch Inflow Constituent (CIN)

This file inputs the concentration of constituents in the incoming flow at the upstream end of the branch. Data should be at a minimum of 8-hour intervals. Constituents included in Kentucky River model are suspended solids, fecal coliform, total dissolved solids, algae, detritium, phosphorus, ammonia, nitrate, dissolved oxygen, alkalinity, iron, L dissolved organic material, R dissolved organic material, total inorganic carbon, and a tracer.

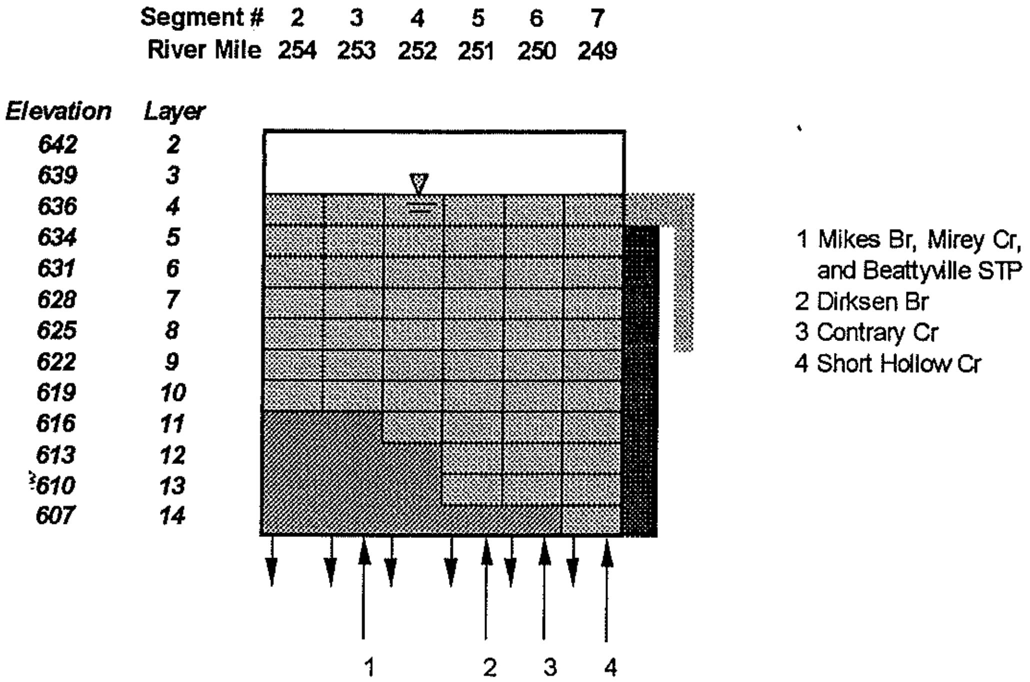
Branch Outflow (QOT)

This file inputs the outgoing flowrate at the downstream end of the branch. Data should be at a minimum of daily intervals.

Appendix B

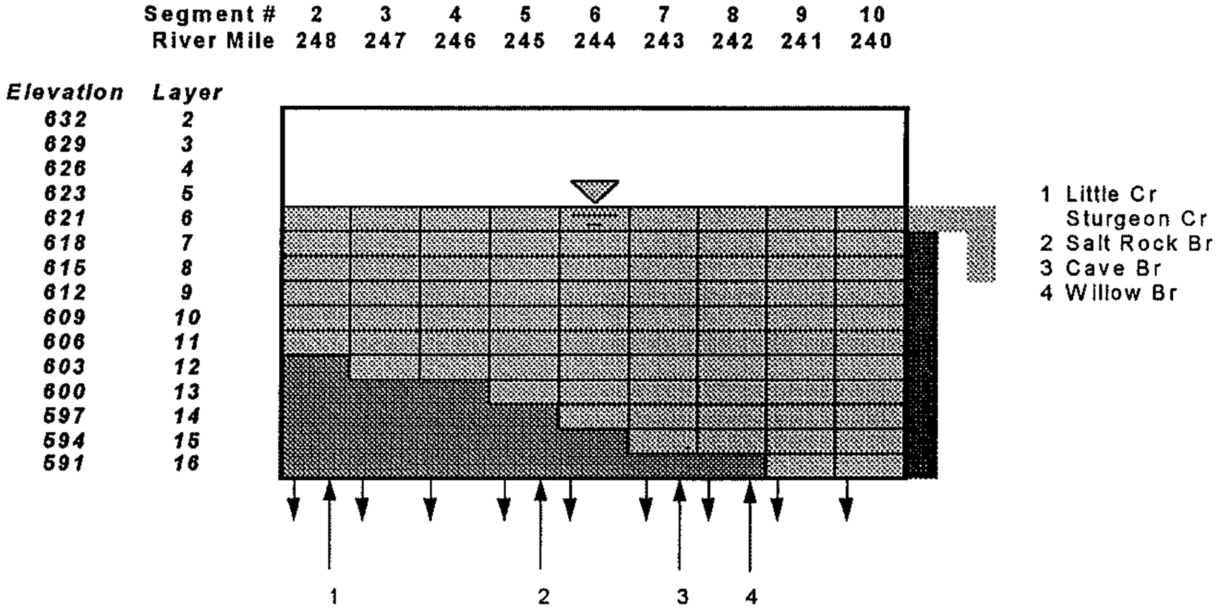
Layout of Pool Grids Spacing

Pool 14



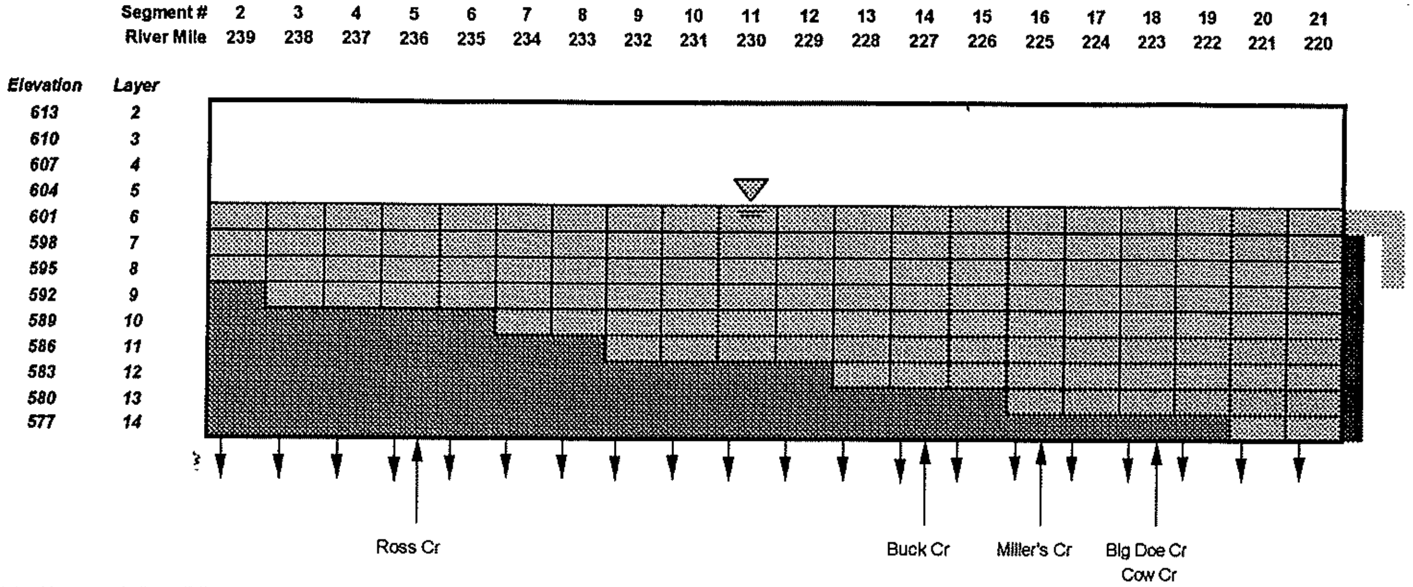
Note: Up arrows indicate Tributary inflow, Down arrows indicate Withdrawals from the segment

Pool 13



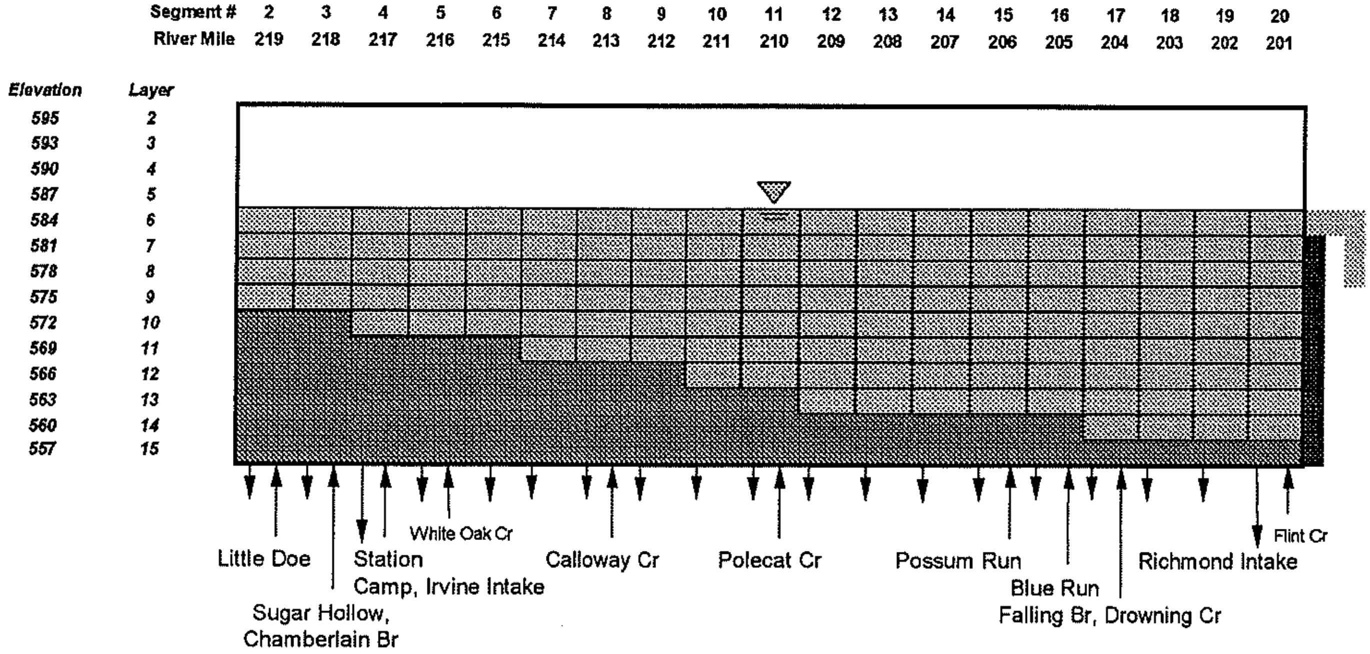
Note: Up arrows indicate Tributary inflow, Down arrows indicate Withdrawals from the segment

Pool 12



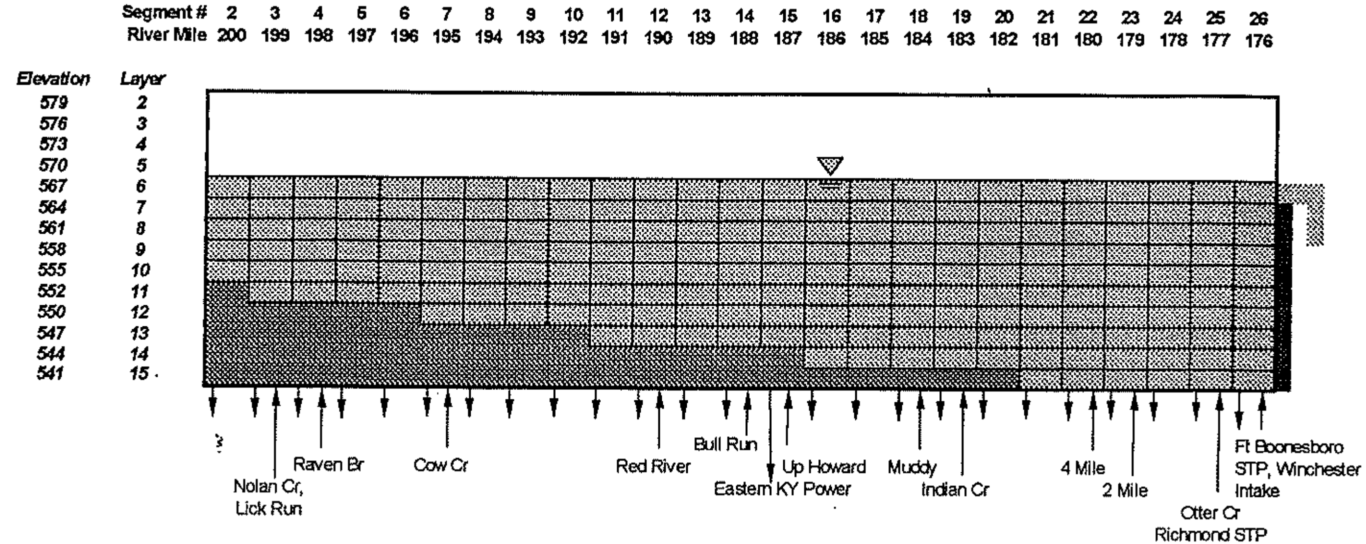
Note: Up arrows indicate Tributary inflow, Down arrows indicate Withdrawals from the segment

Pool 11



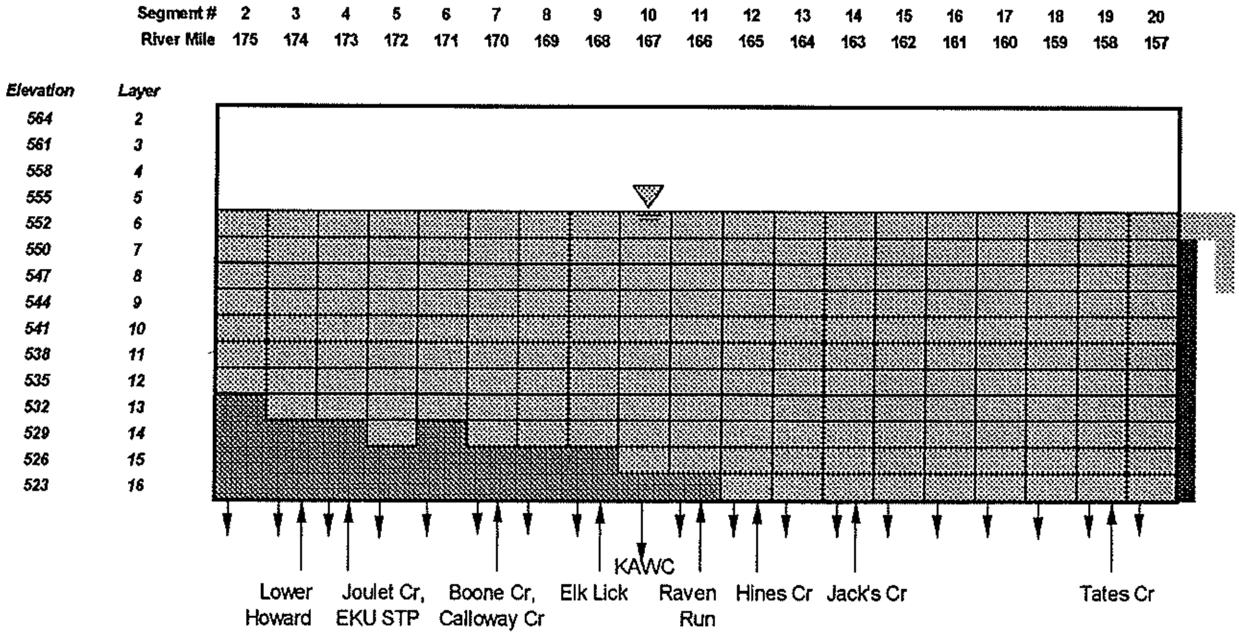
Note: Up arrows indicate Tributary inflow, Down arrows indicate Withdrawals from the segment

Pool 10



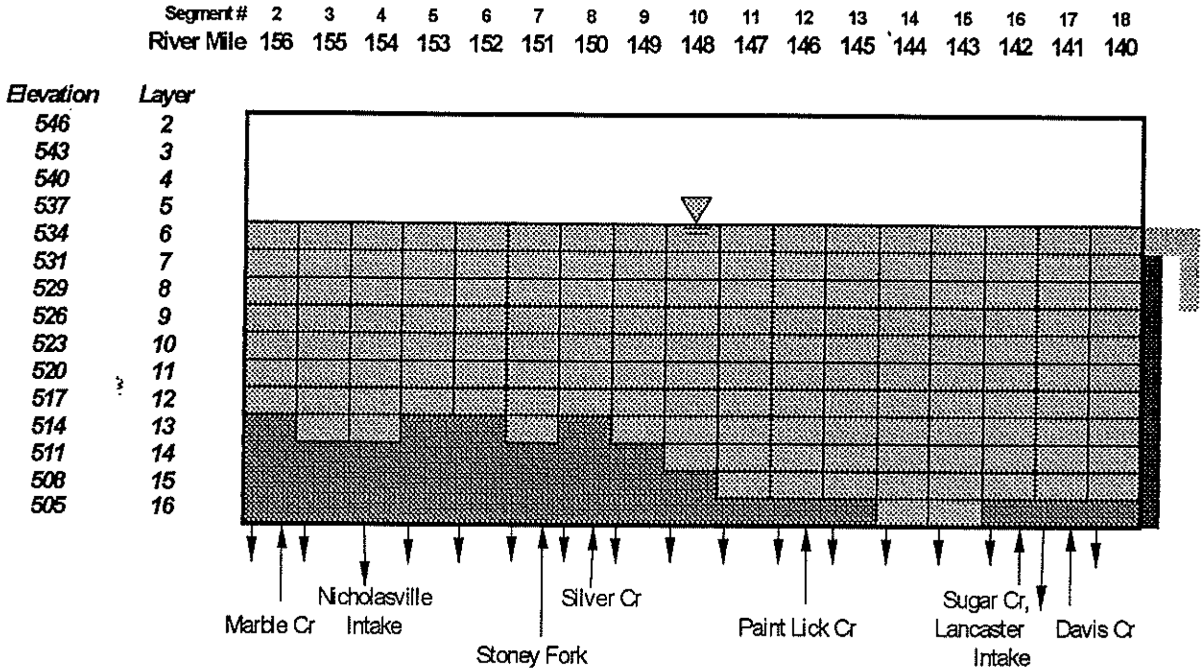
Note: Up arrows indicate Tributary inflow, Down arrows indicate Withdrawals from the segment

Pool 9



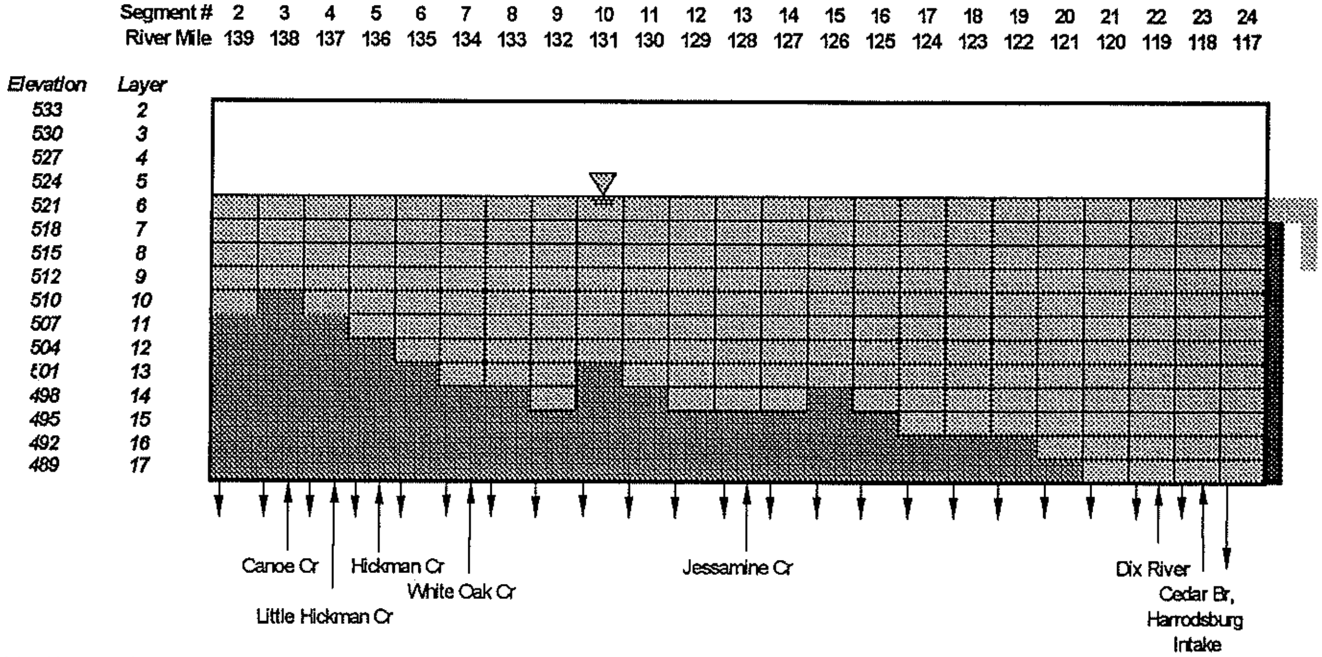
Note: Up arrows indicate Tributary inflow, Down arrows indicate Withdrawals from the segment

Pool 8



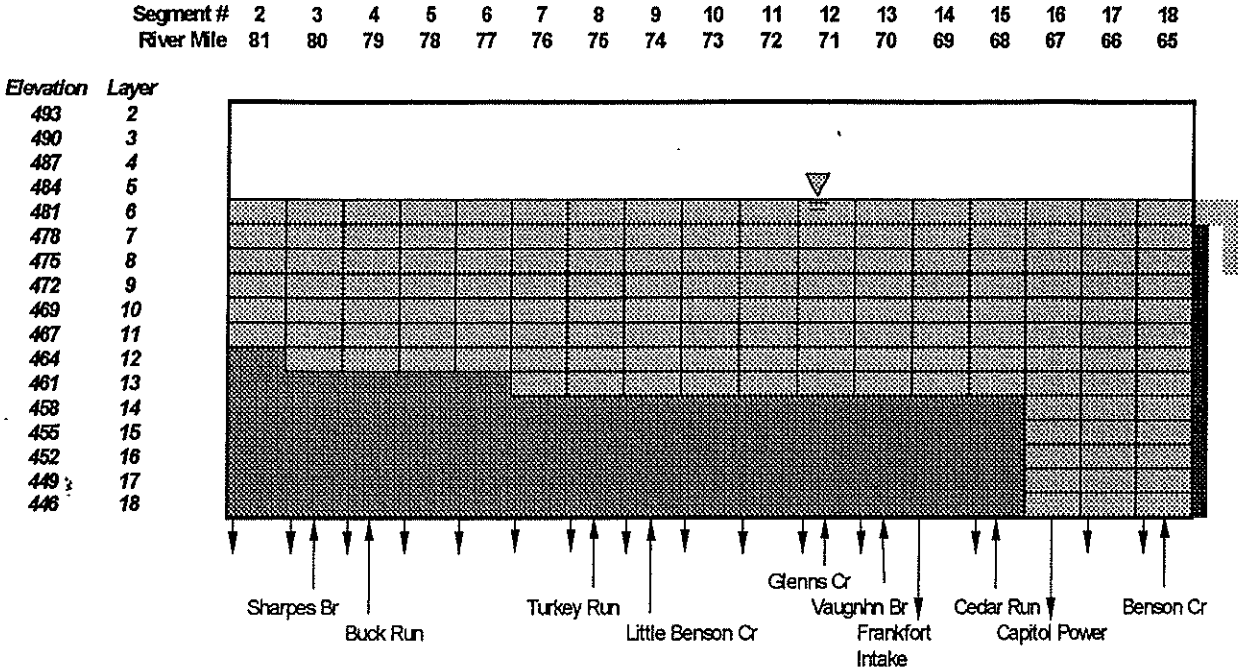
Note: Up arrows indicate Tributary inflow, Down arrows indicate Withdrawals from the segment

Pool 7



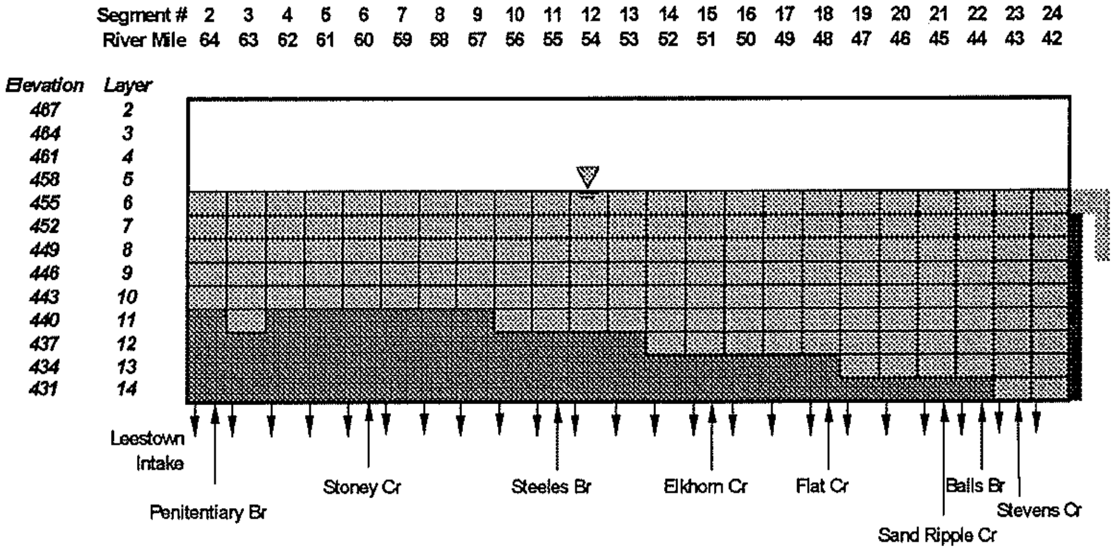
Note: Up arrows indicate Tributary inflow, Down arrows indicate Withdrawals from the segment

Pool 4



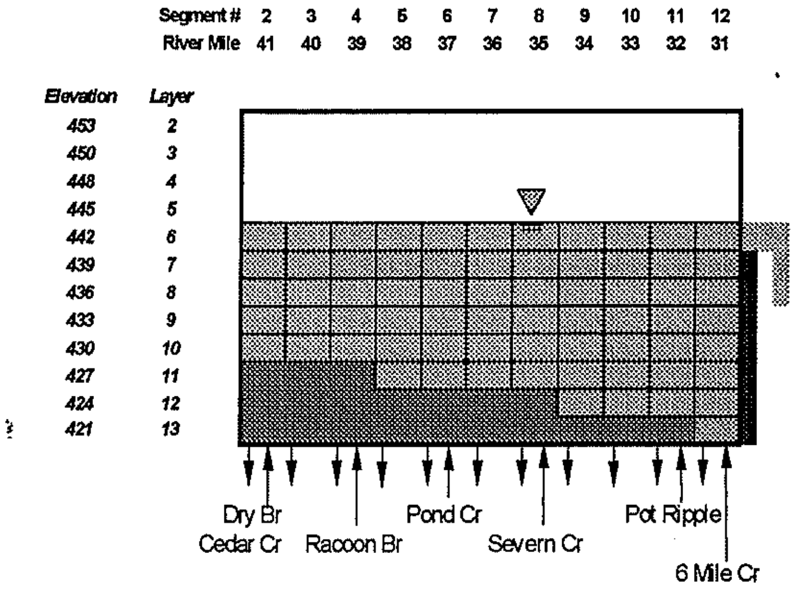
Note: Up arrows indicate Tributary Inflow, Down arrows indicate Withdrawals from the segment

Pool 3



Note: Up arrows indicate Tributary inflow, Down arrows indicate Withdrawals from the segment

Pool 2

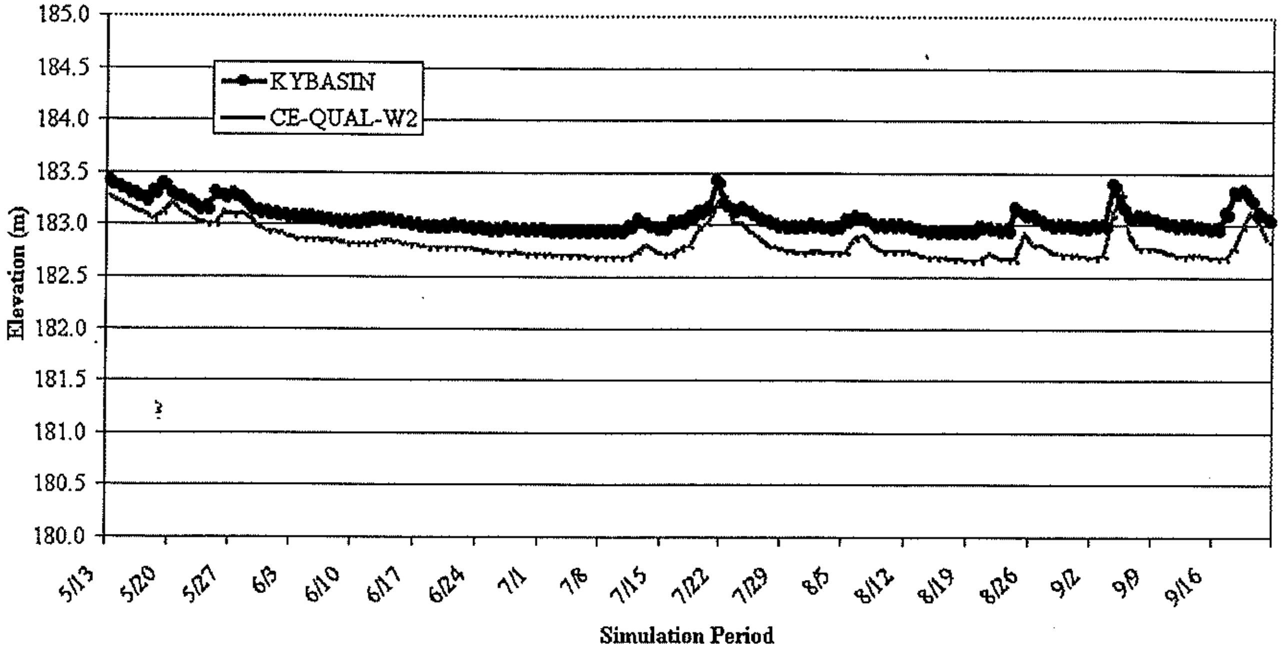


Note: Up arrows indicate Tributary inflow, Down arrows indicate Withdrawals from the segment

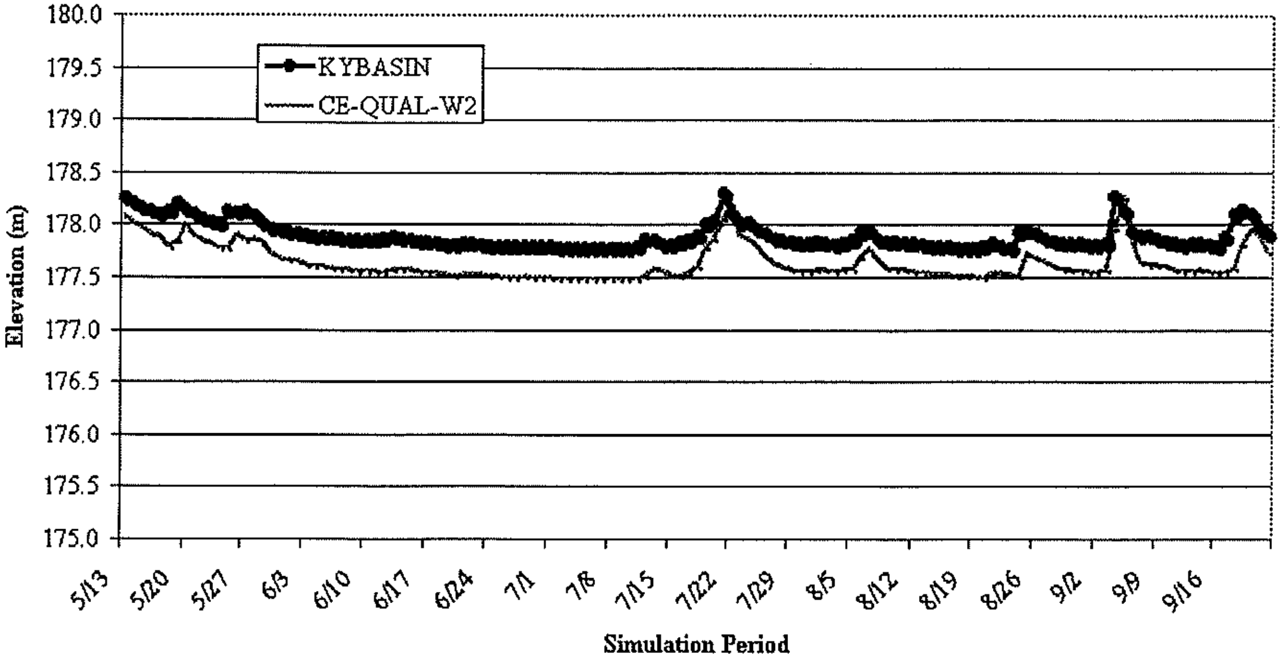
Appendix C

Predicted and Observed Water Surface Time Series for 1988

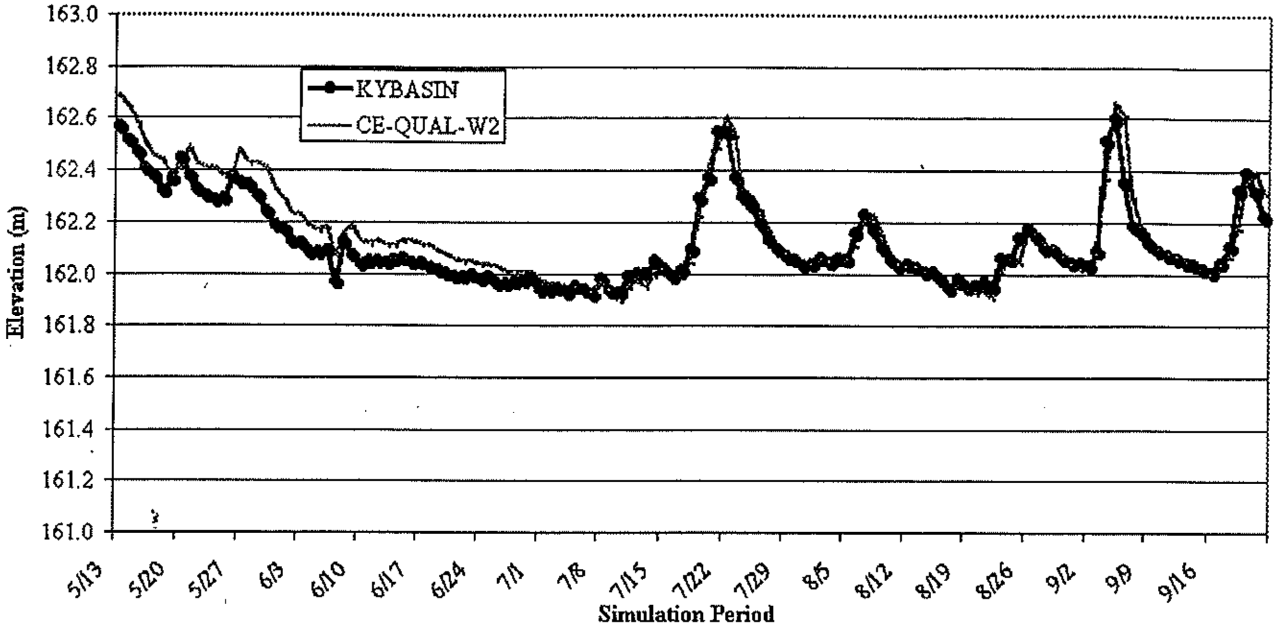
Water Surface Elevations, Pool 12, 1988 Calibration



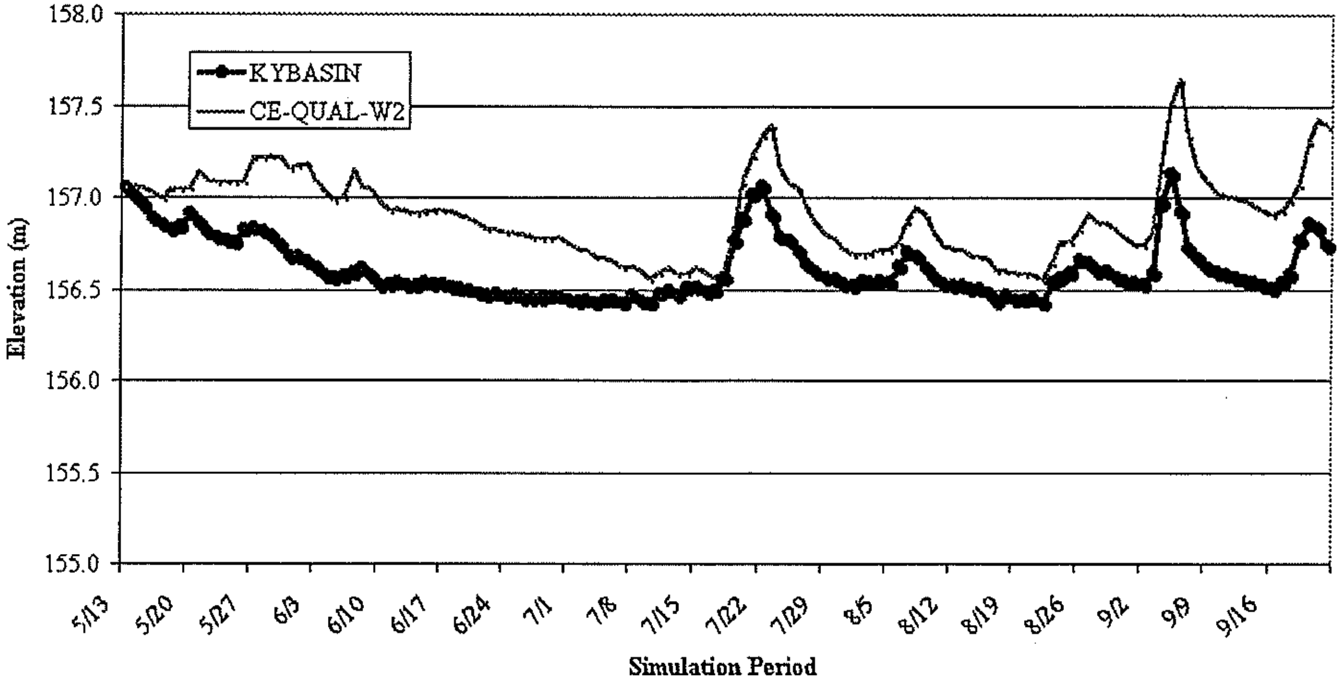
Water Surface Elevations, Pool 11, 1988 Calibration

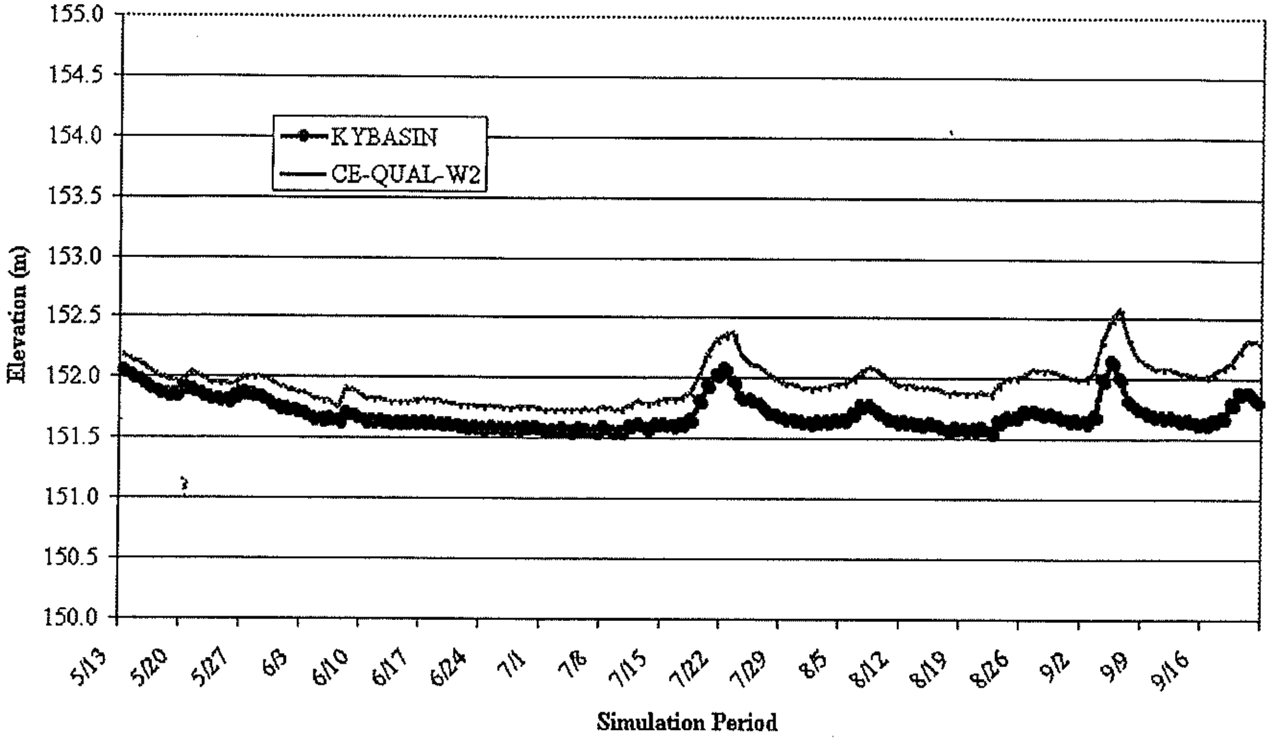


Water Surface Elevations, Pool 8, 1988 Calibration

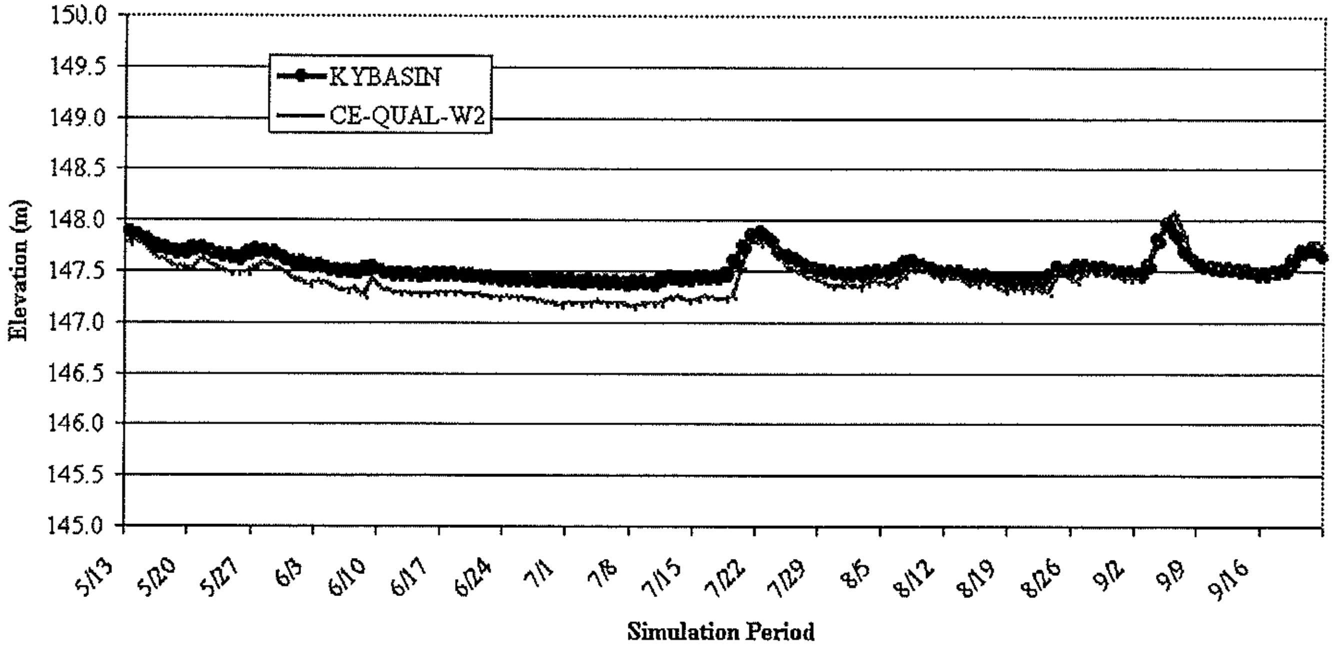


Water Surface Elevation, Pool 7, 1988 Calibration

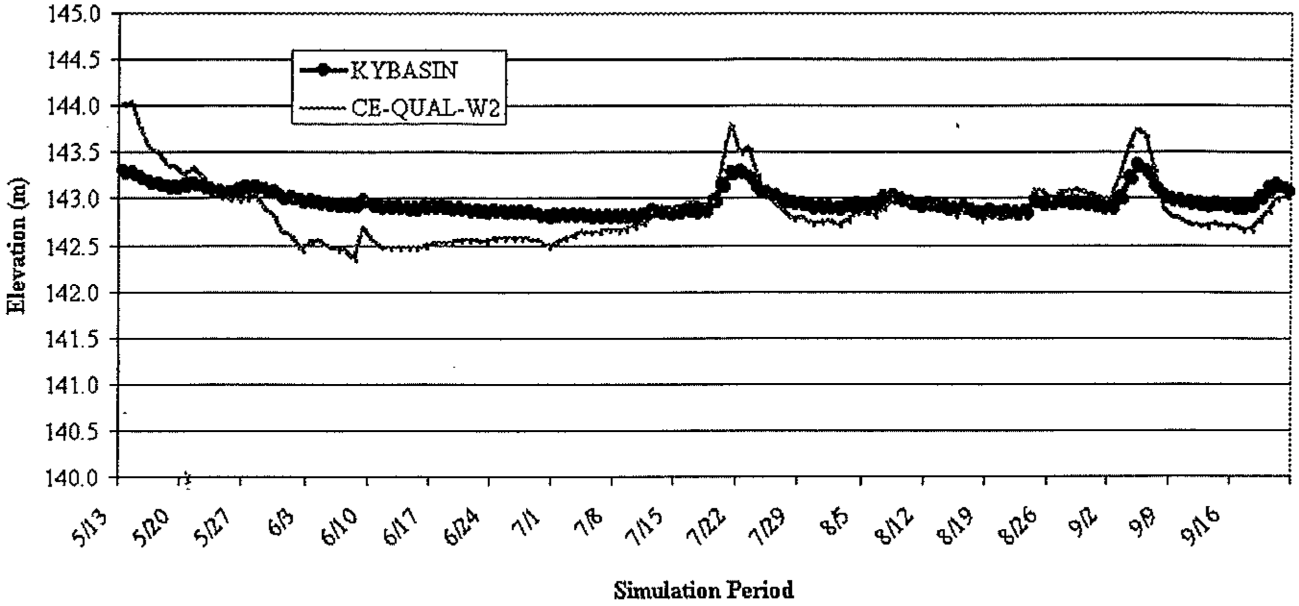


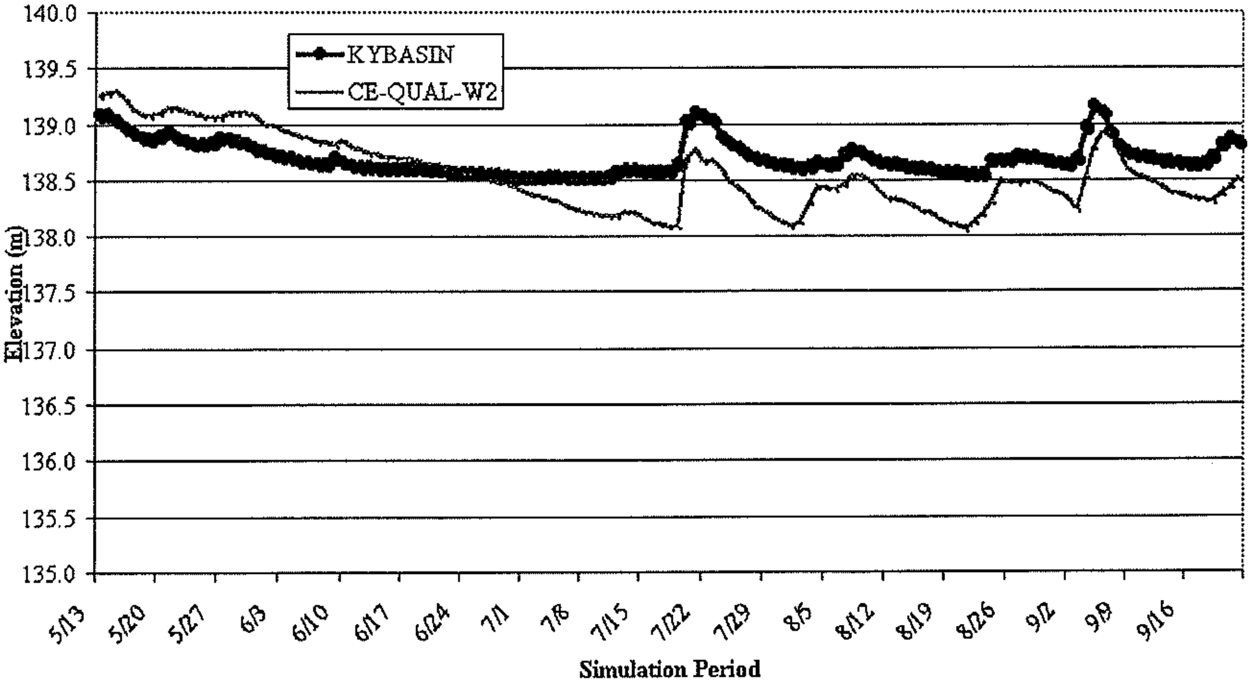


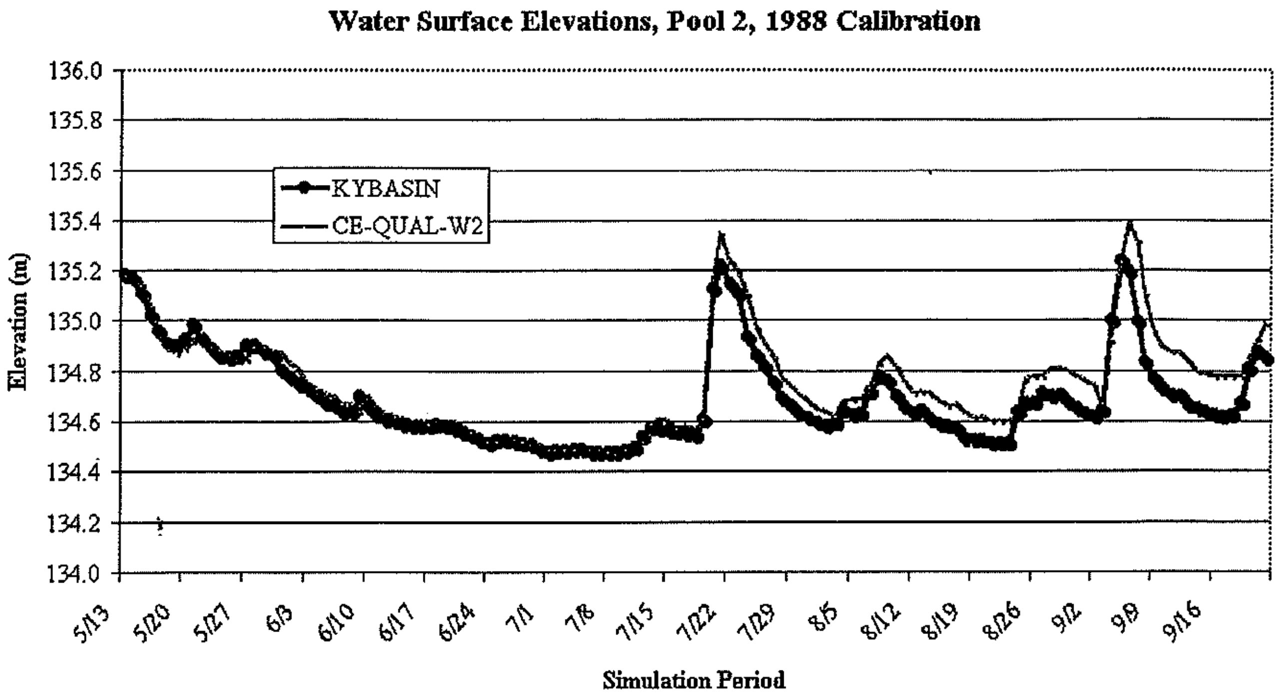
Water Surface Elevations, Pool 6, 1988 Calibration



Water Surface Elevations, Pool 5, 1988 Calibration


Water Surface Elevations, Pool 4, 1988 Calibration


Water Surface Elevations, Pool 3, 1988 Calibration

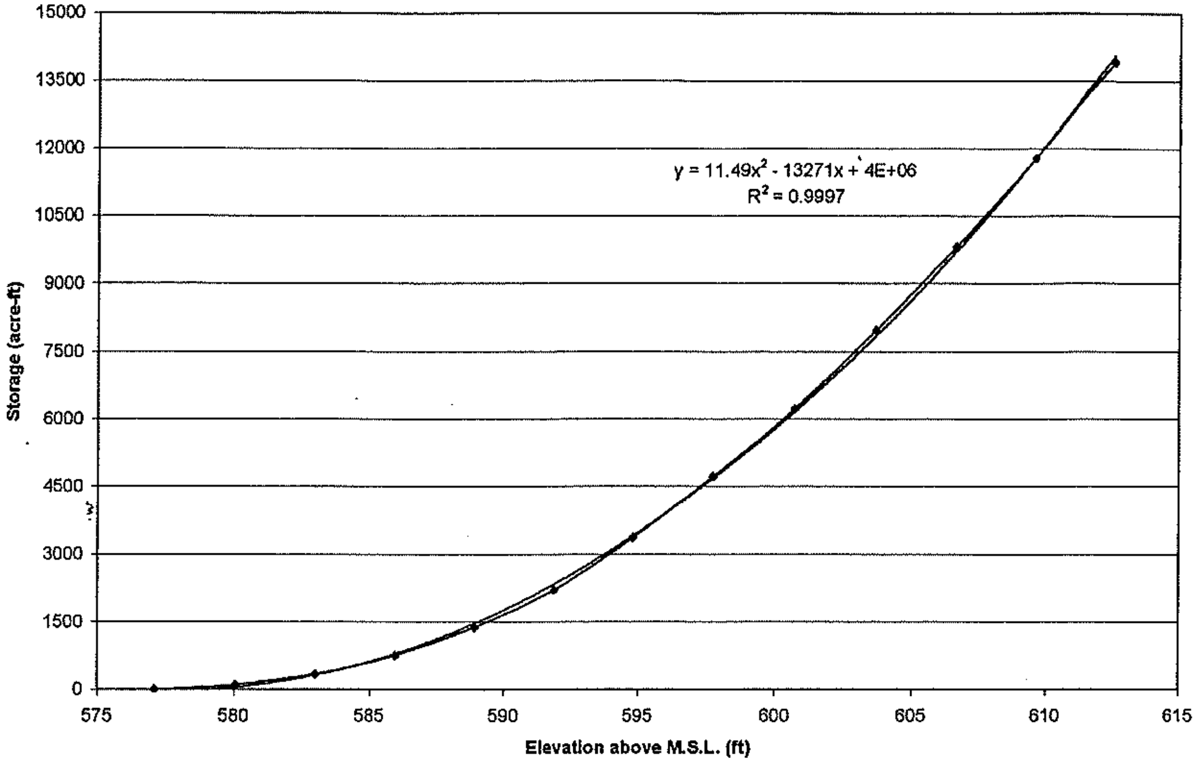


Water Surface Elevations, Pool 2, 1988 Calibration

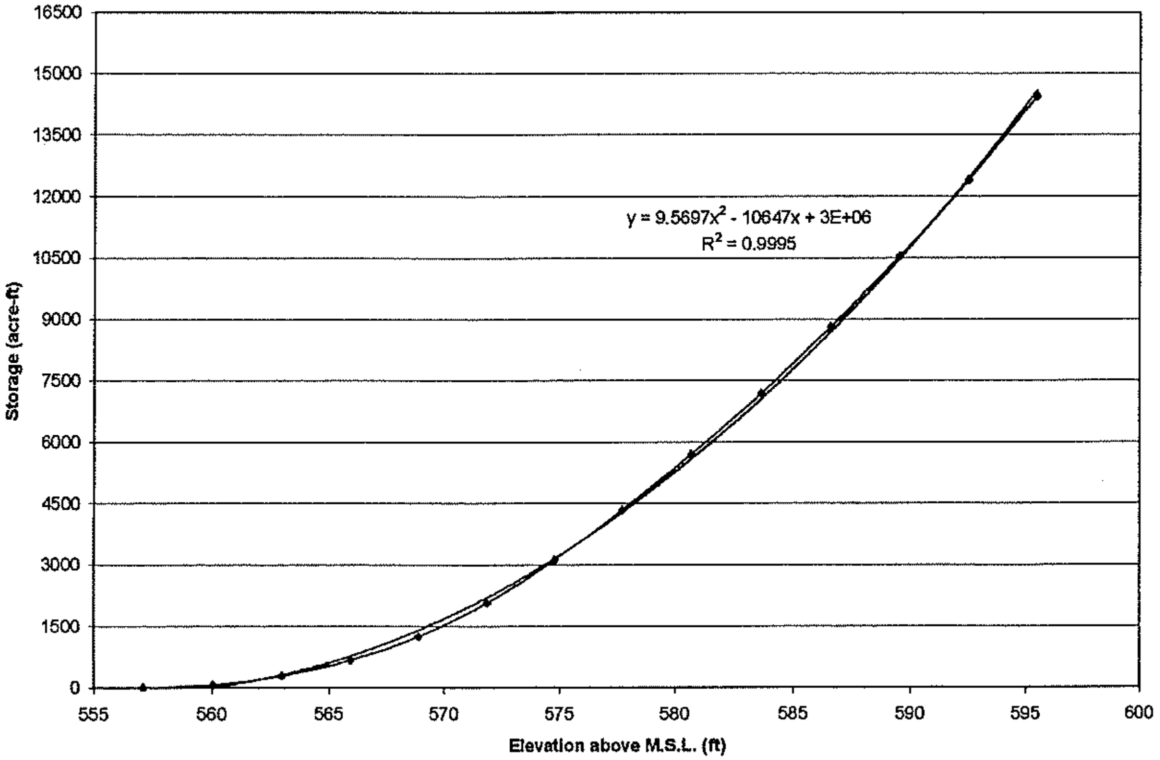
Appendix D

Stage - Storage Curves

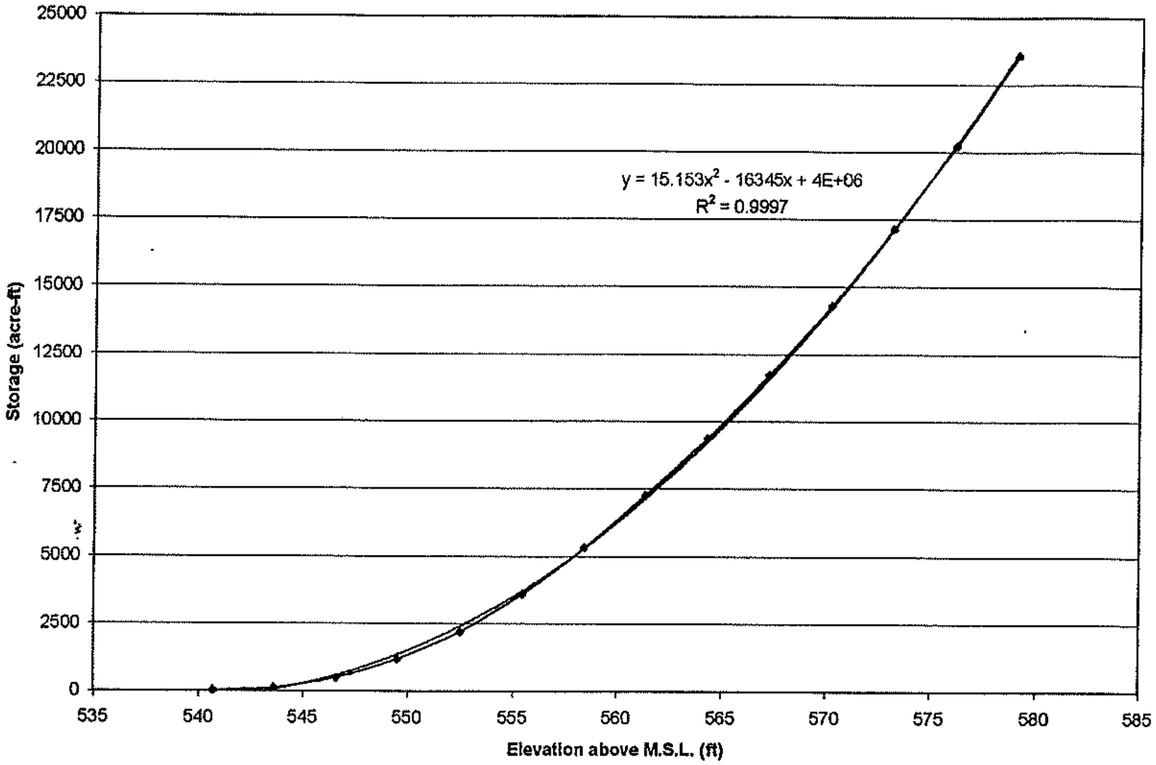
Stage-Storage Curve for Pool 12



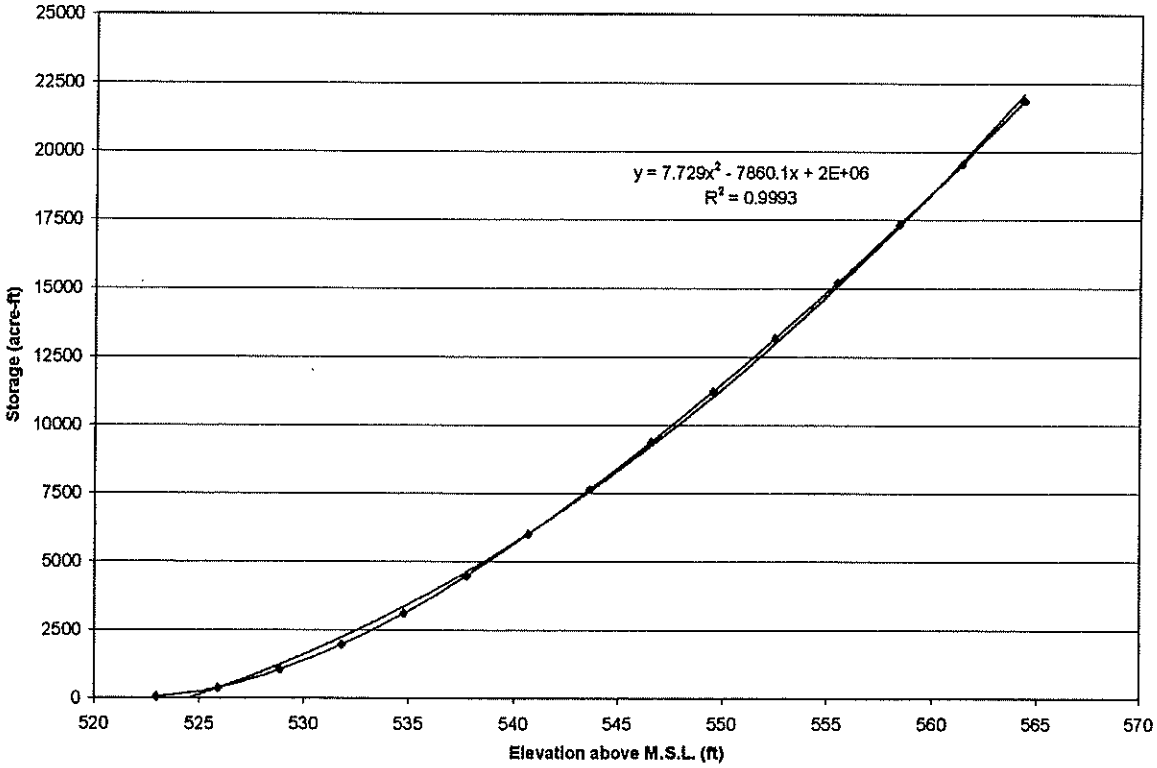
Stage-Storage Curve for Pool 11

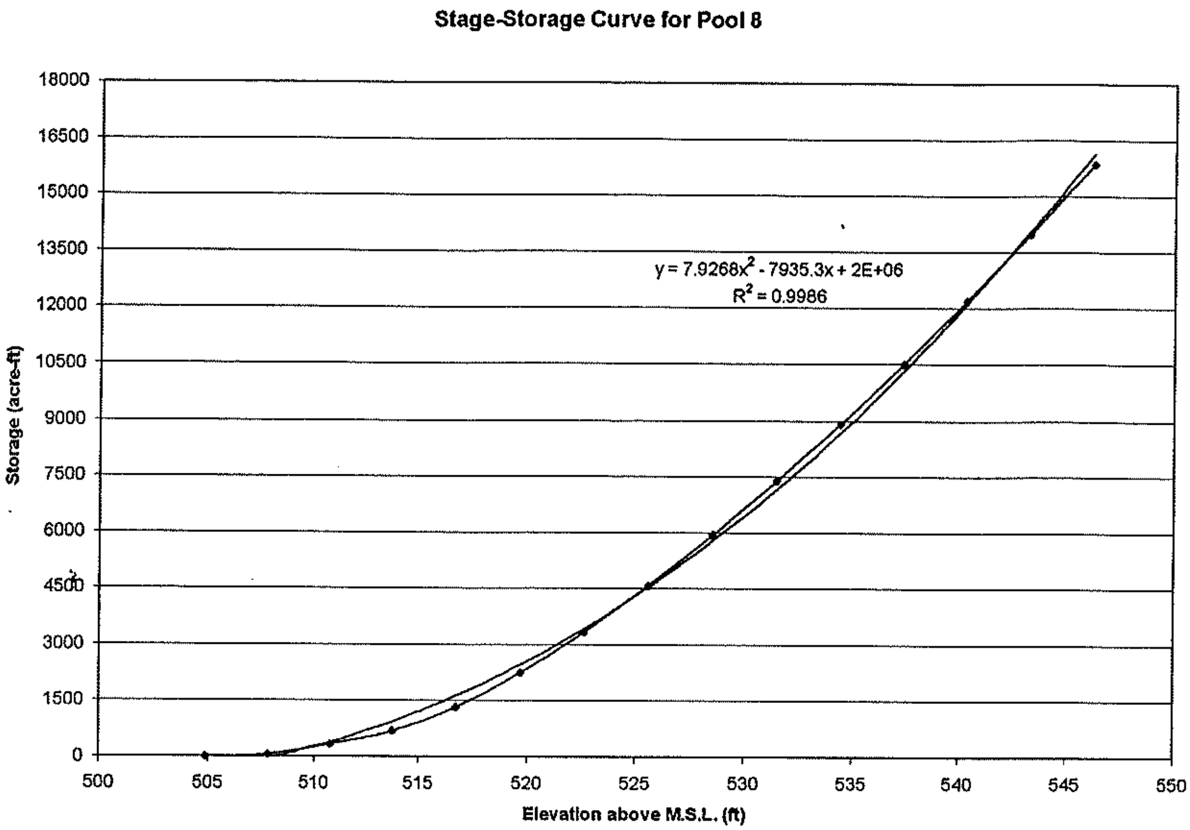


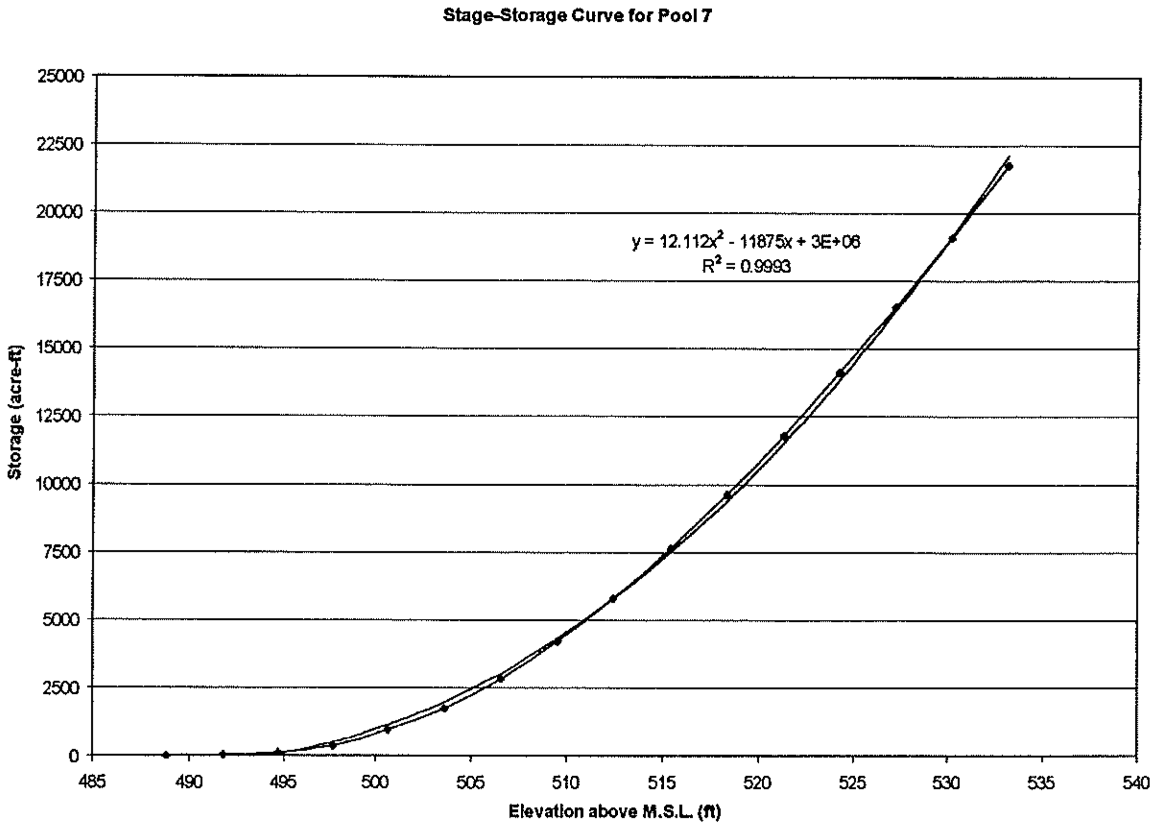
Stage-Storage Curve for Pool 10

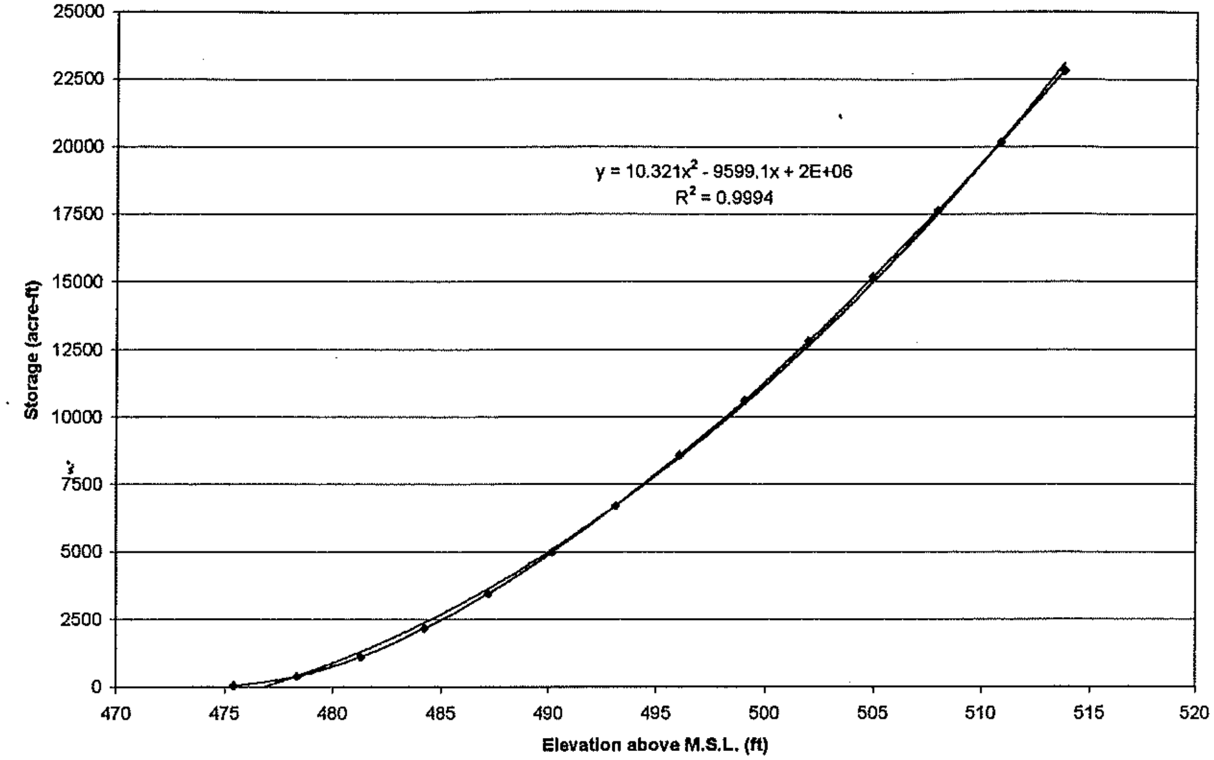


Stage-Storage Curve for Pool 9

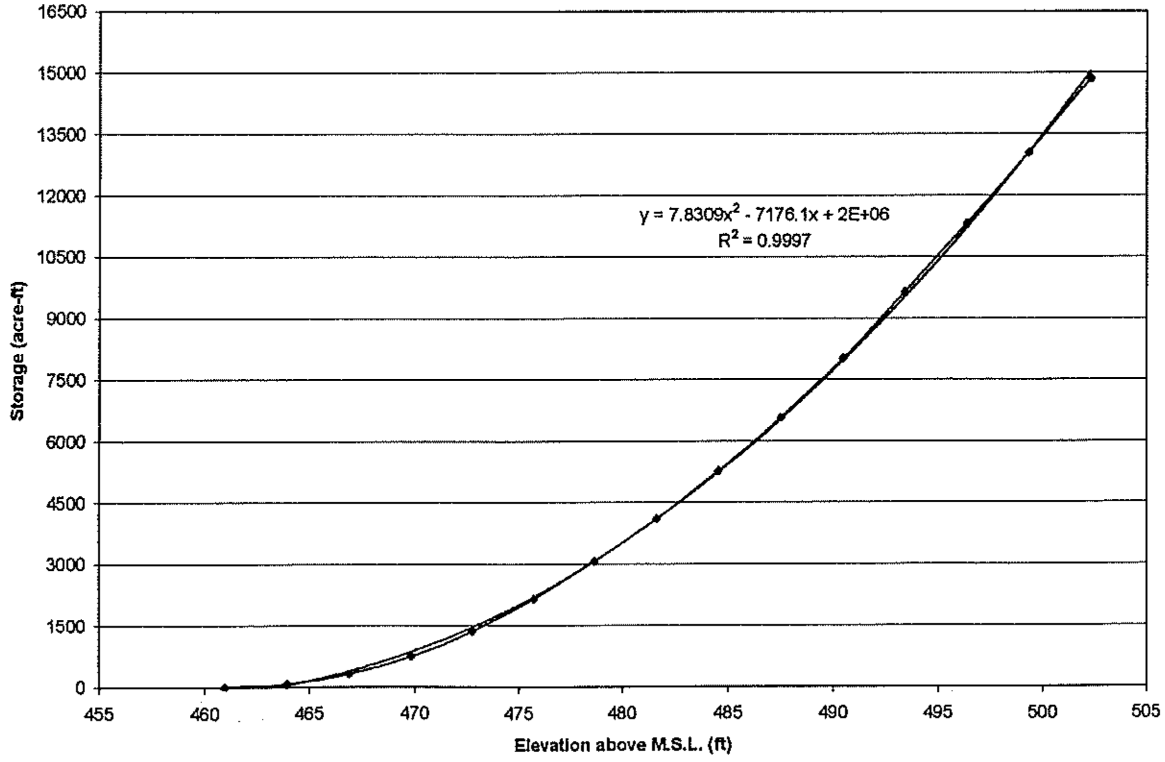



Stage-Storage Curve for Pool 8
y = 7.9268x² - 7935.3x + 2E+06
R² = 0.9986
Storage (acre-ft)
18000
16500
15000
13500
12000
10500
9000
7500
6000
4500
3000
1500
0
500
505
510
515
520
525
530
535
540
545
550
Elevation above M.S.L. (ft)


Stage-Storage Curve for Pool 7
y = 12.112x² - 11875x + 3E+06
R² = 0.9993
Storage (acre-ft)
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
485
490
495
500
505
510
515
520
525
530
535
540
Elevation above M.S.L. (ft)



Stage-Storage Curve for Pool 6

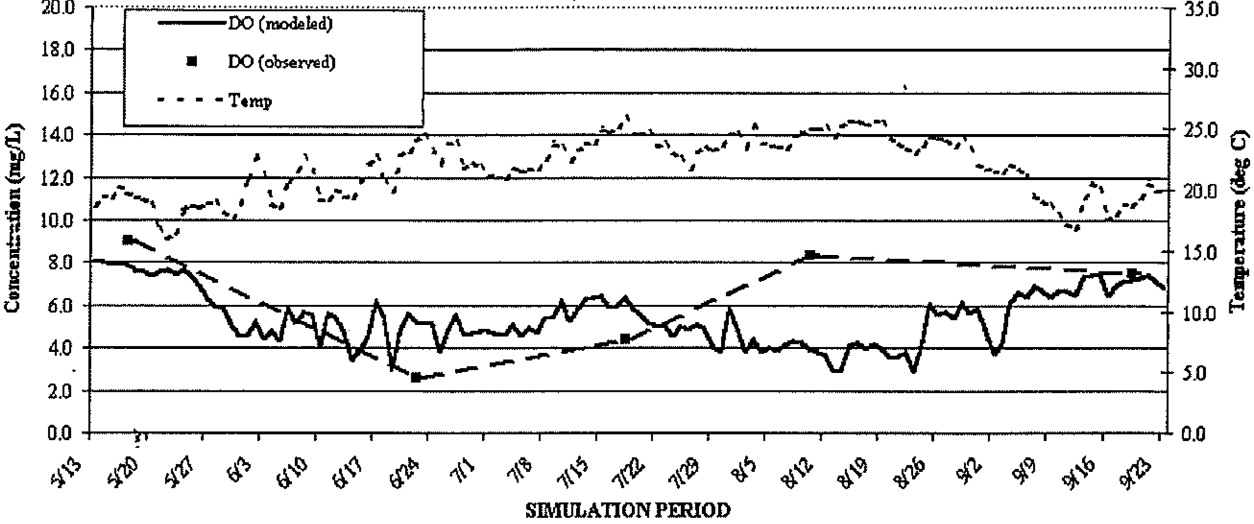


Stage-Storage Curve for Pool 5

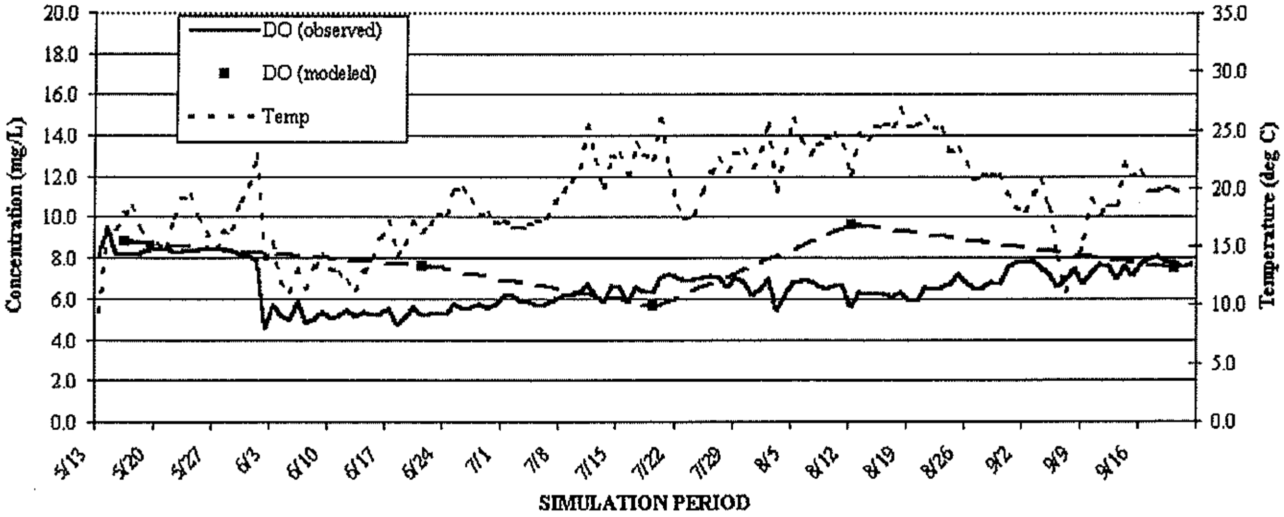
Appendix E

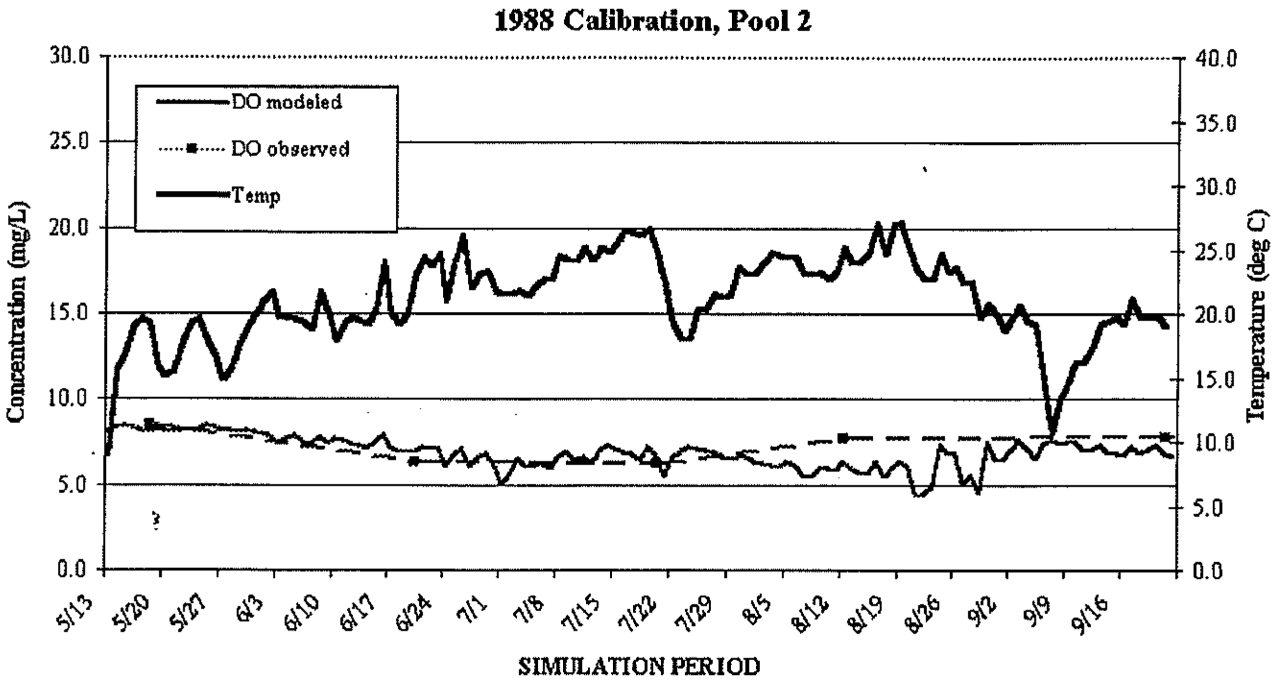
Predicted and Observed Temperature and Dissolved Oxygen Time Series for 1988

Pool 10, 1988 Calibration



Pool 4, 1988 Calibration

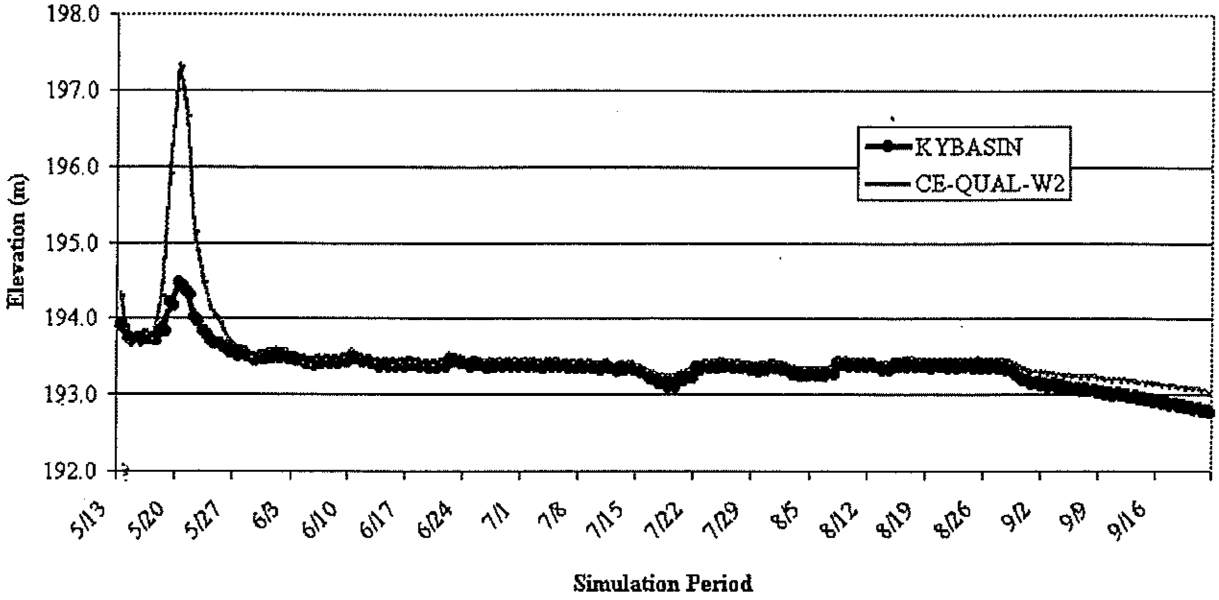



1988 Calibration, Pool 2

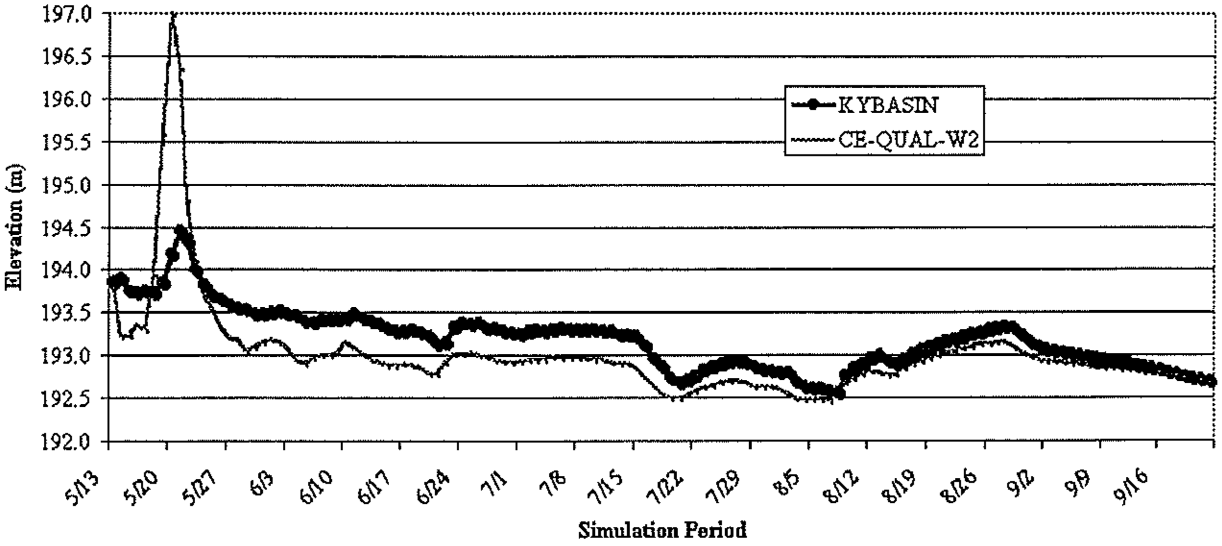
Appendix F

Predicted and Observed Water Surface Profiles for 1930/2020 Scenarios

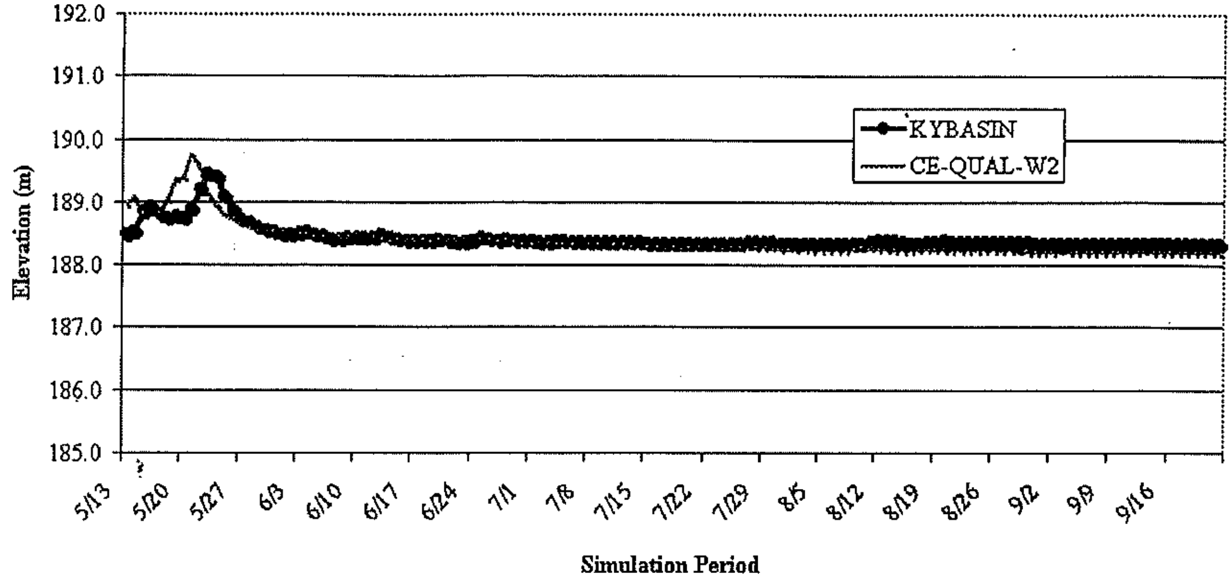
Water Surface Elevations, Pool 14, 1930 without Valves



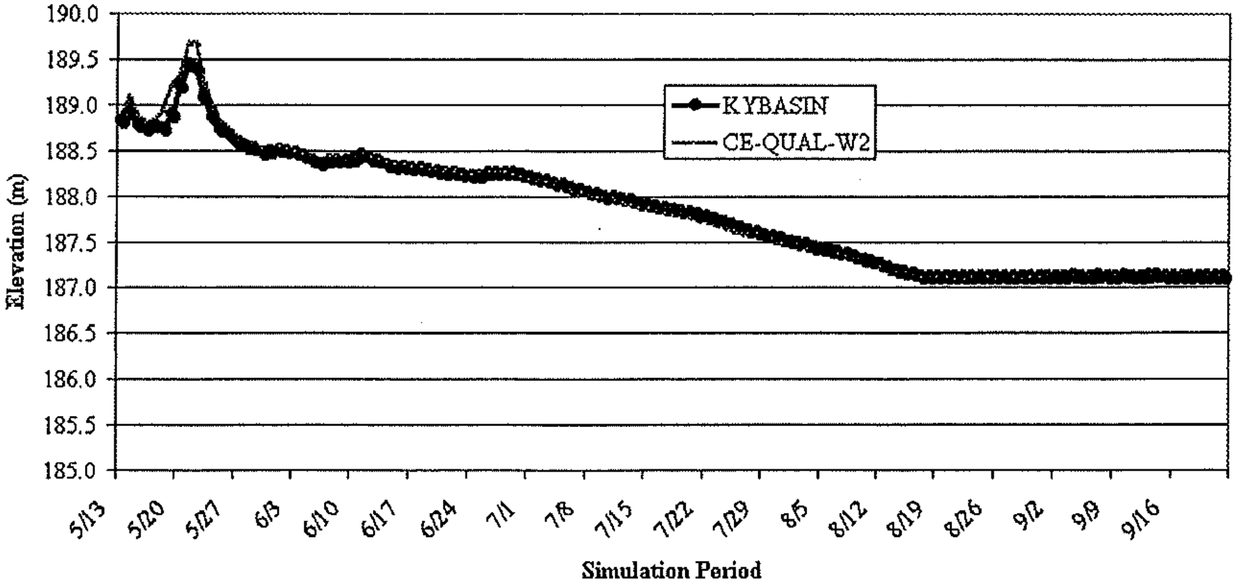
Water Surface Elevations, Pool 14, 1930 with Valves



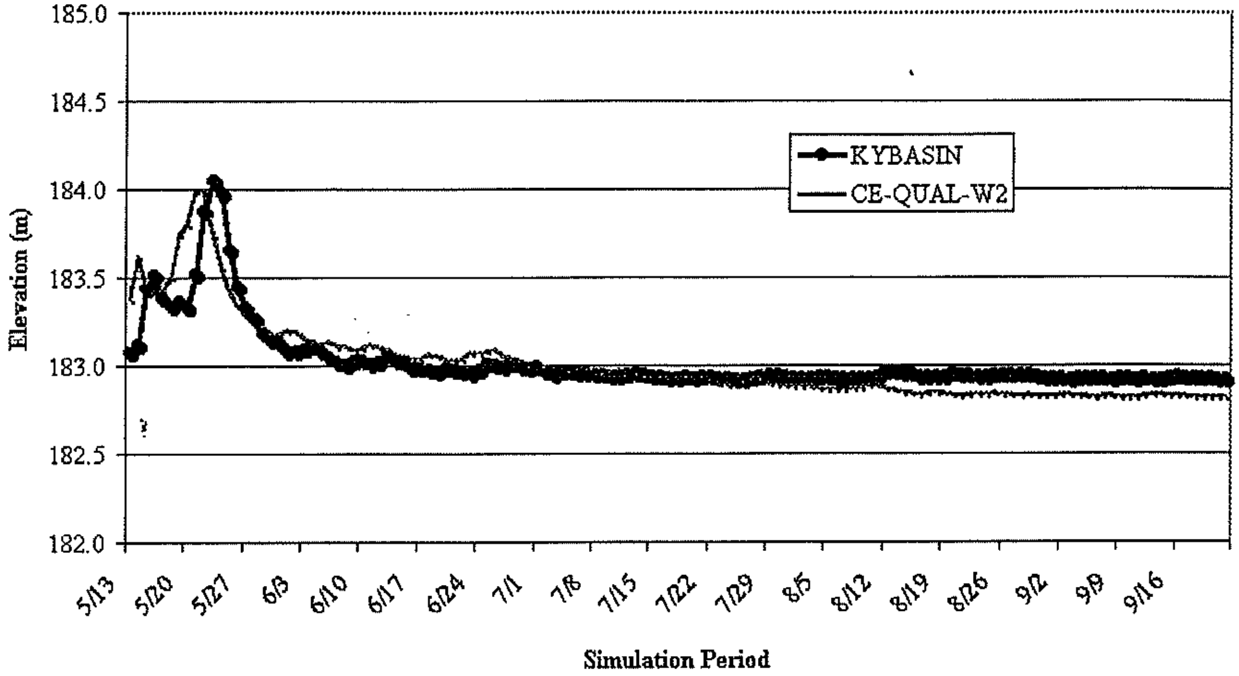
Water Surface Elevations, Pool 13, 1930 without Valves



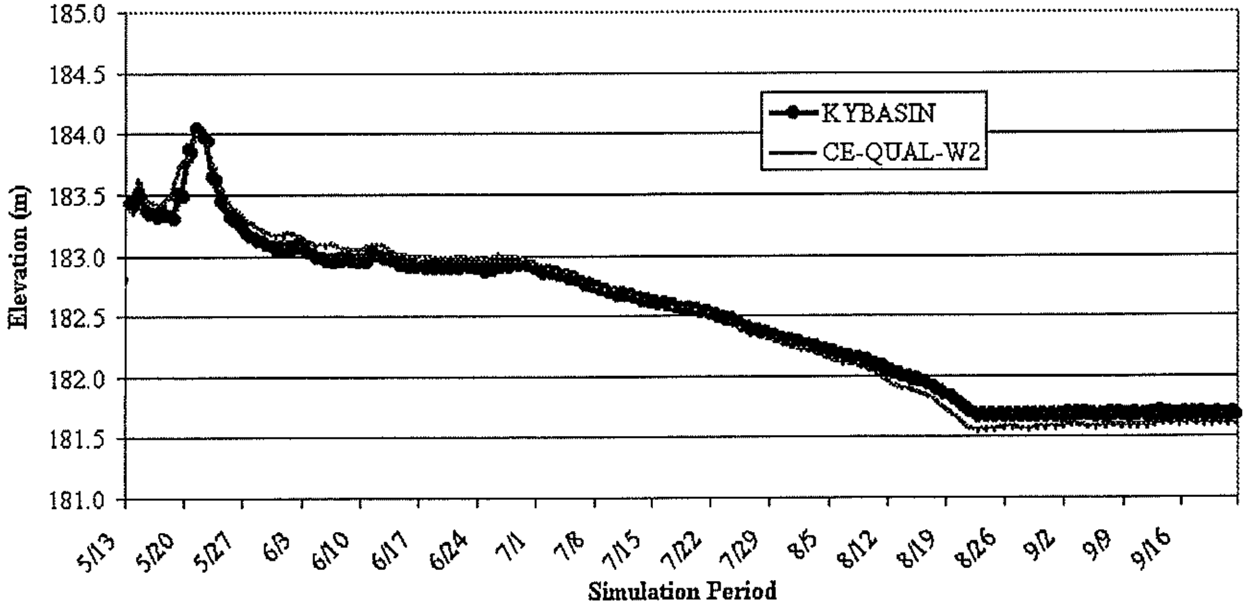
Water Surface Elevations, Pool 13, 1930 with Valves



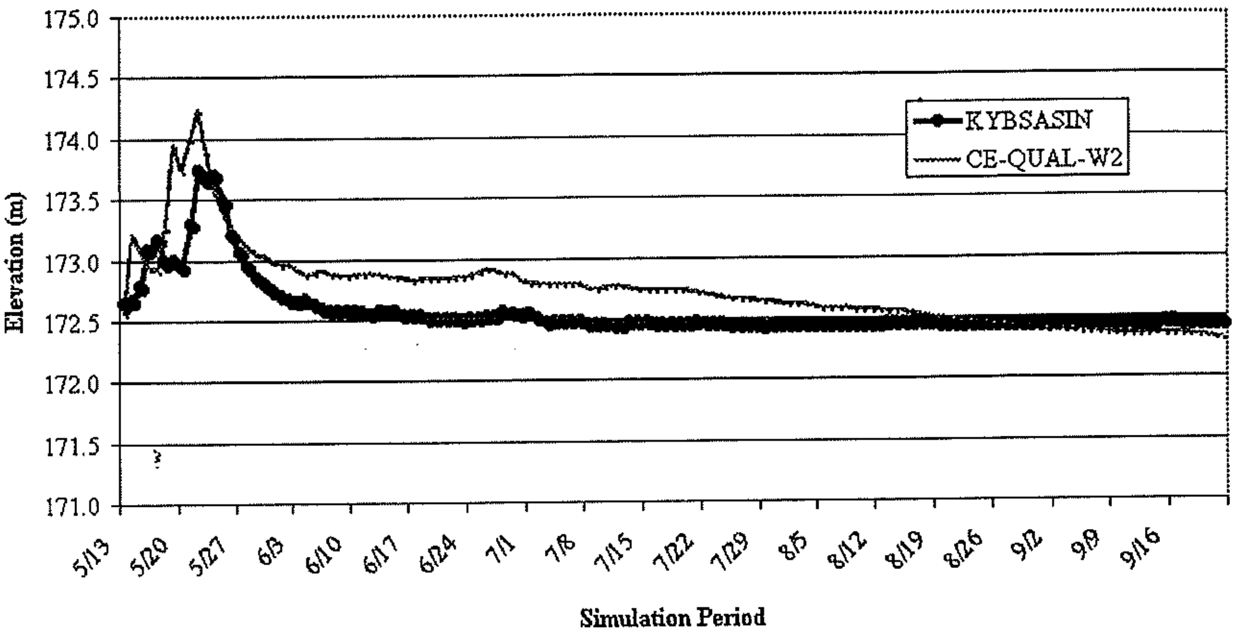
Water Surface Elevations, Pool 12, 1930 without Valves



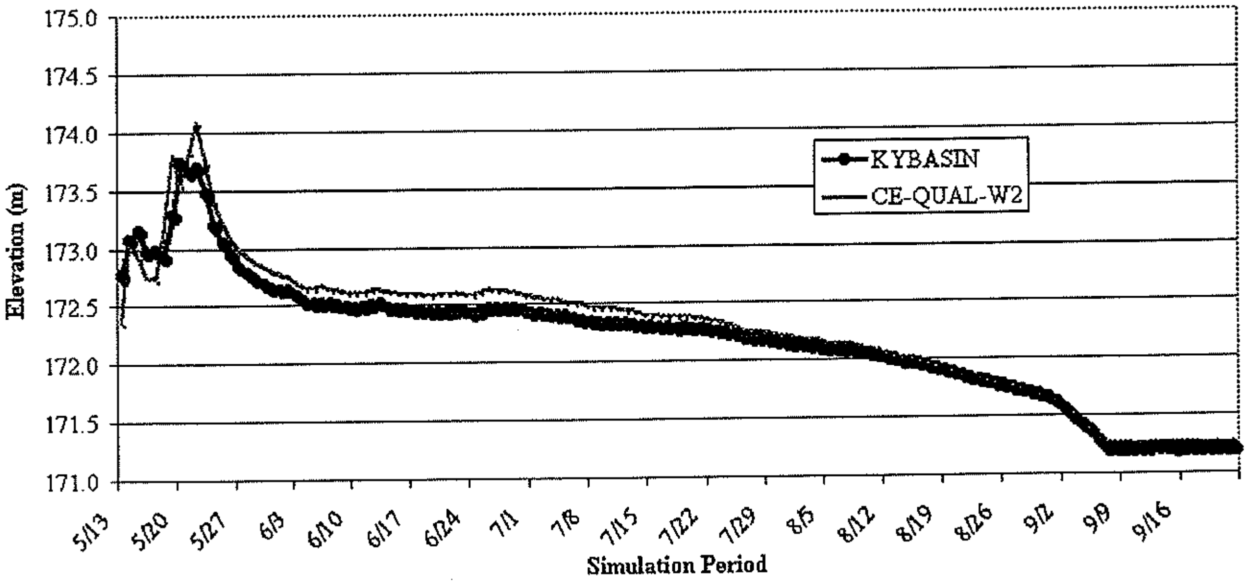
Water Surface Elevations, Pool 12, 1930 with Valves

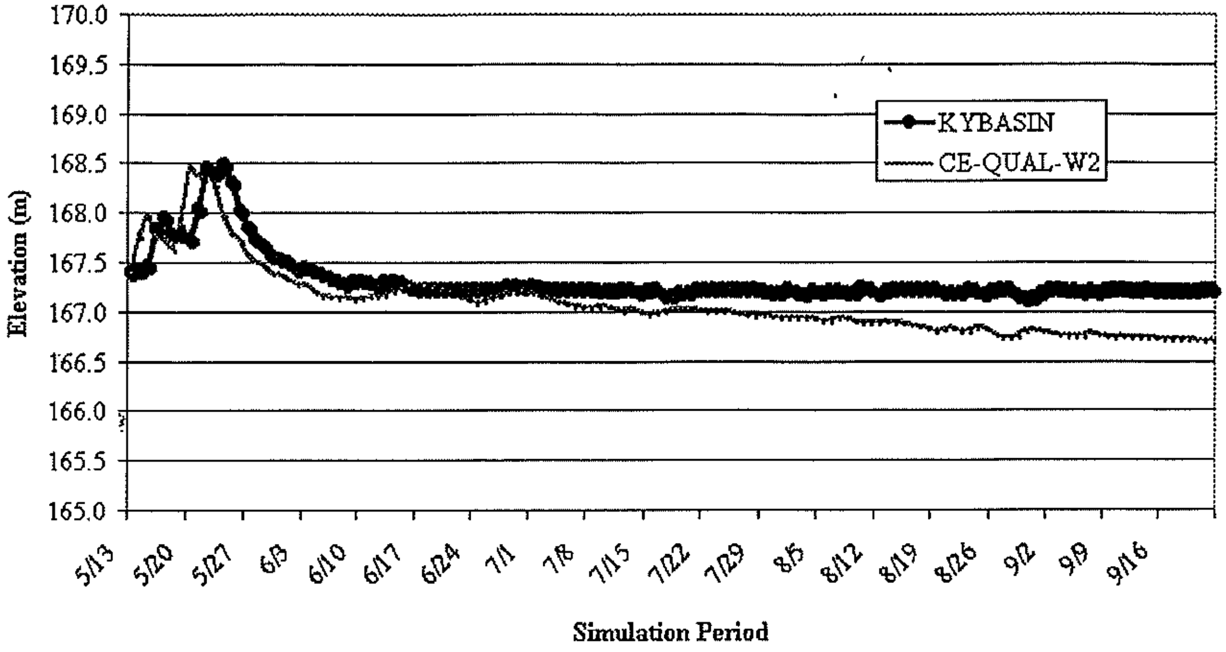


Water Surface Elevations, Pool 10, 1930 without Valves

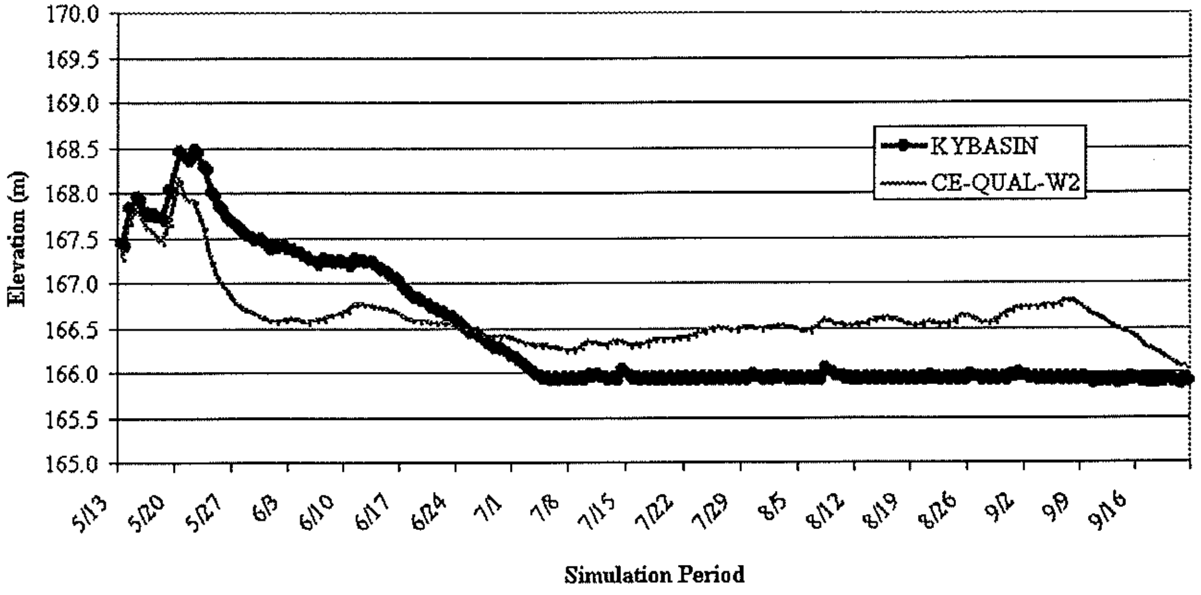


Water Surface Elevations, Pool 10, 1930 with Valves



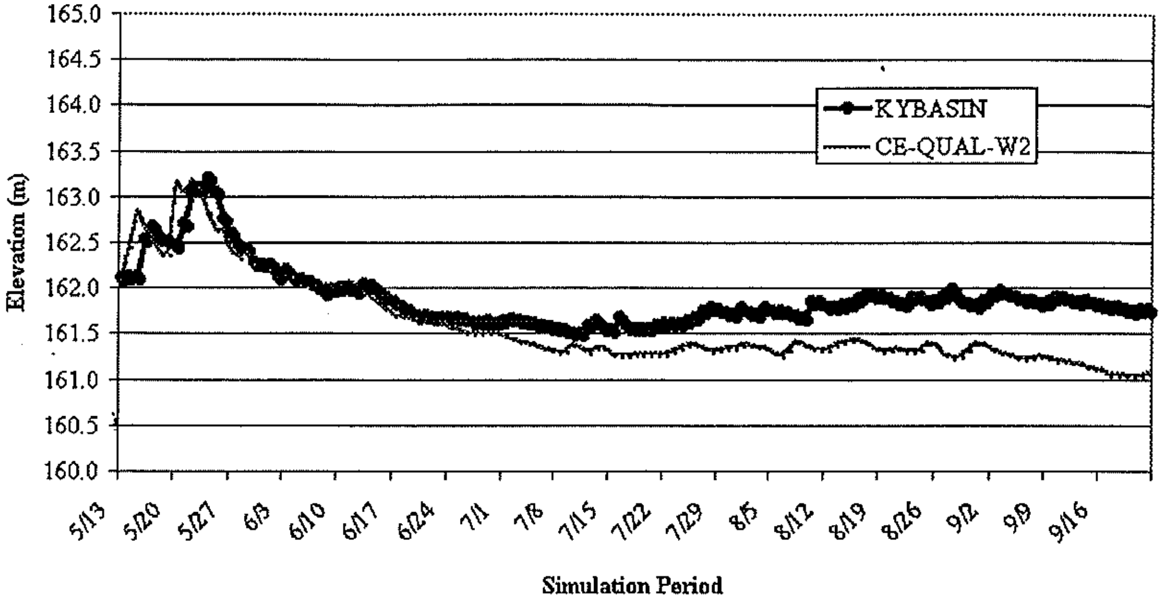


Water Surface Elevations, Pool 9, 1930 without Valves

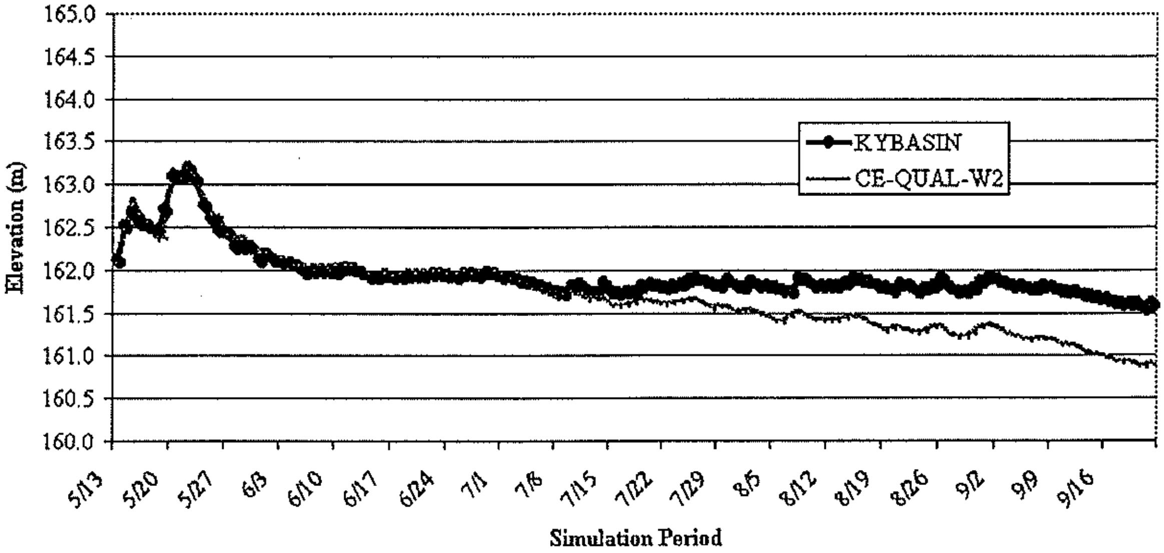


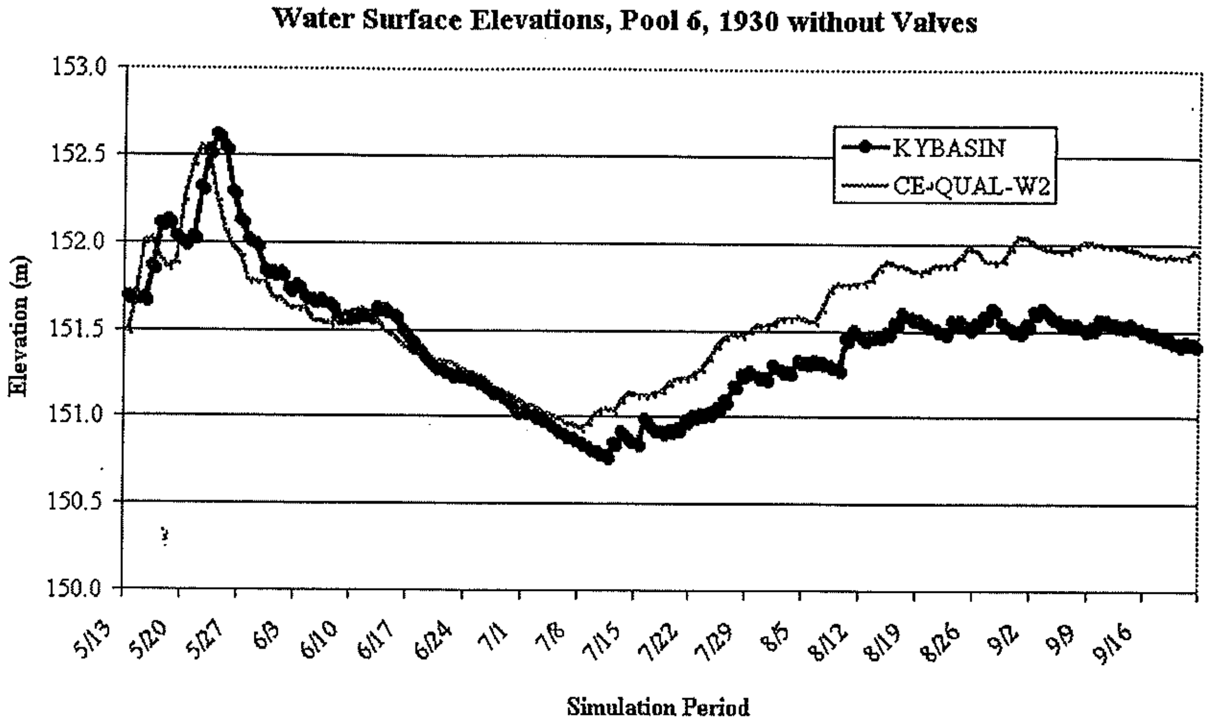
Water Surface Elevations, Pool 9, 1930 with Valves

Water Surface Elevations, Pool 8, 1930 without Valves

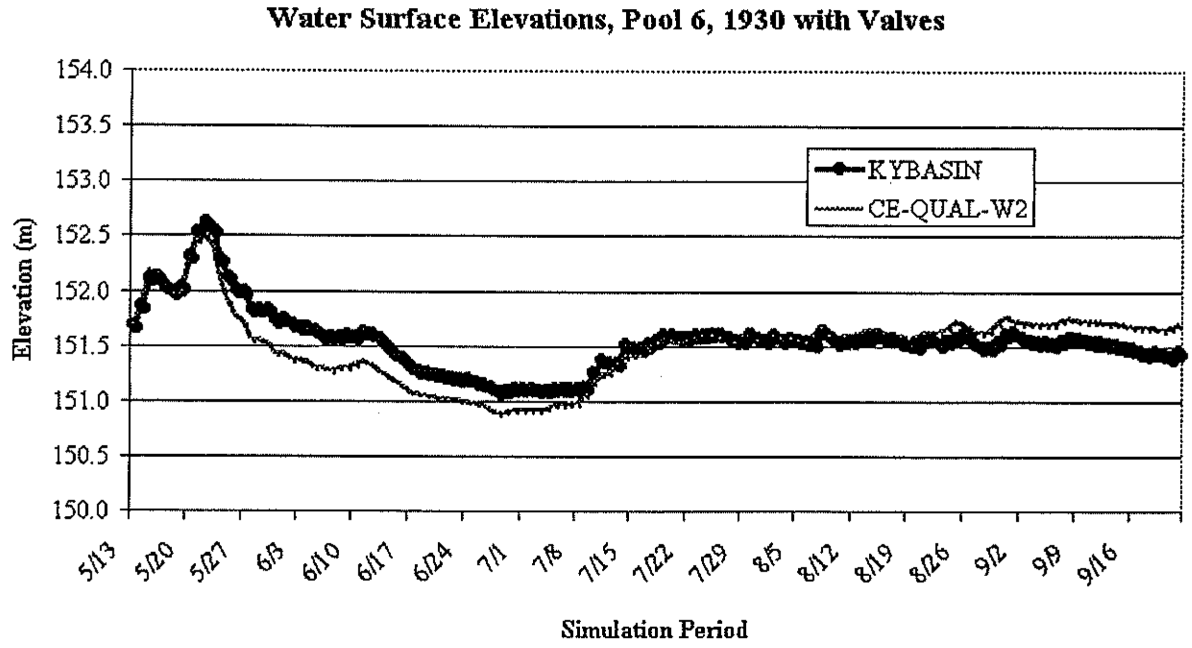


Water Surface Elevations, Pool 8, 1930 with Valves



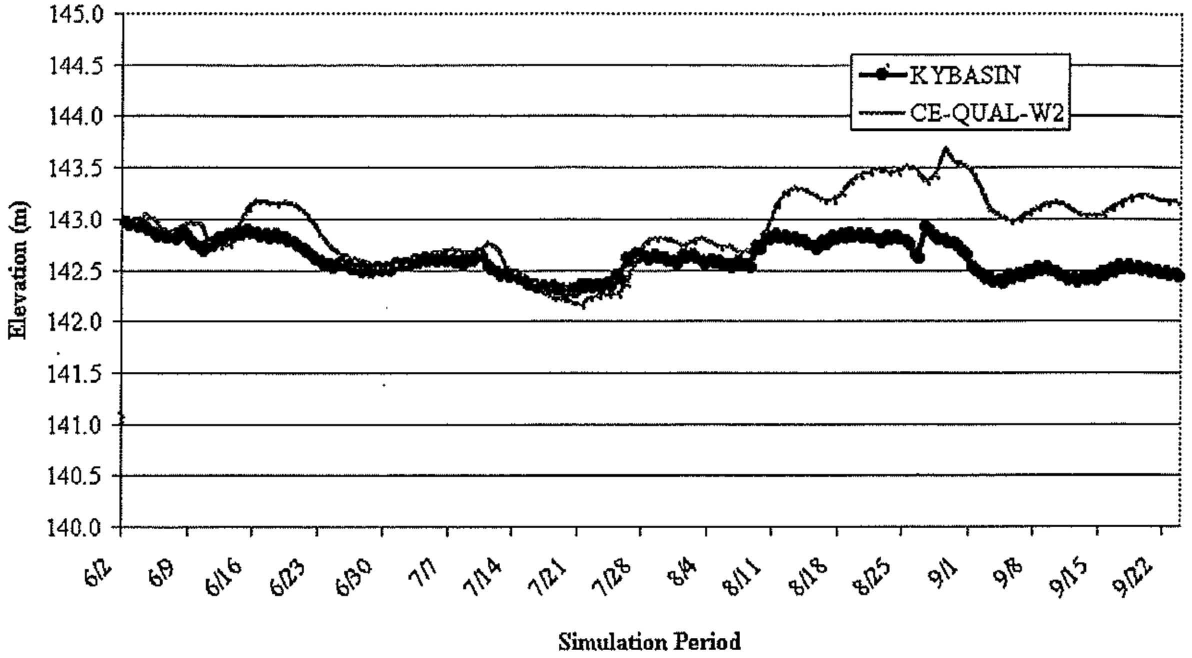


Water Surface Elevations, Pool 6, 1930 without Valves

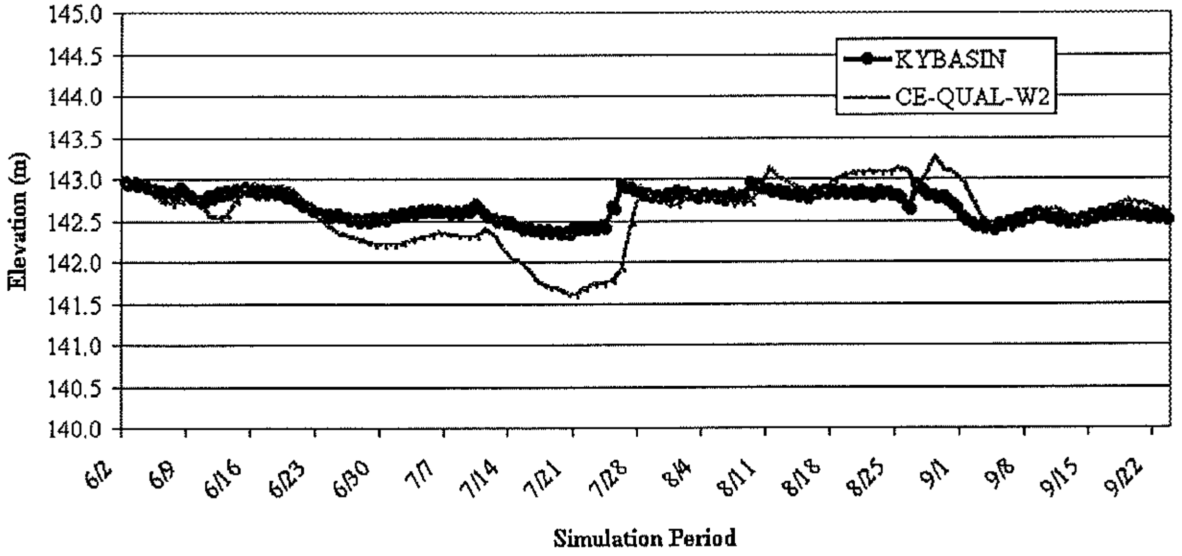


Water Surface Elevations, Pool 6, 1930 with Valves

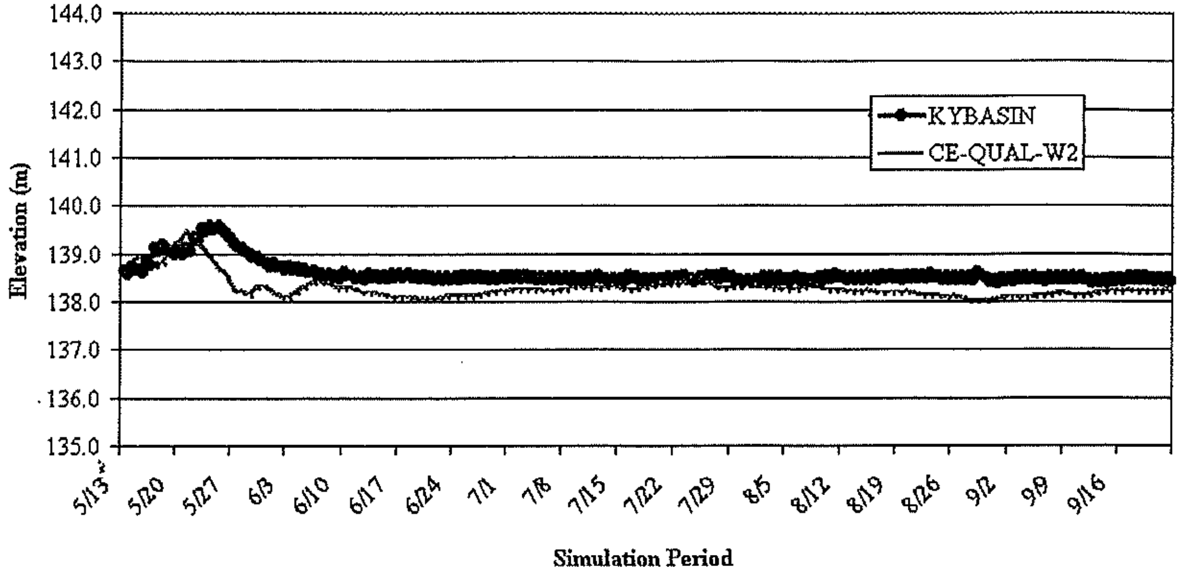
Water Surface Elevations, Pool 4, 1930 without Valves



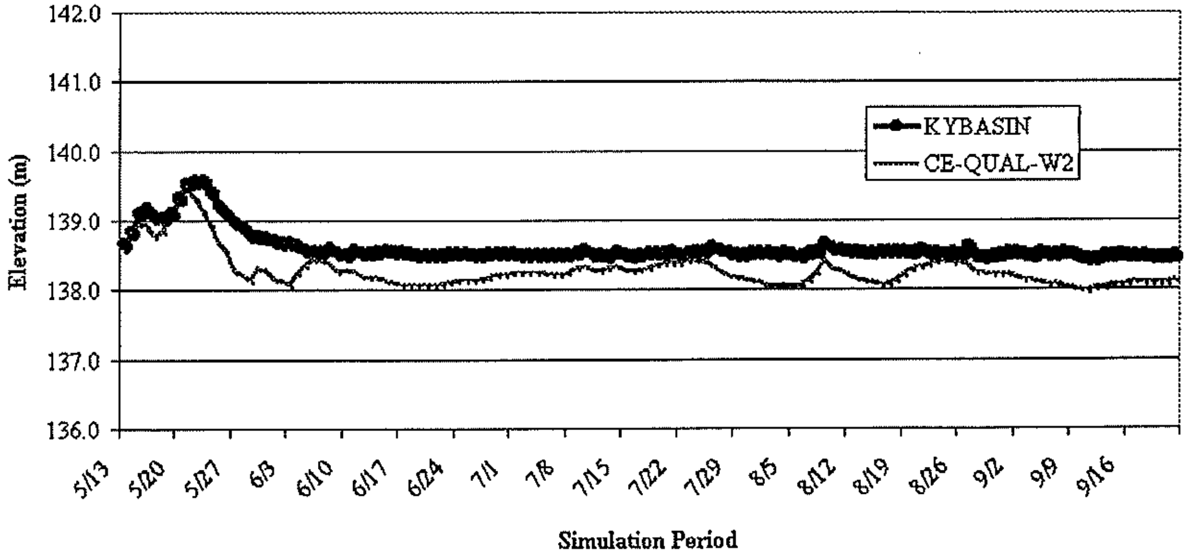
Water Surface Elevations, Pool 4, 1930 with Valves

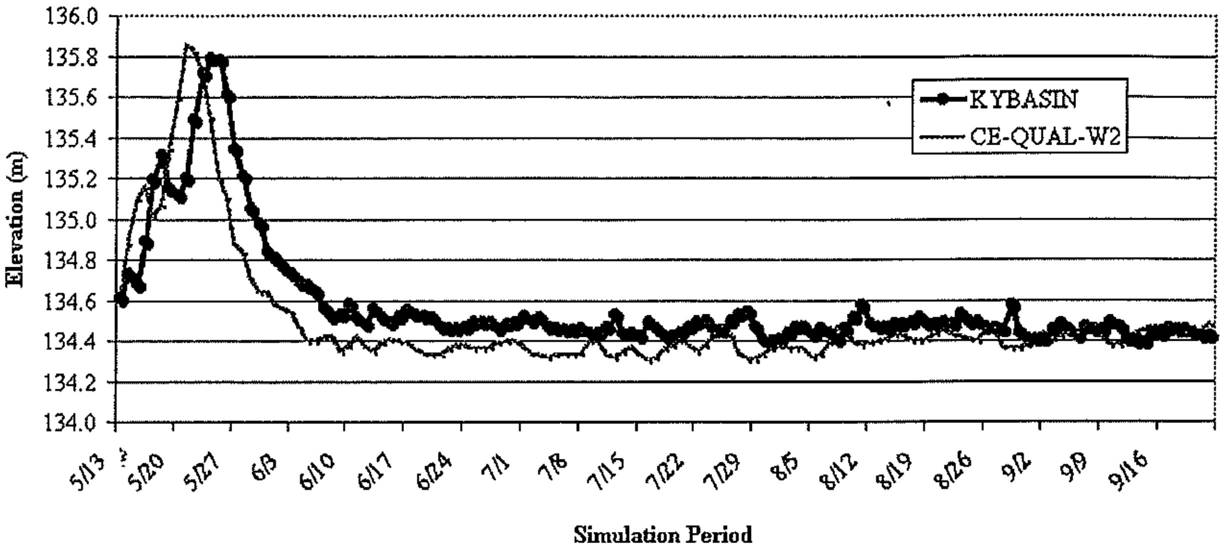


Water Surface Elevations, Pool 3, 1930 without Valves

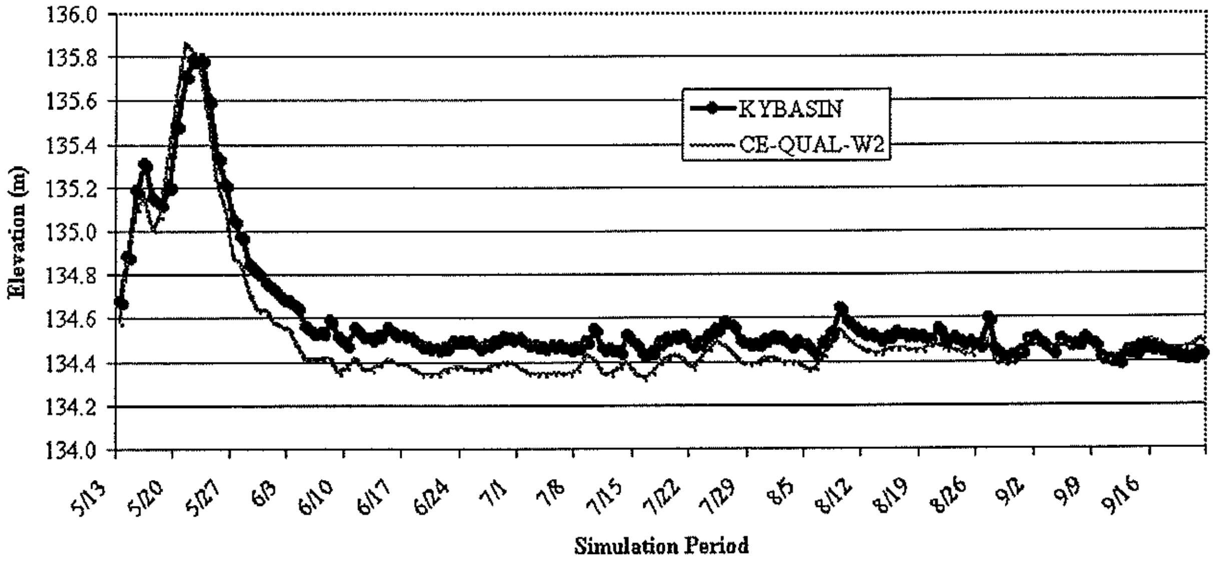


Water Surface Elevations, Pool 3, 1930 with Valves





Water Surface Elevations, Pool 2, 1930 without Valves

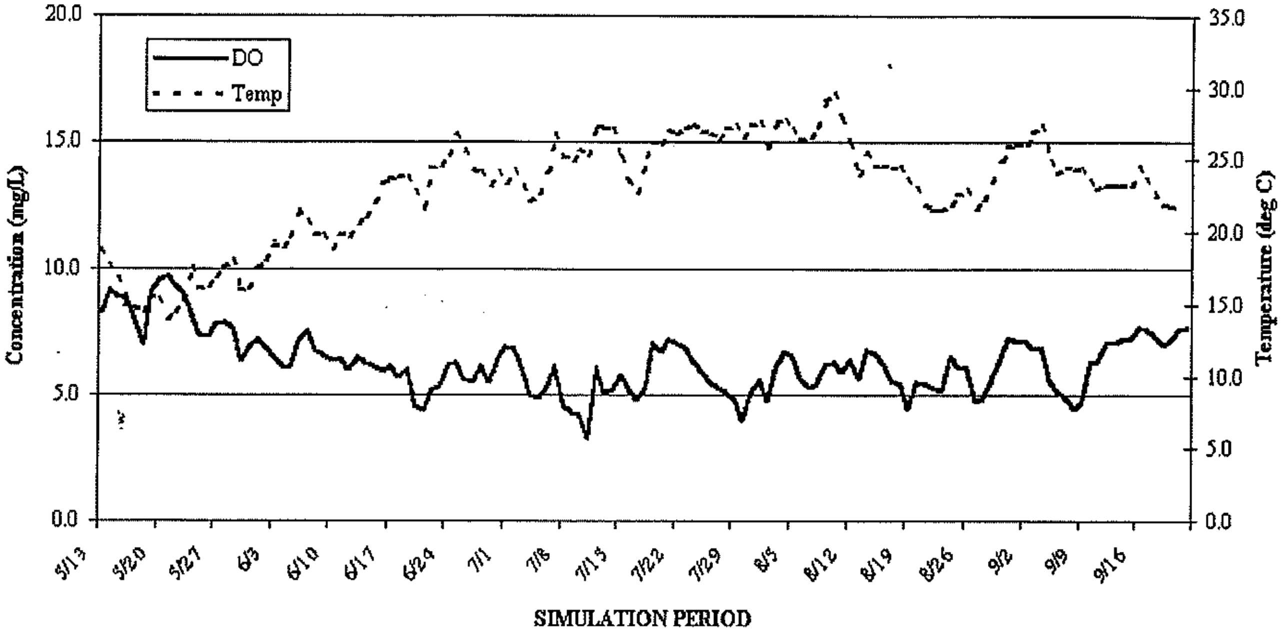


Water Surface Elevations, Pool 2, 1930 with Valves

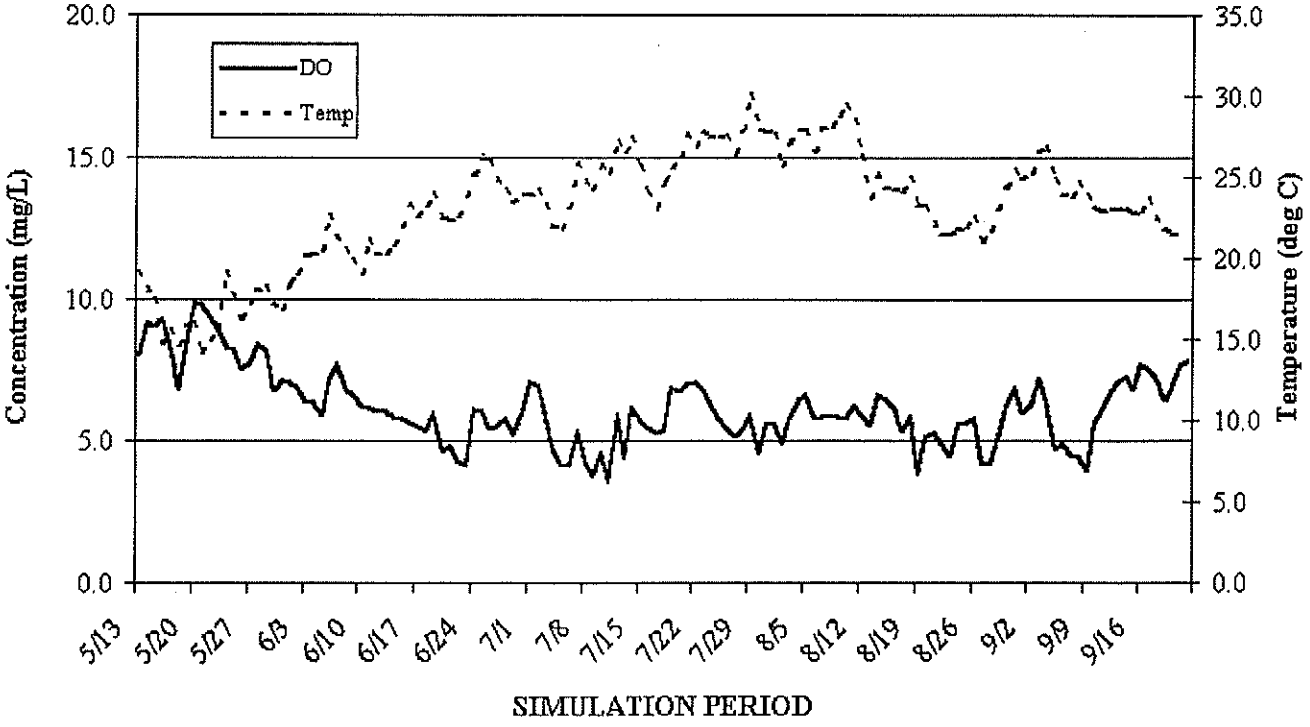
Appendix G

Dissolved Oxygen and Temperature Time Series Plots for 1930/2020 Scenarios

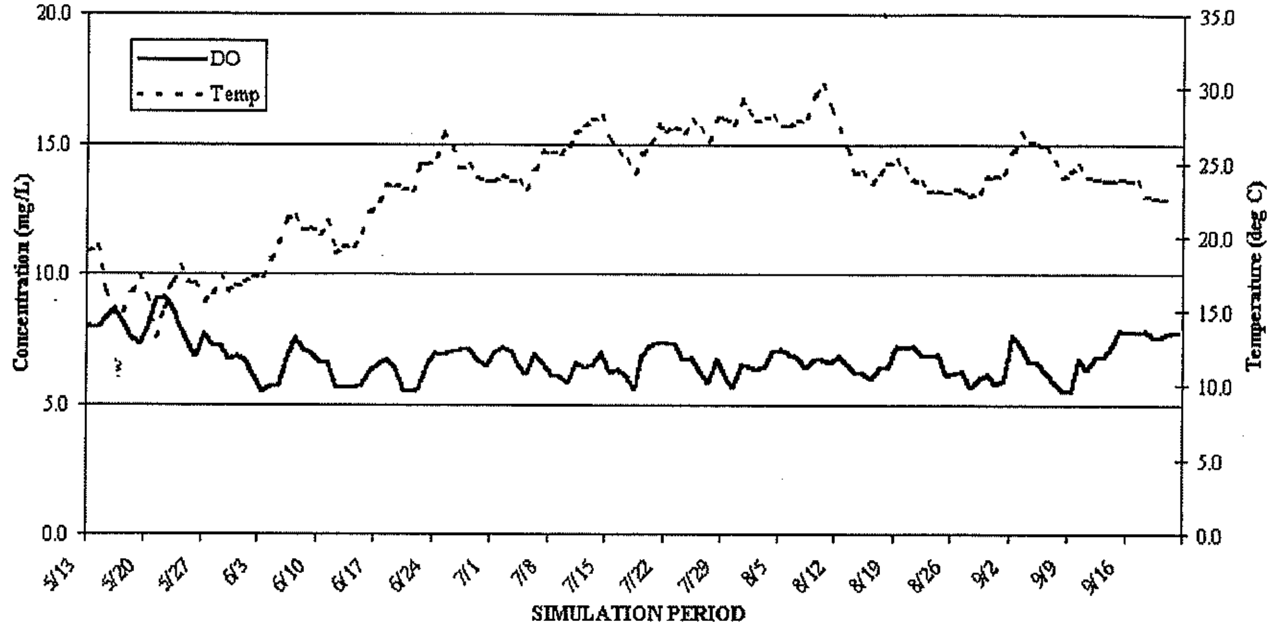
Pool 14, 1930 without Valves, 2020H



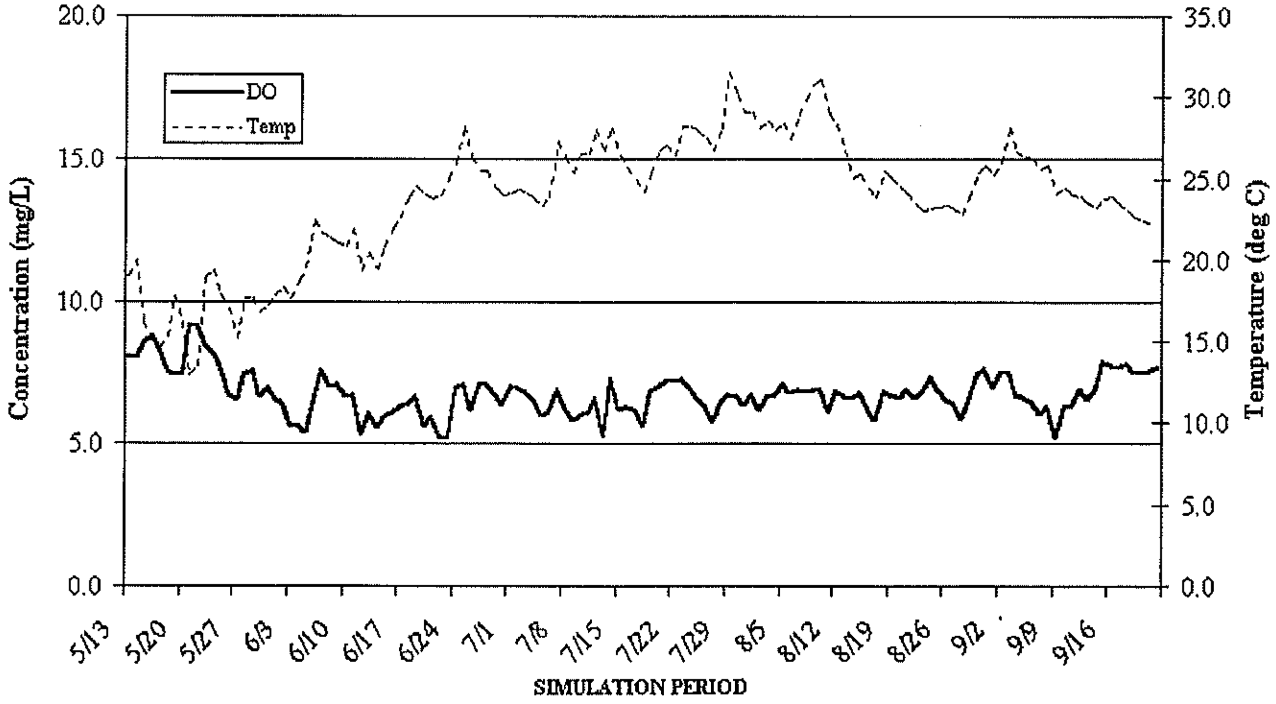
Pool 14, 1930 with Valves, 2020H

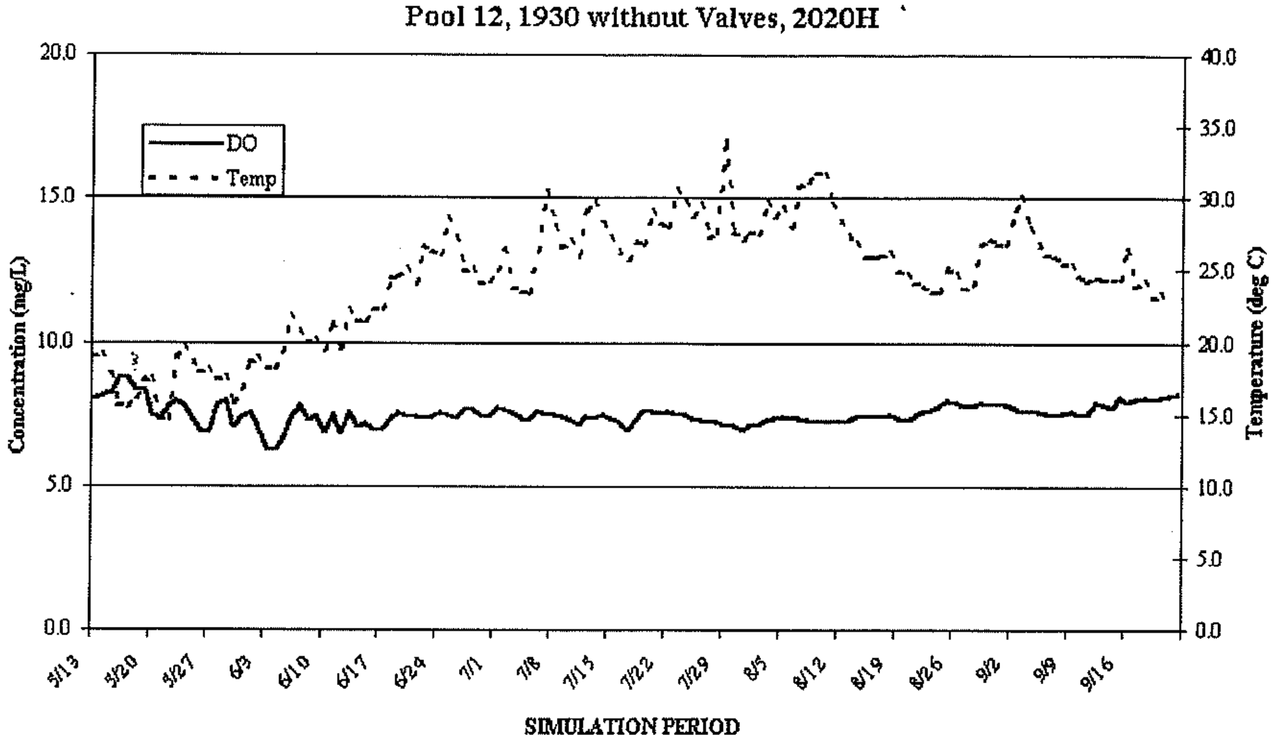


Pool 13, 1930 without Valves, 2020H

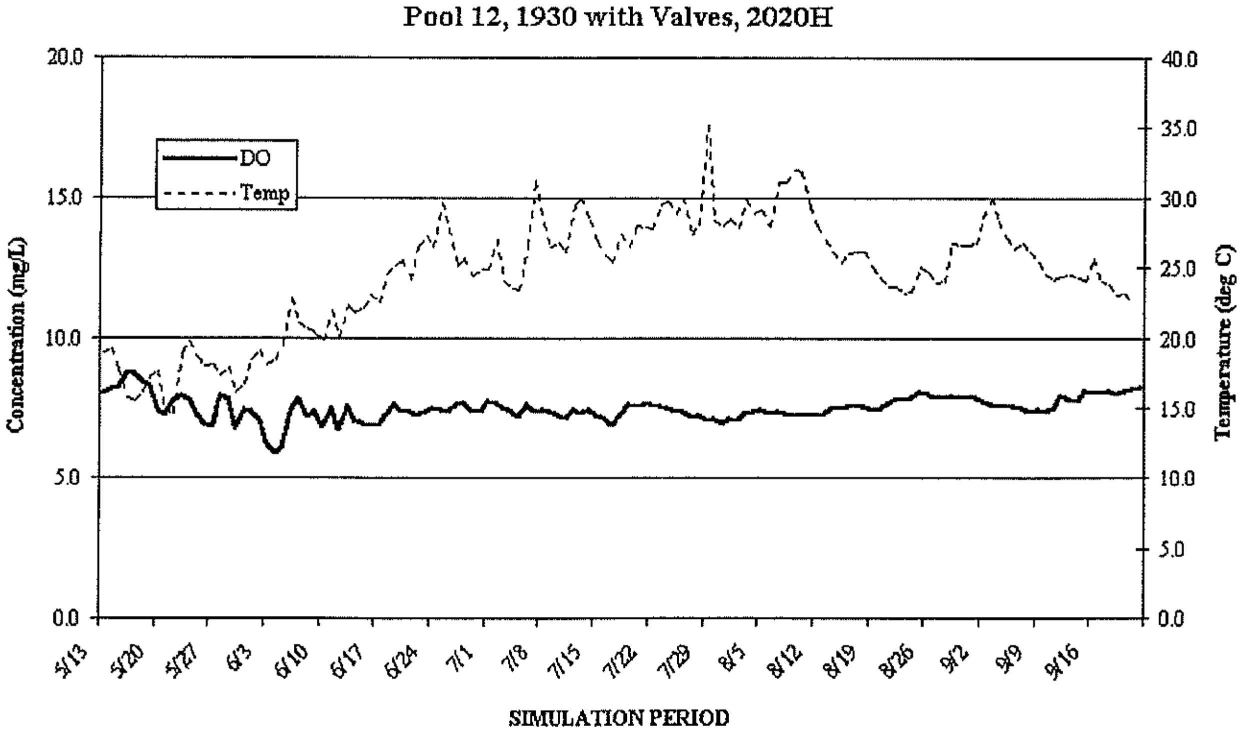


Pool 13, 1930 with Valves, 2020H



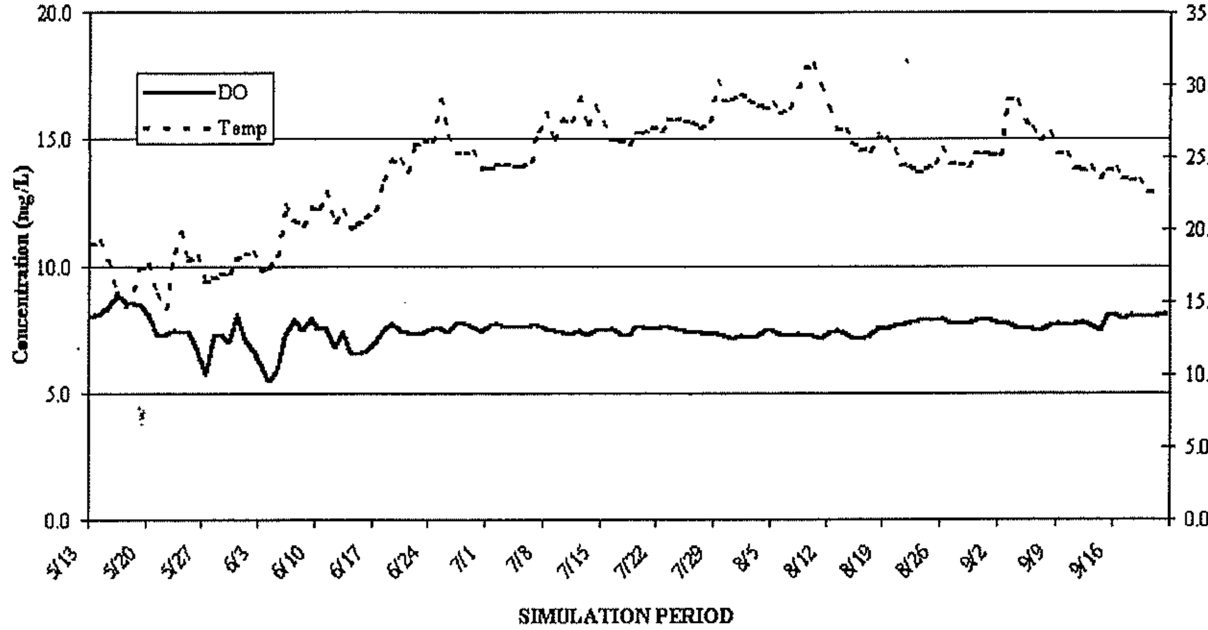


Pool 12, 1930 without Valves, 2020H

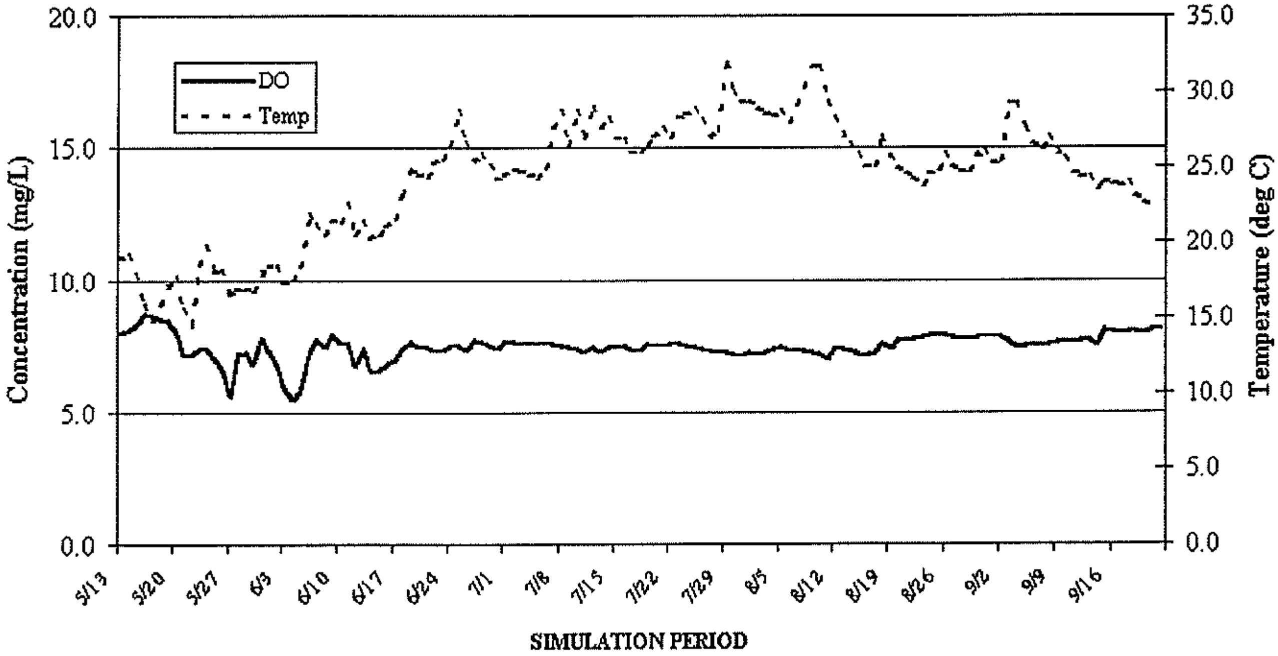


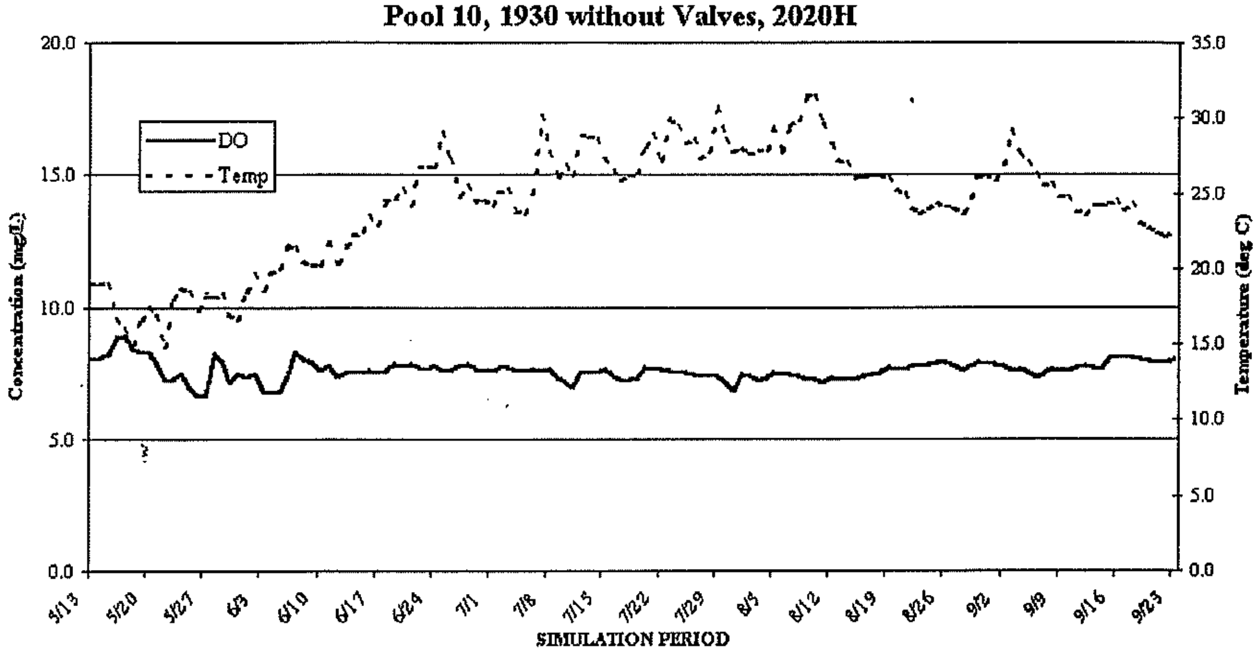
Pool 12, 1930 with Valves, 2020H

Pool 11, 1930 without Valves, 2020H

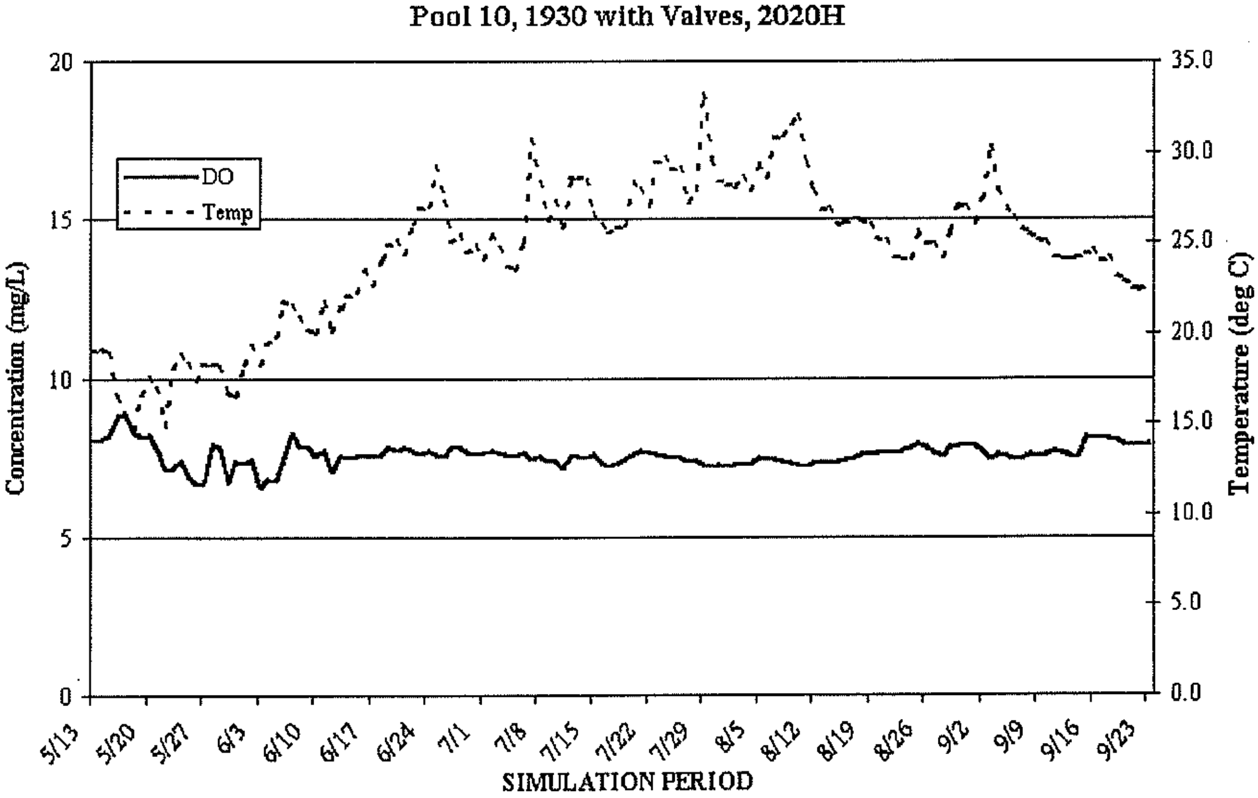


Pool 11, 1930 with Valves, 2020H

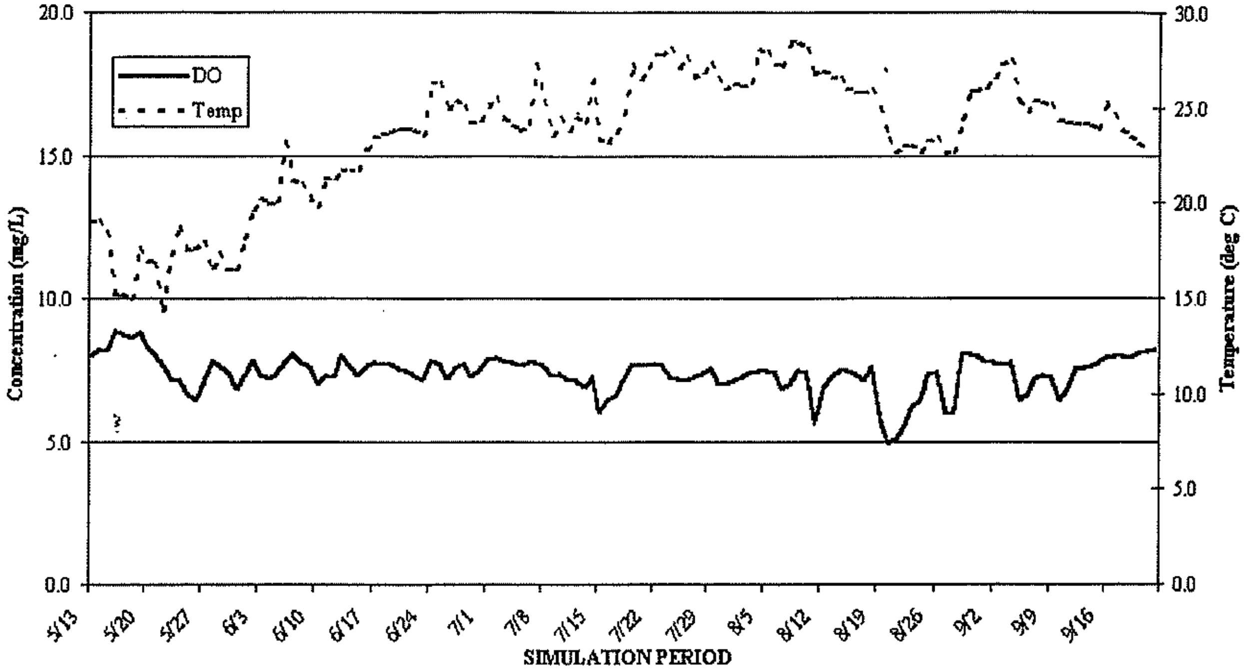


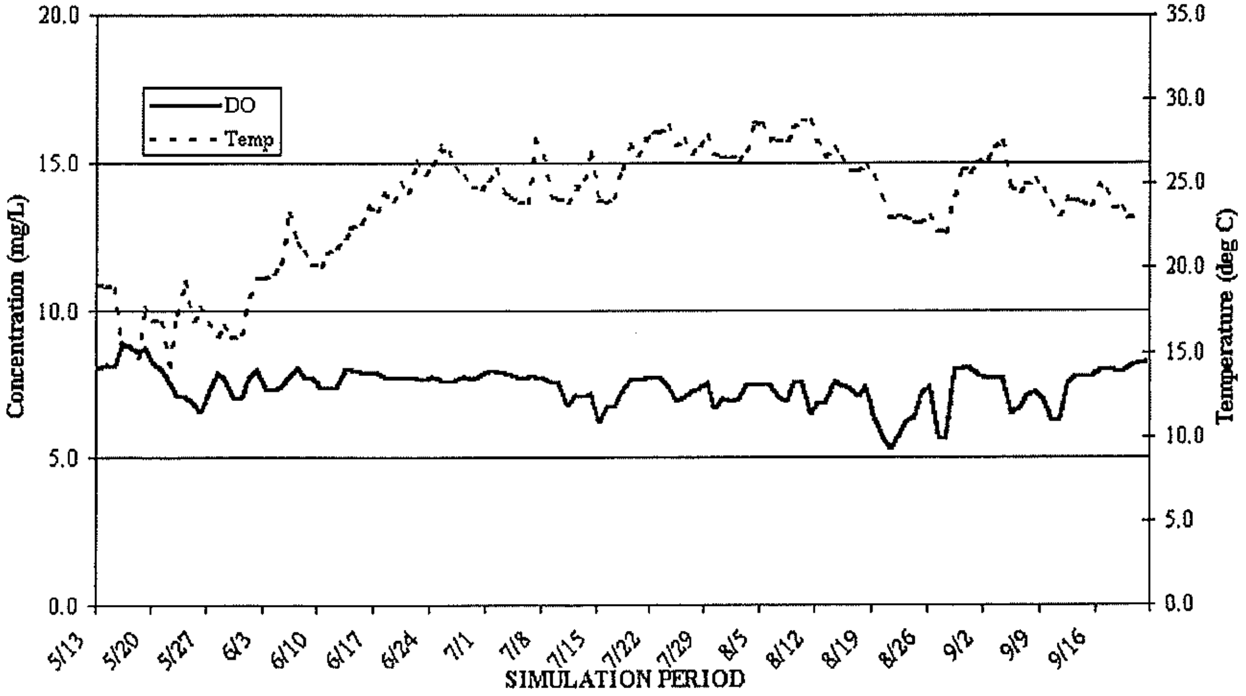


Pool 10, 1930 without Valves, 2020H

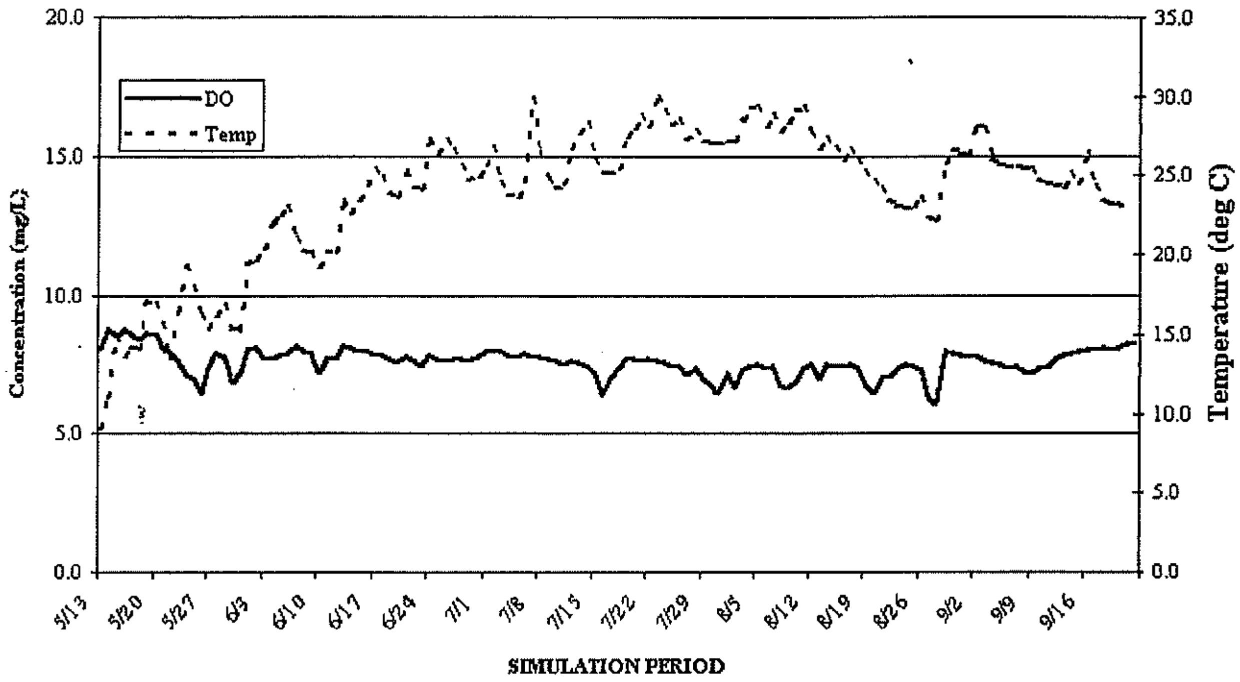


Pool 10, 1930 with Valves, 2020H

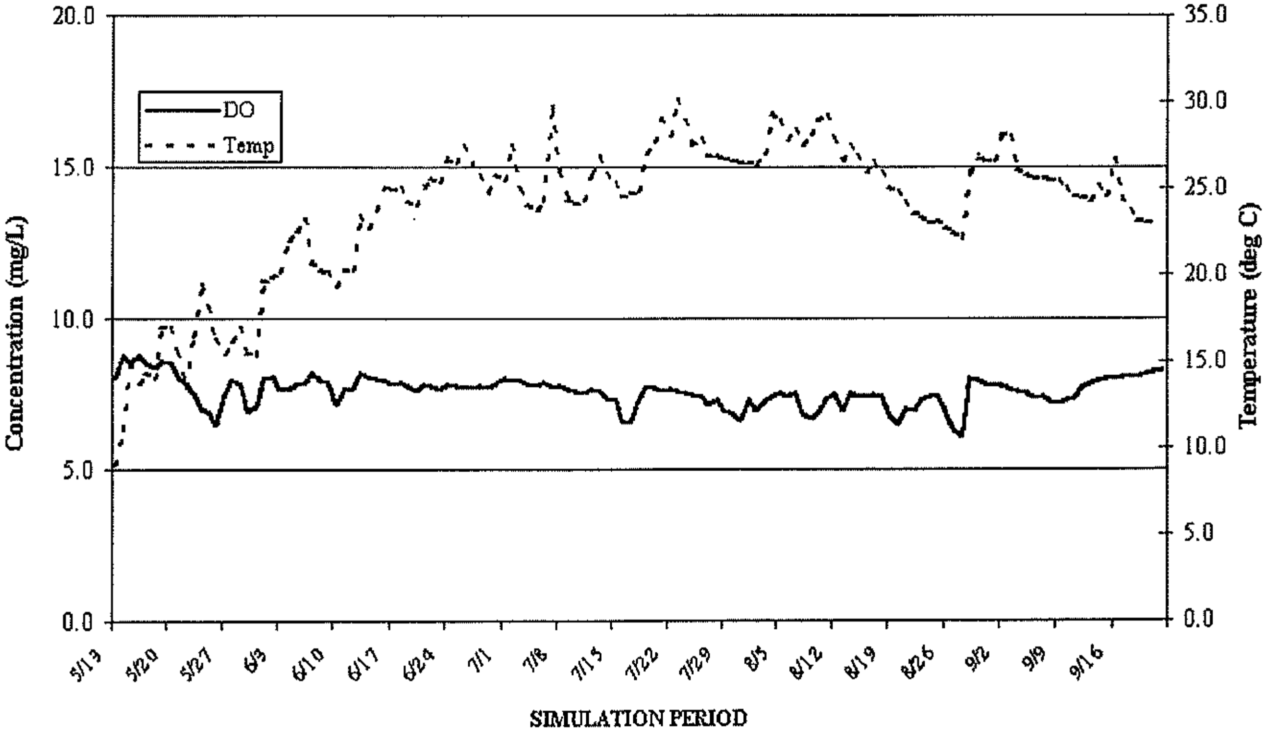

Pool 9, 1930 without Valves, 2020H

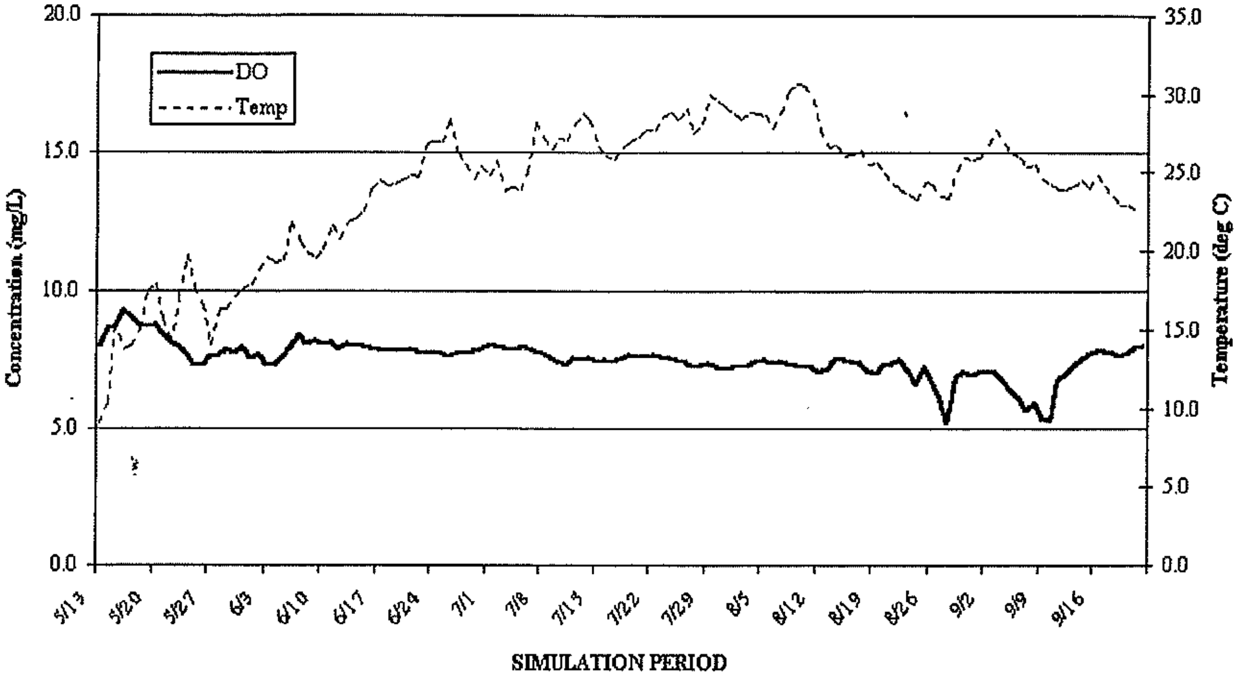

Pool 9, 1930 with Valves, 2020H

Pool 8, 1930 without Valves, 2020H

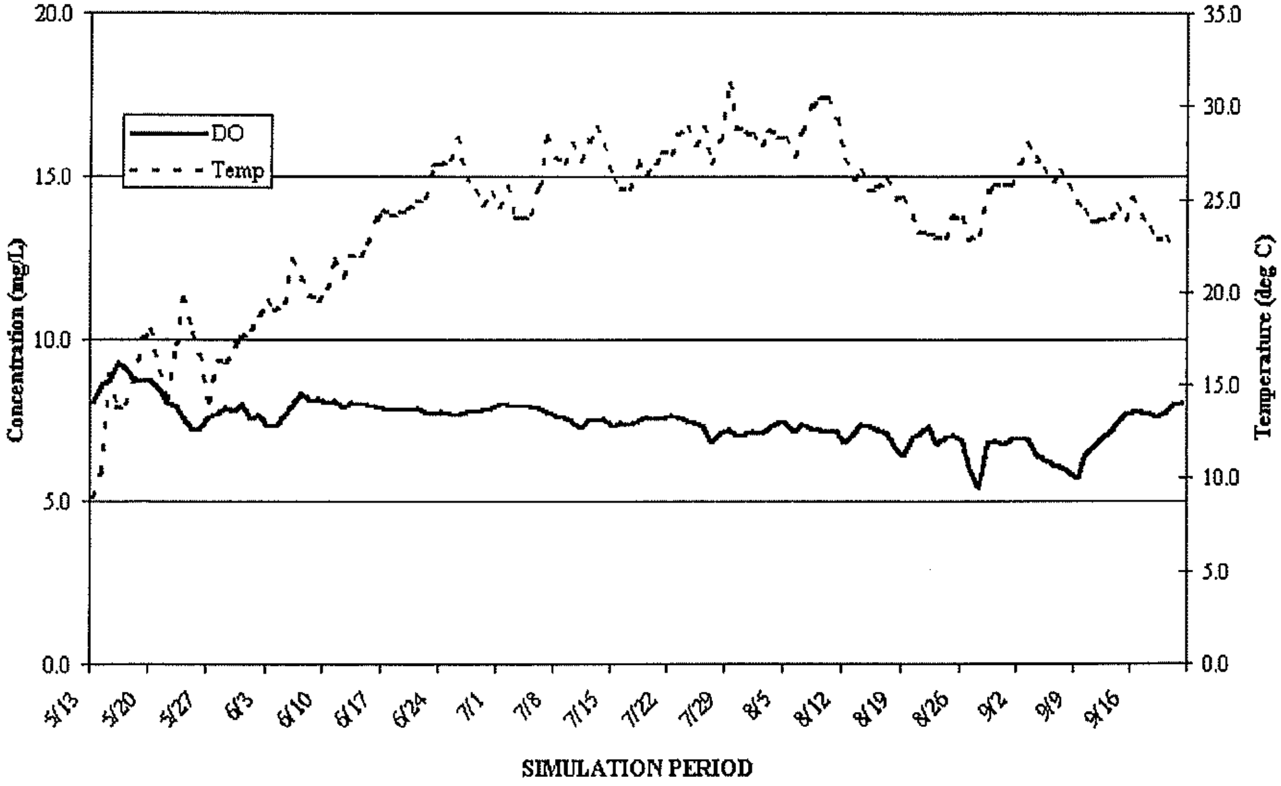


Pool 8, 1930 with Valves, 2020H

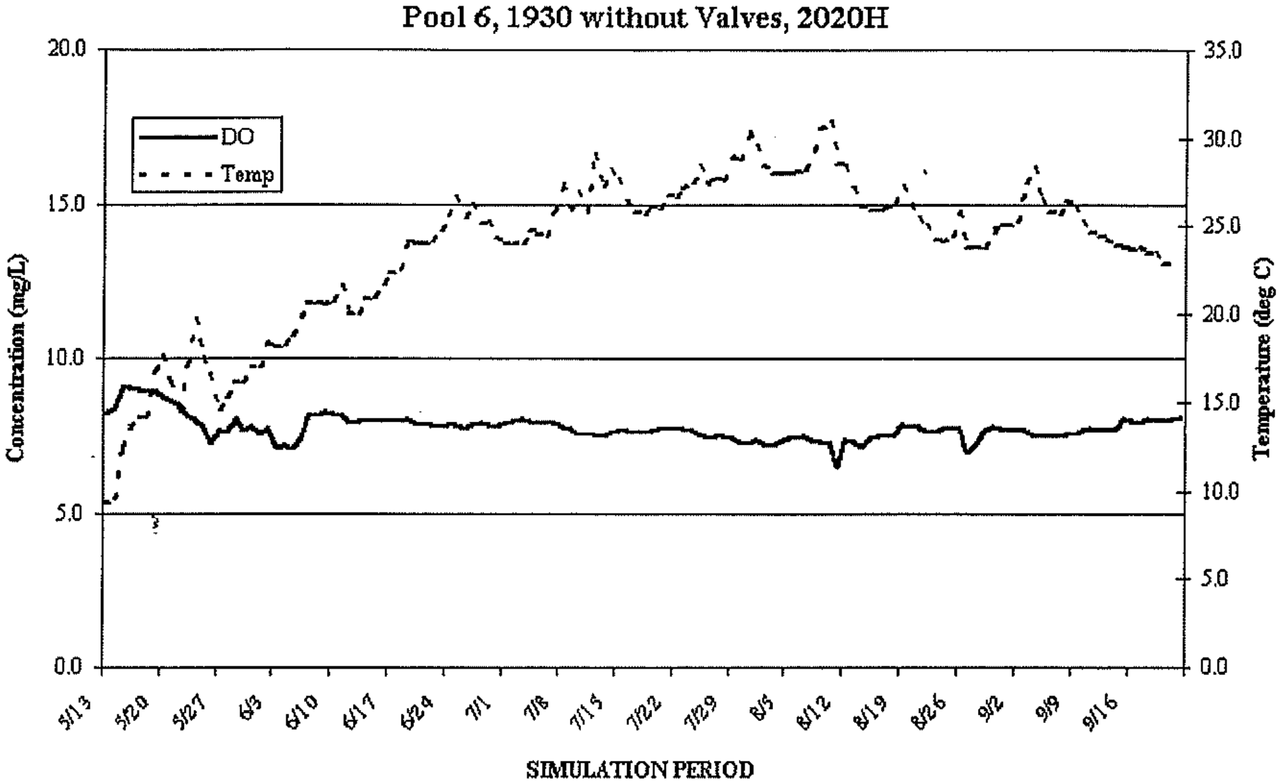




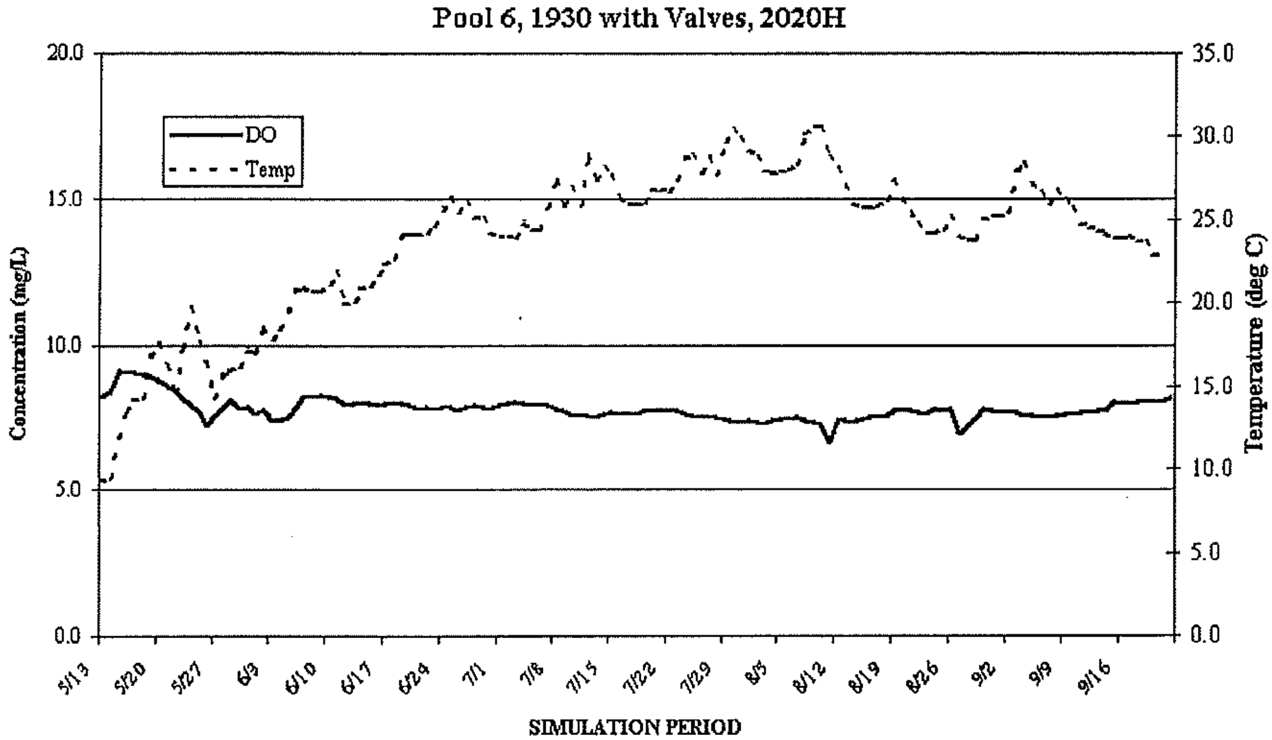
Pool 7, 1930 without Valves, 2020H



Pool 7, 1930 with Valves, 2020H

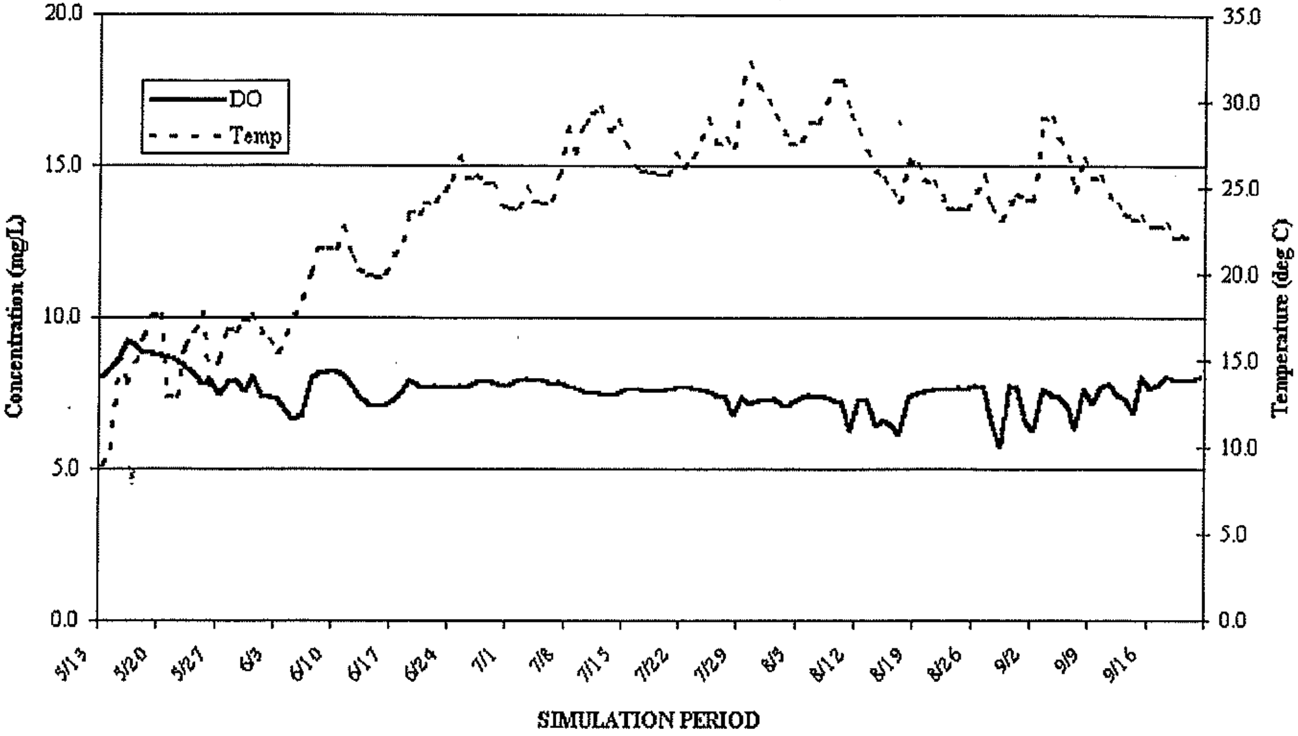


Pool 6, 1930 without Valves, 2020H

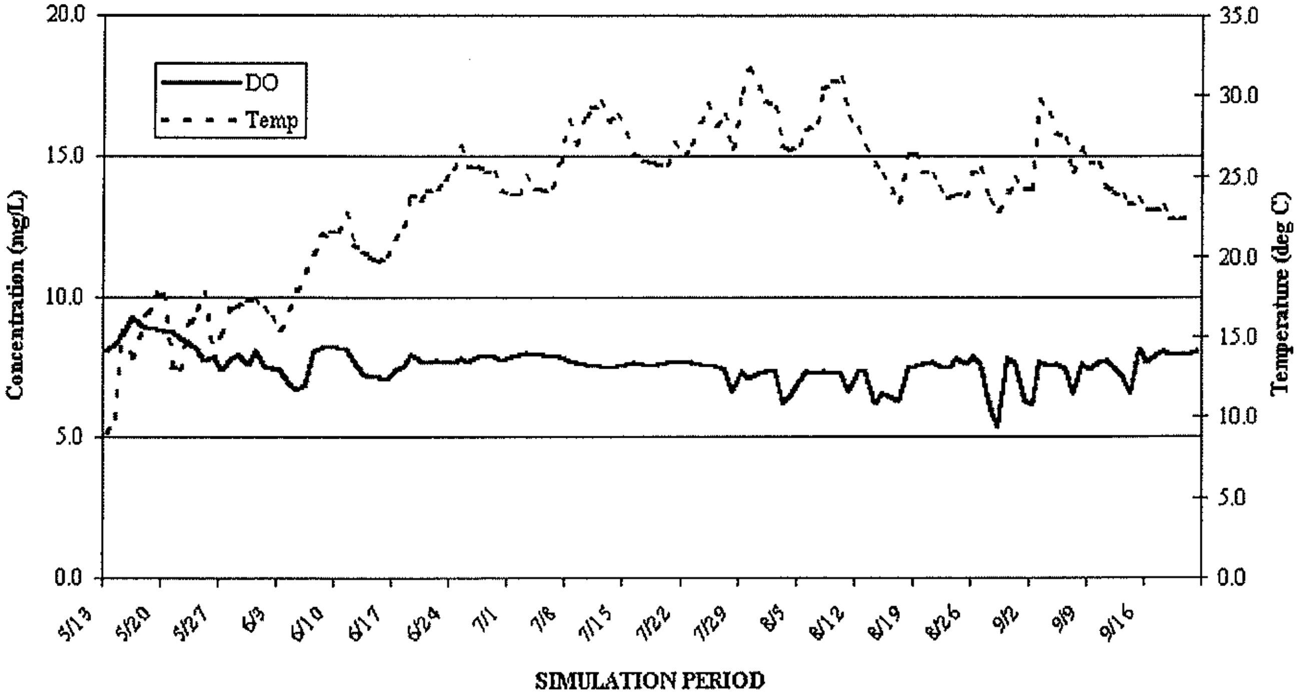


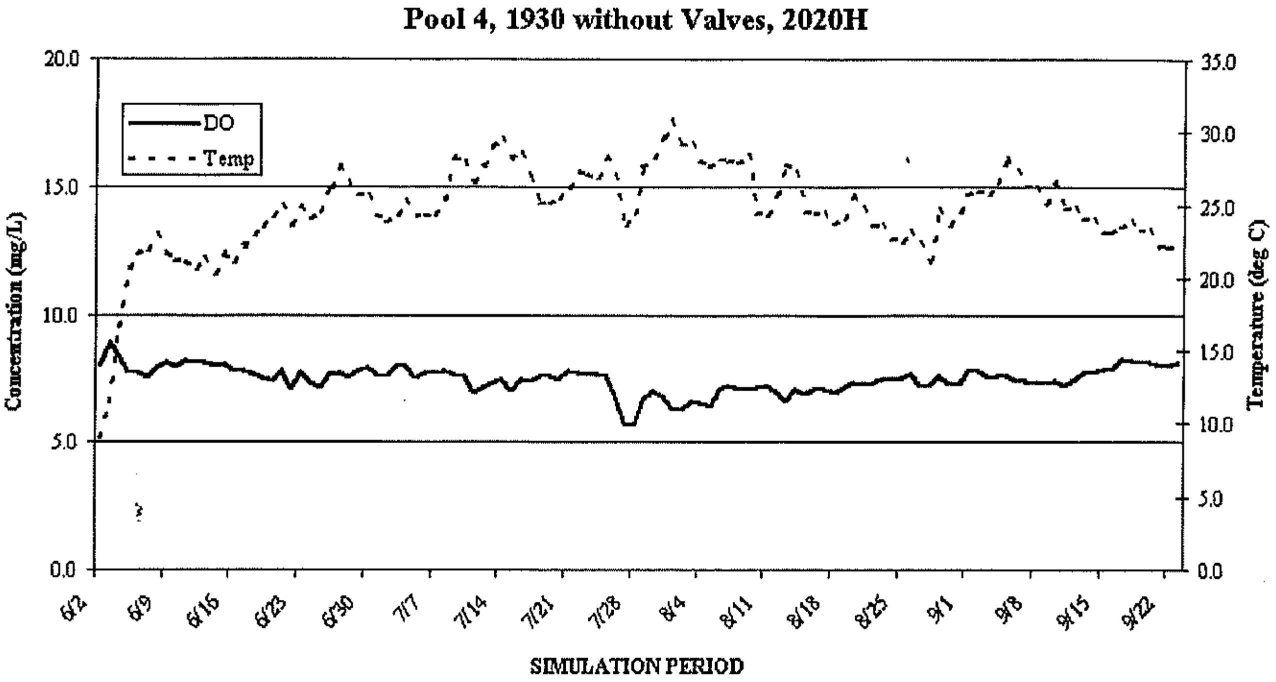
Pool 6, 1930 with Valves, 2020H

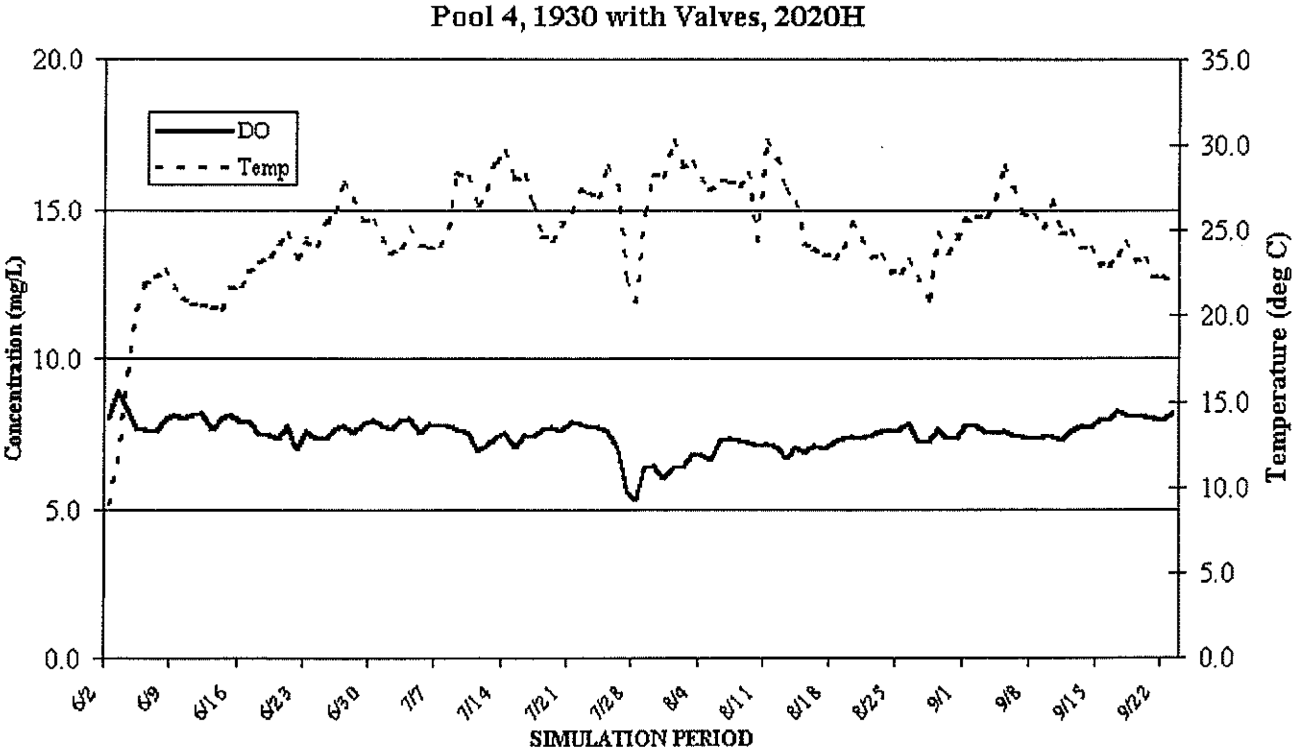
Pool 5, 1930 without Valves, 2020H



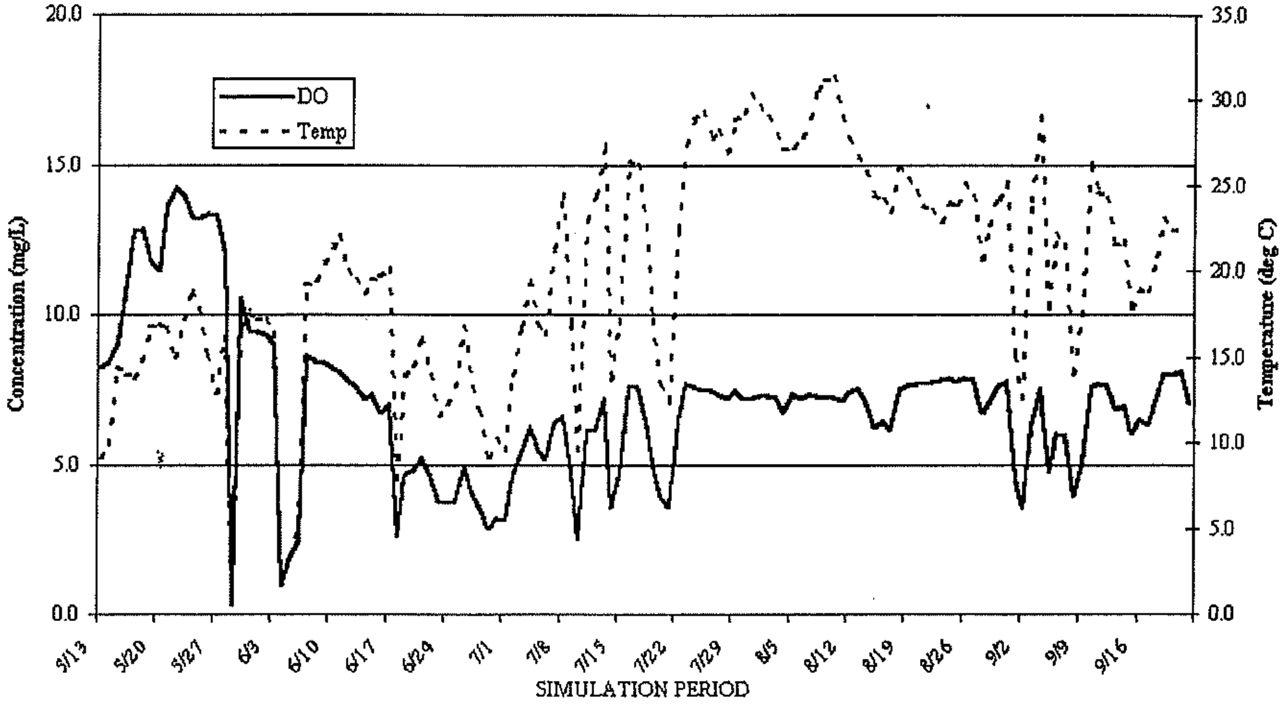
Pool 5, 1930 with Valves, 2020H



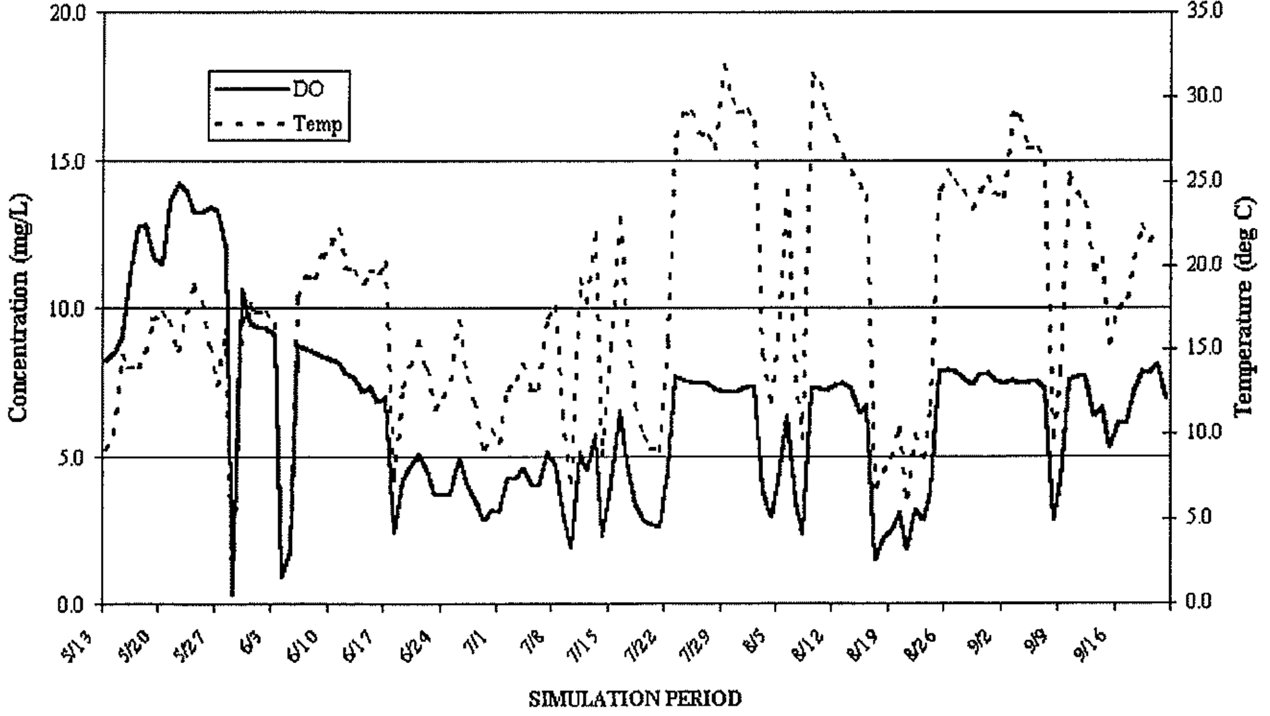

Pool 4, 1930 without Valves, 2020H
DO
Temp
Concentration (mg/L)
Temperature (deg C)
20.0
15.0
10.0
5.0
0.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
6/2
6/9
6/16
6/23
6/30
7/7
7/14
7/21
7/28
8/4
8/11
8/18
8/25
9/1
9/8
9/15
9/22
SIMULATION PERIOD

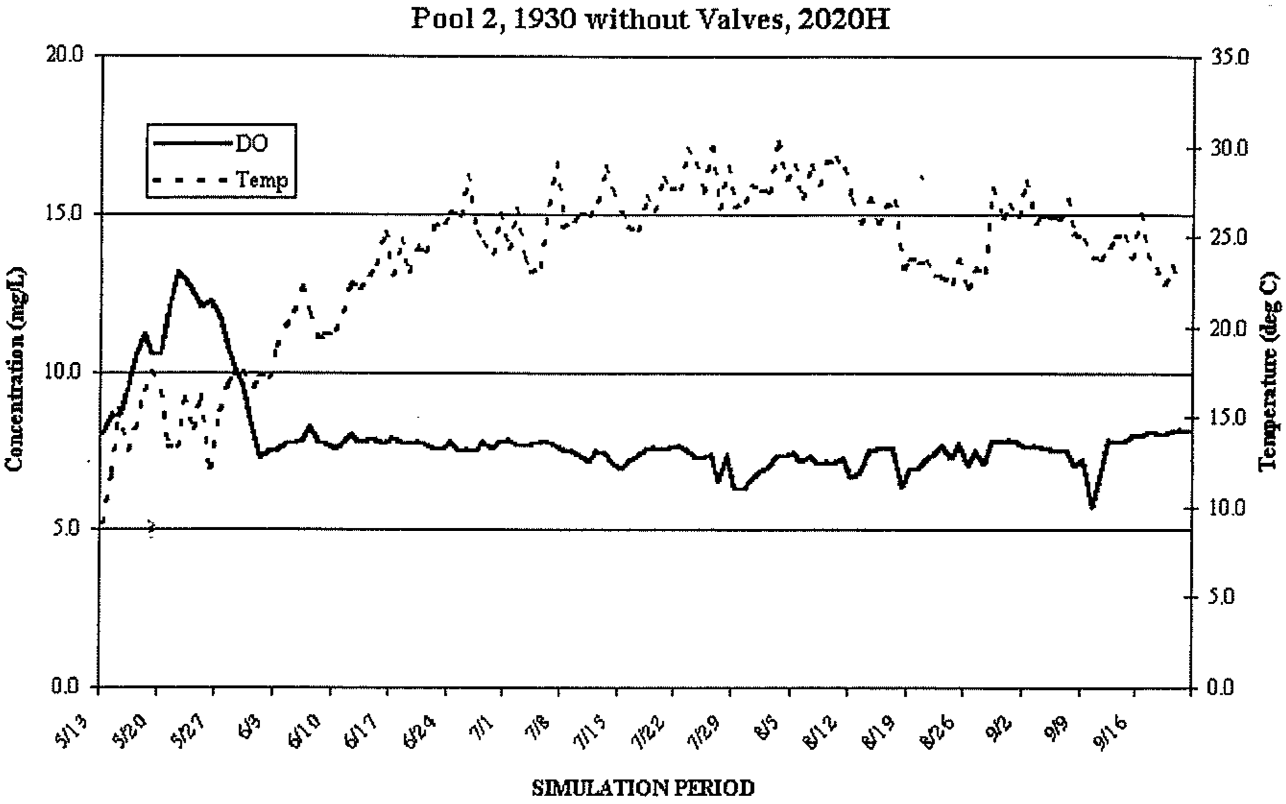

Pool 4, 1930 with Valves, 2020H
DO
Temp
Concentration (mg/L)
Temperature (deg C)
20.0
15.0
10.0
5.0
0.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
6/2
6/9
6/16
6/23
6/30
7/7
7/14
7/21
7/28
8/4
8/11
8/18
8/25
9/1
9/8
9/15
9/22
SIMULATION PERIOD

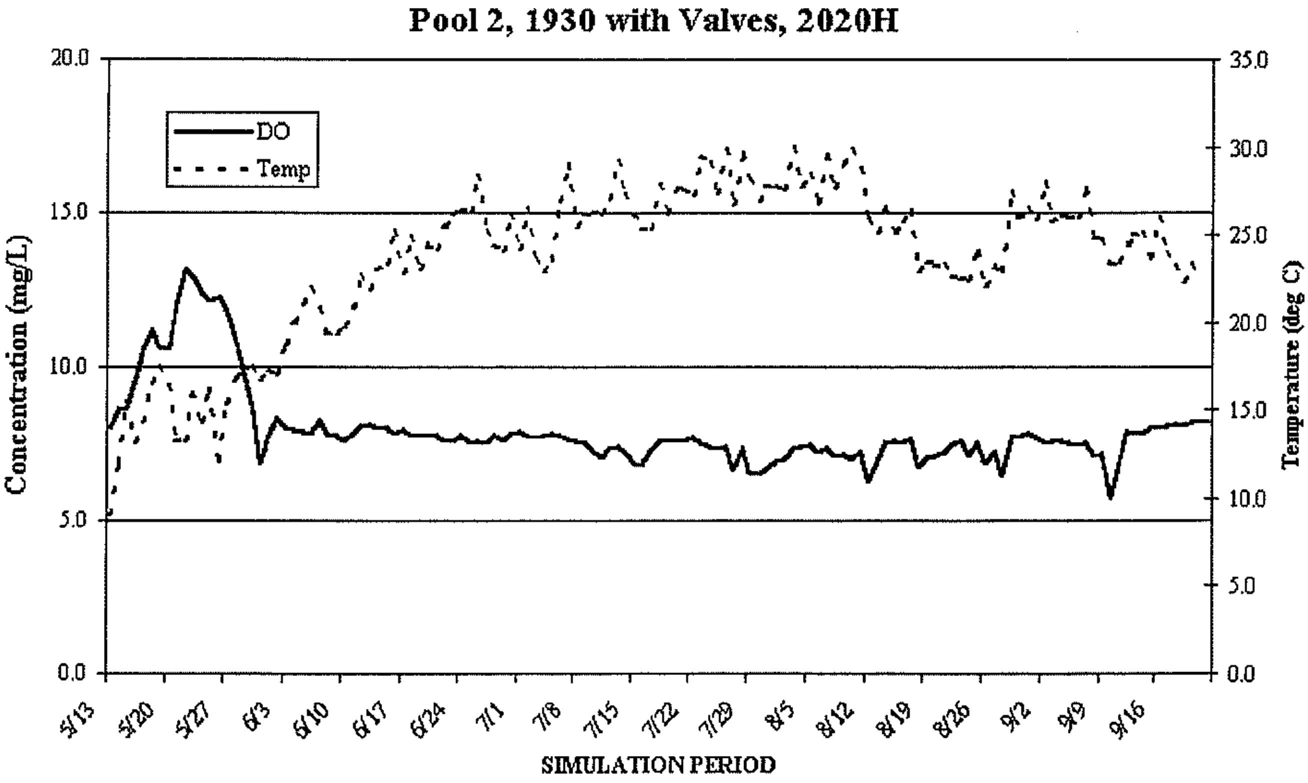
Pool 3, 1930 without Valves, 2020H



Pool 3, 1930 with Valves, 2020H




Pool 2, 1930 without Valves, 2020H


Pool 2, 1930 with Valves, 2020H