Spring Hollow Reservoir:

Application of a two-dimensional water quality model

by

Daniel S. Dorsel

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APPROVED:

Dr. John C. Little, Chair

Dr. Daniel L. Gallagher

Dr. Robert C. Hoehn

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Abstract

The BETTER water quality model, created by TVA, was used to model the temperature and dissolved oxygen (DO) in Spring Hollow Reservoir. The water balance consisted of pump discharge from the Roanoke River, runoff, releases at the dam, leakage, and storage. The geometry of the reservoir was represented by four columns and a variable number of five-foot layers. Through a sensitivity analysis, the parameters that influenced temperature and DO the most were determined. Temperature was then calibrated to a subset of the 19-month simulation period by systematically varying the most sensitive parameters. DO was calibrated to the entire simulation period due to the young age of the reservoir and the inconsistent inflow rates and timing. The verification process showed that the model reasonably reproduced the seasonal temperature patterns. By varying the sediment oxygen demand temporally and spatially, the model depicted the gradual hypolimnetic oxygen depletion in the reservoir. The model results suggest that the inflow organics and subsequent settling and accumulation are key factors in the DO depletion rate. Therefore, to enhance water quality conditions in the reservoir, a monitoring system in the Roanoke River should be installed with filling carried out when water quality in the river is optimal. For future modeling purposes, this research indicated that the model was very sensitivity to meteorological data, especially in determining temperature. Thus, a weather station located at the reservoir would permit collection of more accurate meteorological data, leading to greater confidence in the interpretation of the model predictions.

Keywords: modeling, water treatment, reservoir

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Literature Review

Drinking water reservoirs can be better managed and utilized if the water quality is known. This knowledge is especially useful in reservoirs that have withdrawal points at several different elevations. Based on an understanding of water quality throughout the water column, an appropriate withdrawal can be selected that will reduce the amount of treatment subsequently required at the water treatment facility. Water quality information can be gained by implementing an extensive monitoring program. However, this approach can entail significant cost. If water quality could be accurately predicted, a less-intensive, and hence less-costly, monitoring program would be required. Also, a versatile model would allow for alternative reservoir management strategies to be examined at relatively low cost.

The desire to predict water quality and evaluate the impact of different management techniques lead to the development of water quality models. In the 1920's, the first attempts were made to mathematically model the thermal cycle in surface water impoundments. Models continued to evolve slowly until the 1960's. The emergence of digital computers in the 1960's, coupled with the environmental movement of the time, accelerated the development of mathematical models (French 1983). These new models incorporated the momentum, heat, and mass transfer processes that affect water quality in various waterbodies. The advancement in numerical methods to solve the partial differential equations required to represent these dynamic processes also assisted in the development of the new models (Harleman 1982).

Despite advancements in modeling capability over the past years, models still remain a simplification of the complex nature of ecosystems (Jorgensen et. al. 1996). A number of processes must be simulated in order for a model to be a useful tool. Among these processes are those related to the hydrodynamic, chemical, and biological nature of ecosystems. A model should reproduce the hydrodynamics of an impoundment before attempting to model the chemical and biological mechanisms impacting water quality (French 1983). If the hydrodynamics are not consistent with those found in the impoundment, then processes that depend on the hydrodynamics will in turn be based on inaccurate predictions. The complexities of the chemical and biological processes that occur in an ecosystem will not be discussed in this paper, but can be found in most limnology textbooks (Cole 1994). These processes are often interrelated and a complete understanding of them is still being acquired. In most water quality models, complex processes that are present in an ecosystem tend either to be simplified (e.g., by grouping algae into a single assemblage) or eliminated (e.g. by not employing the momentum equation when determining the flow field).

Models are not only used to reproduce the water quality patterns found in waterbodies, but can also simulate the effects of various management strategies. For instance, in a deep reservoir, the hypolimnion typically experiences oxygen depletion. There are numerous approaches to replenish hypolimnetic oxygen in the waterbody or in the discharge water, such as bubble plume aeration systems and deep turbine releases. In the design phase of hypolimnetic aeration systems it would be useful to be able to predict the impact of system performance on reservoir water quality. Models provide a means for accomplishing this either by having built in capabilities to simulate different management strategies or by coupling the model with a model of the particular hypolimnetic aeration system.

Four models that can be used to simulate lake and reservoir behavior will be discussed; MINLAKE, CE-QUAL-W2, DYRESM, and BETTER. Their ability to simulate water quality has been well documented in the literature, and readers are directed to the sources listed in this paper for additional details of these models and their previous applications. The four models are similar to one another in that they incorporate the processes involved in mixing and transport due to inflows, outflows, and mixed layer dynamics. However, the way in which the processes are modeled and the extent to which the variables and characteristics of waterbodies are represented creates uniqueness between models. The following four sections describes each of the models in turn. Processes and variables that are similar for the models will not be reiterated during the description of each model, but instead, only explained once and then referenced.

MINLAKE

The Minnesota Lake Water Quality Management Model (MINLAKE) was developed in the early 1980's at the University of Minnesota (Riley and Stefan 1988). It is a one-dimensional model, maintaining variation in the vertical direction, created to study lake eutrophication and control strategies. In order to fulfill this purpose, the model has the capability to simulate lake stratification and water quality changes caused by weather, inflow, outflow, exchange processes at the sediment interface, and inlake processes. These processes are modeled using advective and diffusive transport, settling, and chemical and biological kinetic mechanisms, all of which are discussed later in this section.

MINLAKE is a one-dimensional model with horizontal layers that can vary in thickness over time. The user specifies a minimum and maximum layer thickness. Since the model only represents spatial resolution in the vertical direction, localized effects and horizontal heterogeneities are not simulated, and instead are averaged in both horizontal directions for each layer. The model is suggested for use in small lakes (surface area between 50 and 100 km^2) that are either deep or shallow.

The computer model is divided into 5 basic sections: input, heat budget, biological-nutrient kinetics, inflow-outflow subroutines, and a lake-specific subroutine. The input section involves reading in the user provided constants for rate coefficients, yield coefficients, and initial conditions for water quality parameters. These values can be adjusted later to facilitate calibration of the model to a specific site. This section also reads in the daily meteorological data.

The heat budget section uses the meteorological data to determine surface heat exchanges, solar radiation absorption, and the effect of wind mixing. Along with natural convective mixing in which surface water cools and mixes with subsurface water, these processes in the heat budget determine the temperature profile and the depth of the surface mixed layer in the waterbody.

The biological-nutrient section allows for the representation of one to three forms of algae and one group of zooplankton. Phytoplankton growth is limited by phosphorus, nitrogen, or light. In this section, detritus represents decaying organic matter, which consumes oxygen and releases nutrients during the decay process.

Simulation of lake stage and inflowing nutrients occurs in the inflow-outflow section. Inflow is specified by values for flow rate, temperature, nutrient concentrations, detritus, and dissolved oxygen (DO). Its placement into the waterbody is determined by matching densities. The only requirement for outflow is the flow rate. Using that value, a volume of water containing dissolved and suspended materials is removed during each appropriate time step, usually selected to be one day.

In order for the bulk of the programming code to remain consistent and easily adjustable, a lake-specific subroutine was created. This feature allows users to modify the model to simulate a particular waterbody characteristic or treatment process. Also, other models, such as destratification devices, can be linked to MINLAKE via this subroutine.

The basic governing equation for the dynamics of all substances within a layer is the one-dimensional advection-diffusion equation:

$$A\frac{\partial C}{\partial t}+\nu\,\frac{\partial (CA)}{\partial z}=\frac{\partial}{\partial z}\left(KA\frac{\partial C}{\partial z}\right)\pm \text{sources /sinks}$$

where C is concentration or an intrinsic property of the fluid; ν is the vertical settling velocity of the substance; z is the vertical coordinate measured positively downward; K is the vertical turbulent diffusion coefficient (assumed to be identical for each state variable); and A is the horizontal area of the control volume. Settling of algae, detritus, and suspended solids effect the variables within a layer. Algae and detritus settle at a constant rate, while suspended solids settle at a rate, which is a function of particle size and dynamic viscosity. The source and sink terms determine the complexity of the model and the interrelationship between the variables. Using a central difference scheme for dissolved substances and an implicit power-law scheme developed by Dhamotharan et al. (1981) for suspended state variables, a set of linear equations are created and solved for the concentrations or fluid property in each layer.

The bulk of the MINLAKE program focuses on algal biomass prediction and nutrient routines. Algal populations are represented by concentrations of chlorophyll *a*. Growth, diffusion, settling, respiration, mortality, and grazing affect the concentrations in each layer. Three broad classes of algae can be incorporated into the model allowing for diatoms to be modeled early in the season, then green algae, and finally blue-green algae during the summer. Distinctions are made between the various algal forms using different rates of photosynthesis, respiration, settling, and zooplankton grazing and different nutrient requirements.

Unlike phytoplankton, zooplankton movement is not only a function of settling and diffusion, but also depends on individual mobility. During each day, zooplankton follow a vertical migration, which the model incorporates. In order to avoid being visible to predators, zooplankton retreat to deeper depths during the light hours of the day. At this depth, defined in the model as the depth at which the DO is less than 0.5 $mg*L^{-1}$, respiratory and mortality contributions are made to the oxygen and nutrient budgets. Grazing only occurs when the zooplankton begin to rise to the surface at dusk and ceases again when they return to the deeper depths by dawn.

Along with the biological model, the nutrient model is an important part of the program. The model represents soluble reactive phosphorus (SRP) as the only available phosphorus for phytoplankton. SRP is the readily accessible fraction of total phosphorus composed of orthophosphate and polyphosphate ions. Organic phosphorus is indirectly measured as detritus. The phosphorus balance includes consumption during growth and release from respiration, mortality, decay of detritus, grazing, and sediment (constant rate of release during anoxic conditions). Nitrogen is modeled as nitrate-nitrite or ammonium. The processes that effect phosphorus also impact the nitrate-nitrite concentrations, along with nitrification. Only respiration, mortality, and grazing affect the ammonium concentrations.

Nitrification and respiration exert demands on the DO in the waterbody. Along with these demands, DO is consumed by sediment uptake and the decay of detritus in the model. DO is used in the model to directly effect biological decay processes, sediment nutrient release rates, and zooplankton movement and to determine the impact of various restoration techniques. The model allows for two sources of DO, rearation and photosynthesis.

There are numerous interrelated processes involved in a water quality model. The processes that have an effect on the largest number of other processes should be treated first. MINLAKE first solves the physical processes of heat flux, wind mixing, inflow, outflow, and conservative suspended and dissolved substances, and then treats the biological processes of nutrient uptake and depletion, growth, and oxygen depletion (Riley and Stefan 1988).

CE-QUAL-W2

The Water Quality Modeling Group at the U.S. Army Engineer Waterway Experiment Station has been continuously developing CE-QUAL-W2 since 1975 (Cole and Buchak 1995). The model is two-dimensional and laterally averaged. Therefore, it is best suited for long and narrow waterbodies that have little laterally variation. It has successfully been applied to rivers, lakes, reservoirs, and estuaries.

The hydrodynamic part of the model simulates water surface elevation, velocities, and temperature (temperature is included in this section, because of its effect on water density). The water quality portion allows combinations of 21 constituents to be modeled. The geometry is represented as columns of variable length and layers of variable thickness. The model simulates inflows from point and nonpoint sources, branches, and precipitation and outflows from releases at a branch’s downstream segment or lateral withdrawals. No direct term for seepage is included; however, terms for evaporation and ice cover are available.

In the hydrodynamic and transport section, six simplified laterally-averaged equations for fluid motion derived from the full three-dimensional equations are employed. The horizontal momentum equation (the vertical momentum equation is not included) includes the time rate of change of horizontal momentum, the horizontal and vertical advection of momentum, the force imposed by the horizontal pressure gradient, the horizontal dispersion of momentum, and the force due to shear stress. The constituent transport equation includes horizontal and vertical advection and diffusion, kinetic source and sink terms, and inflows and outflows. The remaining four equations involve free water surface elevation, hydrostatic pressure, continuity, and density.

Six unknowns result from these six equations: free water surface elevation, pressure, horizontal velocity, vertical velocity, constituent concentration, and density. The basic model formulation involves the solution of these six equations and six unknowns. The solutions can vary from explicit to implicit, i.e. diffusion is always fully implicit, while solutions can range from explicit to fully implicit for vertical advection depending on user-defined choices.

For the remainder of this section on CE-QUAL-W2, some of the water quality variables modeled will be mentioned in order to briefly explain their purpose and effect in the waterbody.

- Inorganic suspended solids effect water density, light penetration, and nutrient availability. As these solids settle out of the water column, no accumulation occurs.
- Coliform bacteria are used as an indicator of pathogen contamination. This information can be helpful for drinking water and recreational purposes.
- Total dissolved solids (TDS) or salinity impact water density and ionic strength.
- Dissolved organic matter (DOM) is split into labile and refractory DOM. Both exert a demand on oxygen during decay; however, the refractory DOM decomposes at a slower rate. Nutrients are also released during the decay of DOM.
- Detritus represents the particulate organic matter. As it decays, phosphorus, nitrogen, and carbon are released while oxygen is consumed. Accumulation of settled detritus can occur at the bottom and continue in the sediment.
- Algae are represented as a single compartment with light, phosphorus, or nitrogen limiting growth. Similar to detritus, algae can accumulate in the sediment. When algae die they are converted to labile DOM or detritus. The model does not incorporate zooplankton, and therefore, the effect of grazing on algae is not simulated.

- Phosphorus is represented as orthophosphate and is assumed to be completely available for uptake by phytoplankton. The closest field measurement to the model value is soluble reactive phosphorus. In addition to the above-mentioned releases of phosphorus, the sediment will also release phosphorus under anoxic conditions. Phosphorus can also be adsorbed onto particles under anoxic conditions and is then lost from the system when that particulate matter settles.
- Nitrogen is represented as ammonia-N or nitrate-N, which includes nitrite-N. Ammonia-N can be released from the sediment and used during the nitrification process, while nitrate-N is created during the nitrification process, but will be consumed during the denitrification process.
- DO allows for the assessment of the general health of the system, especially in identifying problems with metalimnetic and hypolimnetic oxygen depletion and possible management alternatives. The demands on DO include decay of detritus, labile DOM, and refractory DOM, sediment oxygen demand, nitrification, algal respiration, and reaeration. The sources for oxygen in the model are photosynthesis and reaeration.
- The sediment contribution of nutrients and DO demand can be modeled in two ways. First, sediment release and DO demand can be represented using a zero-order process, which is independent of concentration. The second option is to use a sediment compartment that accumulates sediment and allows decay to occur within the sediment. This involves a first-order process which is dependent on concentration for release and DO demand.
- Alkalinity indicates the buffering capacity of the water and its resistance to changes in pH from acid or alkaline loadings. Alkalinity is modeled as a conservative parameter.
- Carbonate species and pH are computed using temperature, TDS or salinity, alkalinity, and total inorganic carbon. Both variables are not subject to transport, but instead are updated during each water quality interval.

- Finally, total iron is included because of its effect on nutrient concentration through adsorption and settling. During anoxic conditions, iron can be released from the sediment (Cole and Buchak 1995).

DYRESM Water Quality Model

DYRESM is a hydrodynamic model created by Imberger and other colleagues at the University of Western Australia. It has been improved during the past 20 years and has been well established through numerous applications to lakes and reservoirs. Hamilton and Schladow, while at the University of Western Australia, coupled the hydrodynamic model with a water quality model consisting of an ecological section and a particle settling section to create the DYRESM Water Quality model (DWQ).

“The hydrodynamic component includes separate algorithms for individual mixed layer processes, inflow (both riverine and groundwater), natural and man-made outflows, and hypolimnetic mixing. The particle settling component allows for the gravitational settling of a spectrum of particle sizes with variable degree of coagulation. The ecological component models phytoplankton production, nutrient cycling, and the dissolved oxygen budget” (Hamilton and Schladow 1997).

The model is one-dimensional, retaining variability in the vertical direction, with adjustable layer thickness to adequately represent the vertical density gradient. The user-defines a minimum thickness that layers can be before they are automatically mixed with the smaller of the two bounding layers. Likewise, as mixing of layers occur, if the user-defined maximum thickness is reached the layer is automatically divided into smaller layers within the acceptable thickness range.

The model employs two time steps. Inflows and outflows use a set 24-hour time step. Another subdaily time step, ranging from 15 minutes to 12 hours, depends on thermal transfers and wind stress. The minimum time step (to the nearest 15 minutes) needed to capture the increased mixing activity caused by either of these two features is used as the subdaily value and is determined at the end of each time step.

The particle settling model will not be described in this paper other than to mention that it simulates settling, aggregation, and diffusion of particles in the water column. References to it can be found in the article by Hamilton and Schladow (1997). The ecological model is similar to the models previously described and will not be discussed further in this paper. (One note on the ecological model is that up to three types of phytoplankton can be modeled, as well as one group of zooplankton.) The hydrodynamic component of the DWQ model, DYRESM, is the feature that makes it unique from the other models (Hamilton and Schladow 1997).

In the hydrodynamic portion, each one-dimensional physical process is described separately and the parameters involved have been determined from laboratory or field investigations, independent of the modeling procedure. Therefore, no calibration of the model is needed when applying it to different sites. This calibration-free characteristic has been documented with numerous applications to lakes and reservoirs (Hocking and Patterson 1991).

In the model, meteorological data are used to compute the transfer of heat, momentum, and moisture across the air-water interface. The long-wave radiation emitted from the surface and the long- and short-wave radiation absorption also add to the surface heat exchanges (Hocking and Patterson 1991). The surface layer dynamics are based on wind, convective cooling, interfacial shear production, and Kelvin-Helmoltz billowing (Hamilton and Schladow 1997). Turbulent kinetic energy (TKE) from wind stirring and surface cooling are added to the near surface layers. Energy from shear production is added to this TKE, and thus, increases the energy available for the deepening of the surface mixed layer (Imberger 1982). The TKE produced by these processes in the surface mixed layer is compared to the potential energy required to mix the layer below it. Mixing will continue until there is not enough TKE remaining to overcome the potential energy required to mix the layers together (Hamilton and Schladow 1997). The "Kelvin-Helmoltz billowing is used to smear out the sharp density interface remaining at the base of the mixed layer" when deepening ceases within a time step (Imberger 1982).

The hydrodynamic model tries to simulate the insertion of inflow water as it actually occurs in a waterbody. As water from a river enters a waterbody, it continues to move forward until buoyant forces stop it, at which point the water will flow over the top of the surface water or plunge to a neutrally buoyant depth entraining water as it flows downward. At the depth of neutral buoyancy, the inflow water and entrained water are inserted. The model estimates the time it takes to reach this insertion point, and after that many days, the water is inserted into the appropriate horizontal layer. Groundwater intrusion is treated in a similar manner, except there is no entrainment of water (Hamilton and Schladow 1997).

The other aspects of the hydrodynamic model concern outflows and hypolimnetic mixing. Withdrawals affect the layers surrounding the outflow. Withdrawal layer thickness below the offtake level is limited to the distance between the offtake level and the sill height. The replenishing of water to layers is proportioned more to the above layers than to the layers below (Imberger 1982). Hypolimnetic mixing is accounted for by a turbulent diffusivity coefficient, which depends on the dissipation of TKE and inversely on stratification (Hamilton and Schladow 1997).

BETTER

BETTER is an acronym for Box Exchange Transport Temperature and Ecology of a Reservoir (Bender et al. 1990). The two-dimensional model divides a reservoir longitudinally and vertically into boxes (also referred to as cells or volume elements) that are laterally averaged. Through a series of mass balance calculations, observed seasonal patterns of temperature, dissolved oxygen, nutrients, pH, and algal biomass can be simulated. The BETTER model has been applied to a number of mainstream and tributary reservoirs with success in reproducing observed temperature and DO patterns over a specified time period.

An overview of how mixing is represented and how temperature and DO values are calculated in the model will be provided within this section. In the model, new constituent values are determined using the amount of constituent in each volume element remaining from the last time step along with transfers from the cells above, below, upstream and downstream of the current cell. Flow and transport of constituents are driven by advection in the horizontal and vertical directions. Reservoir inflows and outflows cause advective water movement within the cells. As a volume of water leaves a cell, the concentration of a constituent in that cell decreases relative to the mass of constituent in the volume of water leaving the cell. Similarly, as water enters a cell, the constituent concentration increases relative to the mass introduced from the volume of water transferred into the cell.

Other than advective transfers, constituent values are also affected by volumetric exchanges between cells used to simulate vertical mixing caused by wind, surface cooling, and turbulent flows. These volumetric exchanges are instantaneously mixed with the constituent concentration in the cell, rather than by mixing through a diffusive mechanism. The amount of water exchanged due to wind mixing depends on the balance between the kinetic energy transferred to the water from the wind and the potential energy required to lift a volume of cooler water into the surface mixed layer. As long as the kinetic energy is greater than the potential energy, instantaneous mixing of the surface mixed layer with the layer or fraction of the layer below the surface mixed layer will occur. During nighttime or cooling events, surface water will cool and sink to its matched density level. Convective mixing is simulated by instantaneously mixing the volume of water at this matched density level with the surface mixed layer. Turbulent mixing is simulated by vertical volumetric exchanges between layers caused by flow moving across the interface of the layers.

Mixing affects the temperature for each volume element by combining various amounts of water of different temperatures in an energy balance. However, the governing processes that control temperature changes and determine thermal stratification are the heat exchanges occurring at the surface. The surface heat exchange terms employed in the model include long-wave radiation between the water and atmosphere, evaporation and convective cooling, and solar radiation absorption. The solar radiation absorption term depends on a light extinction coefficient, which is a function of the suspended solids and algal concentrations in the water column, while the other terms are a function of the daily meteorological data and existing surface layer temperatures.

Surface cooling and wind mixing determine the temperature and depth of the surface mixed layer. The deepening of this layer depends on the balance between the kinetic energy produced by the wind and the potential energy required to lift cooler water into the mixed layer. Deepening will continue until the kinetic energy produced is no longer greater than the potential energy required. Also, the depth of the mixed layer is changed as surface water cools and sinks to its matched density. This causes density instability in the mixed layer. To re-establish density stability, the mixed layer adds cooler metalimnetic water to the mixed layer, thus deepening and cooling it.

The following processes and variables that affect DO will be briefly explained: inflow, outflow, mixing, reaeration, respiration and photosynthesis, decay, nitrification, biochemical demand, and sediment demand. Inflows, outflows, and mixing directly increase or decrease the amount of DO in a cell according to the transfer of DO in or out of an element and the volume of that element. A larger volume will experience smaller changes in DO due to dilution if the mass of DO transferred is not large. Reaeration occurs when water below the surface is mixed to the surface and transfer of oxygen occurs between the atmosphere and the water.

Algae effects DO through respiration and photosynthesis. The BETTER model represents algae as a single assemblage. This assemblage produces a more-or-less constant photosynthetic output of oxygen during the summer with the occasional occurrences of DO supersaturation and elevated pH levels due to algal blooms. In the model, the growth of algae is limited either by light, nitrogen, phosphorus, carbon dioxide, or the maximum growth rate. As algae grow and produce oxygen, they also begin to respire and consume oxygen.

The BETTER model does not include a term for zooplankton, instead when algae die they are converted directly to detritus (particulate organic matter). The decay and settling of detritus exerts an oxygen demand in the reservoir. The decay of dissolved organics, the soluble fraction of the traditional BOD_5 measurement, also consumes oxygen. Along with decay of organics, nitrification also causes a demand on the oxygen in the reservoir as ammonia is converted to nitrate. Algal respiration, detritus and dissolved organics decay, and nitrification comprise the BOD_5 term calculated in the model.

Another process that depletes oxygen in the model is sediment oxygen demand. The microbes in the sediment consume oxygen from the volume elements that are in contact with the sediment. This demand can occur due to organics that have settled into the sediment or from sediment that has been transported into the reservoir via inflows (Bender et al. 1990).

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Introduction

Spring Hollow Reservoir is located in Roanoke County in the mountains of western Virginia. It is a side storage reservoir that draws water from the Roanoke River and feeds it, by gravity, to a newly constructed water treatment plant. The reservoir currently supplies an average of 2.2 million gallons per day, although it was designed to meet a projected demand of 17 million gallons per day by the year 2040.

After the construction of the reservoir was completed, filling continued through spring of 1996, at which time a water quality monitoring program was initiated. Temperature versus depth profiles revealed a strongly stratified water column which persisted through the summer and fall with overturn in early February. Oxygen concentrations in the hypolimnion declined fairly rapidly during the stratified period revealing the need for replenishment of oxygen to avoid hypolimnetic anoxia and the associated water quality problems. A linear bubble plume aeration system was therefore installed in the fall of 1997. The long-term goal of this research is to develop a water quality model for the reservoir and couple it with a model that is able to predict the performance of the bubble plume diffuser. This coupled model should enable the optimization of various operational techniques to be explored in order to enhance drinking water quality. Furthermore, the coupled model can be used for designing aeration systems to be installed in other reservoirs.

The first phase in accomplishing the long-term goal of creating a coupled model was to select and calibrate an appropriate water quality model for Spring Hollow reservoir so that seasonal variations in temperature and dissolved oxygen (DO) could be predicted. This first phase was completed in a number of steps. The first step was to select a model that was appropriate for Spring Hollow reservoir. Secondly, available model input information had to be collected, including details on geometry and meteorology, as well as inflow and outflow data. After this information was gathered, a sensitivity analysis was performed to determine which variables have the largest impact on temperature and DO. Finally, the model was calibrated using a subset of the available monitoring data, and verified using the remainder of the field data.

Selection of Model

General Descriptions

Four relatively common water quality models were considered. DYRESM, which was created at the University of Western Australia, is a one-dimesional model used to predict hydrodynamics and water quality in lakes and reservoirs (Hamilton and Schladow 1997). MINLAKE is a one-dimensional model created to study lake eutrophication and control strategies and was developed at the University of Minnesota (Riley and Stefan 1988). CE-QUAL-W2, which was developed at the U.S. Army Waterways Experiment Station, is a two-dimensional model used to simulate the hydrodynamics and water quality found in water bodies (Cole and Buchak 1995). Finally, the BETTER model, created by the Tennessee Valley Authority (TVA) (Bender et al. 1990), is a two-dimensional model employed to simulate the water quality in hydropower reservoirs.

BETTER Model

The BETTER model was selected for use in this research. It has previously been used to model the seasonal patterns of temperature, dissolved oxygen and other water quality variables in mainstream or tributary reservoirs. It has also been used to explore different methods of improving release DO from various dams and the impact of point and nonpoint sources on water quality. The BETTER model was also selected for this research because of its two-dimensional nature and the possibility to work with the researchers who developed it and presently apply it to other reservoirs.

A brief description of the model will be provided in the following two paragraphs. For a thorough discussion of the model’s input requirements, capabilities and limitations, conceptual development, subroutines, and suggested applications, a technical reference manual and user’s guide is available (Bender et al. 1990).

BETTER is a two-dimensional model that divides a reservoir longitudinally and vertically into boxes or volume elements that are laterally averaged. Through a series of mass balance calculations, observed seasonal patterns of temperature, DO, nutrients, pH, and algal biomass can be simulated. The flow and transport of constituents are driven by advection in the horizontal and vertical directions. Other than advective transfers, constituent values are influenced by volumetric exchange between elements; a process used to simulate vertical mixing caused by wind, surface cooling, and turbulent flows.

These volumetric exchanges affect the temperature for each volume element; however, the governing process that controls temperature and determines thermal stratification is heat transfer at the surface. The surface heat exchange terms employed in the model include long-wave radiation between the water and atmosphere, evaporation and convective cooling, and absorption of solar radiation. The prediction of DO is more complex, encompassing the following processes: inflow, outflow, mixing, reaeration, respiration and photosynthesis, organic decay, nitrification, biochemical oxygen demand, and sediment oxygen demand.

Previous Applications of the BETTER Model

The BETTER model has previously been applied to Nottely and Tellico Reservoirs. At normal pool, Nottely Reservoir has a surface area of 418,000 acres, a volume of 1,703,000 acre-foot, and a depth of 166 foot at the dam. The watershed area for the reservoir is 214 square miles. Turbines near the bottom of the dam facilitate the release of water from the reservoir. Model predictions showed that the gradual thermal stratification in the early spring and destratification in the fall were adequately reproduced. The fall turnover was predicted to occur about a week earlier than was actually observed. The mixing algorithm used in the BETTER model most likely caused this timing difference. Instantaneous mixing of layers occurs when the stability criterion is not met. In other words, when a layer has a greater density and is heavier than the layer below it, the two layers are mixed together instantaneously. Surface cooling will cause this instantaneous mixing, and thus, lead to a fall turnover that is predicted to occur sooner than it actually does. As for DO, algal activity and SOD dominated its predicted concentration in the reservoir. The model was able to reproduce the seasonal patterns of DO in the reservoir, although not as accurately as it did the temperature (Shiao and Hauser 1995).

Tellico Reservoir is smaller than Nottely and has surface release of water, which allowed the deeper water to become stagnant. The objective of the BETTER model application to Tellico was to determine if deep turbine releases of water would increase the DO in the bottom de-oxygenated layer of water. From the various model runs, it was predicted that having bottom releases would improve the DO conditions by an average of 1 mg/L. However, the model also indicated a possible negative effect: bottom releases could cause an increase in bottom temperature, thus accelerating the local sediment oxygen demand (Shiao and Hauser 1994).

Spring Hollow Reservoir

Construction of the reservoir was completed toward the end of 1993 and operation of the water treatment facility began in early 1996 (Table 1). At normal pool elevation (1410 foot above sea level) the reservoir reaches 220 foot deep at the dam, with a water surface area of a quarter of a square mile (158 acres) and a reservoir volume of 3.2 billion gallons (9,800 acre-ft). The reservoir extends a maximum length of just over a mile (5,550 foot) from the dam, with an average width of a quarter of a mile (1,240 foot).

The map of Spring Hollow Reservoir in Fig. 1 shows the locations of the four sampling stations. SH10 is the station closest to the dam, while SH40 is the most upstream station from the dam. Water quality monitoring began in June 1996 and continued until August 1997. Using a YSI 600XL Environmental Monitoring system, the parameters in Table 2 were measured at 5 to 10 foot intervals throughout the water column. Water samples were also taken at the bottom, middle, and surface of the water column using a two-liter kemmerer and analyzed for the constituents shown in Table 3. During the months when the reservoir was strongly stratified (April through November) sampling was completed three to four times a month. During the other months of weak stratification, samples were only collected once or twice a month.

A few inconsistencies existed in the monitoring program. On the majority of sampling days, measurements were taken and samples were collected at each of the four stations. However, on some days sampling only occurred at the station closest to the dam, SH10, due to inclement weather and time constraints. Also, at the beginning of the monitoring program (June 1996), stations SH20, SH30, and SH40 were not marked with buoys, but instead were located using visual landmarks on the shore. Only in May 1997 were buoys installed to mark the station locations. Without the buoys, the boat had a tendency to drift, meaning that measurements and samples were sometimes taken at slightly different locations. The location of station SH40, the most upstream station, varied the greatest over time. At first, measurements and samples were taken at depths of around 35 foot, and then the sampling location drifted closer toward the dam to a depth of around 70 foot. When the buoys were installed in 1997, the buoy for station SH40 was placed at the original site of 35 foot.

Another difficulty in the monitoring program occurred in the spring of 1997 when the dissolved oxygen probe of the YSI 600XL Environmental Monitoring system failed. Therefore, some periods in 1997 do not have DO measurements.

Despite these shortcomings, the measurements and samples taken provide a good reflection of the reservoir's water quality over time. The temperature measurements showed Spring Hollow to be a warm monomictic reservoir that completely destratified in February (Fig. 2). Profiles of DO concentration and percent saturation illustrated the depletion of oxygen in the hypolimnion during the summer months, the replenishing of oxygen during turnover, and the subsequent depletion during the next summer (Figs. 3-4). The profiles in Figs 2-4 also showed changes in pool elevation. The decrease in elevation was attributed to the filling pattern of the reservoir, which is explained in more detail in the following section. Spring Hollow had similar temperature profiles spatially throughout the reservoir (Fig. 5); however, DO tended to vary from one station to another (Figs. 6-7). The spatial variation in water quality characteristics lead to the need for at least a two-dimensional water quality model.

Information required to model Spring Hollow Reservoir

The BETTER model satisfies the initial criteria for predicting water quality in Spring Hollow. The two-dimensional nature of the model allows variations in the vertical and longitudinal directions to be simulated. The model has previously been successful in reproducing temperature and DO patterns in hydropower reservoirs. Daily values for inflows (river, point discharges, and runoff) and their corresponding water quality parameters, outflows (outlets and point withdrawals), and meteorological data can be incorporated into the input files. The modeler can specify initial reservoir conditions, as well as coefficients that control the rate and extent of chemical and biological processes (e.g. nitrification and algal growth) occurring in the reservoir.

Geometrical Data

In the model, the geometrical configuration of the reservoir consisted of four columns, one for each monitoring station, with similar lengths and a variable number of five-foot layers depending on the pool elevation (a maximum of 44 layers in this application) (Fig. 8). Using this representation of the geometry, the reservoir was divided into volume elements, also referred to as cells. In order to capture diurnal variations, a 12-hour timestep was selected. During each timestep and for every cell, the model calculates values for volume, surface area, and conveyance area from user-provided tables of this data (Fig. 9). These user-provided tables were created in the following way. First, the surface areas were obtained by digitizing a contour map of the reservoir. Volume was then calculated by multiplying the surface areas by the elevation change between contour lines. Finally, the conveyance areas were determined by dividing the volume by the length of each column.

Meteorological Data

For each timestep, meteorological data had to be provided. This data consisted of dry bulb and dew point temperatures, wind speed, and solar radiation. These values were obtained from a weather station at the Roanoke Airport, which is at an elevation of 1176 foot and less than 10 miles from Spring Hollow.

Inflow and Outflow Data

Water is supplied to and withdrawn from Spring Hollow through 42-inch diameter pipes, and therefore, is modeled as a point source and release. The influent is discharged at an elevation of 1300 foot and at a point between stations SH20 and SH30 (Fig. 1). The withdrawal tower is located near station SH10 (Fig. 1) and has four possible outlets at 1374 foot, 1344 foot, 1300 feet, and 1220 foot. Water is gravity fed through these gates to the water treatment facility. Only one withdrawal gate or release is open at a time, and the selection depends on the pool elevation and the water quality characteristics at that elevation.

Throughout the simulation period of January 1, 1996 (day 1) to August 30, 1997 (day 608) the daily inflow from the pump discharge was variable – an average of 22 cfs per day in the first 162 days, then no pump inflow, then an average of 5 cfs per day during the last 158 days (Fig. 10). The runoff hydrograph was obtained from a USGS streamflow gage at a nearby station on the Roanoke River. The flow values from that gage, which were scaled to represent the 540 acre (0.84 mi^2) watershed area, suggested small amounts of inflow (1-2 cfs per day) with an occasional storm event.

For each timestep, influent rates for the pump discharge and runoff and their corresponding constituent concentrations had to be provided. Four values for the pump inflow from the Roanoke River were available: temperature, pH, turbidity, and alkalinity. These values were obtained from the Salem water treatment facility located downstream of Spring Hollow and were used for the pump discharge and the local runoff. For the remaining, required constituents, constant concentrations were assumed (Table 4).

The outflow from the releases steadily increased from 2 cfs per day in the middle of February 1996 to 5 cfs per day at the end of the simulation period in September 1997. The water balance incorporated the pump inflow, local runoff, release, the pool elevation change, and a leakage term. The leakage was back calculated from the storage and other known flow terms and was treated as an outflow at an elevation of 1340 foot at the dam.

Sensitivity Analysis

In order to efficiently calibrate the model, a sensitivity analysis was completed for temperature and DO. By isolating the variables that caused changes in temperature and DO, the relative influence of each variable was estimated and ranked for later use in calibration. The sensitivity analysis spanned the entire simulation period, January 1996 to August 1997.

The sensitivity analysis for temperature was completed first. After determining the variables that had an affect on temperature, a base case was run using best guesses for the initial values of each variable. Then for each parameter, two runs were completed with either an increase or decrease of a similar amount, e.g. 50%, in that variable, while all other variables were held constant. Thus each parameter had a base case, a high case, and a low case. After all variables were tested, a table ranking and detailing the change in surface temperature, hypolimnion temperature, and epilimnion depth was created to aid in the calibration (Table 5).

The daily inputs of wind speed, solar radiation, dry bulb temperature, and dew point temperature were found to have the greatest impact on the reservoir water temperature. These input values were obtained from meteorological data taken at the Roanoke Airport and were not altered to compensate for the distance between Spring Hollow and the airport. The need for accurate meteorological data is evident judging by the impact these values had on temperature. For future modeling purposes, a weather station located at the reservoir would be valuable.

The constants that controlled temperature were the initial reservoir temperature and the parameters that affected wind speed, evaporation, and light extinction. Wind speed and evaporation played important roles in determining the heat exchanged at the surface, while light extinction determined how much heat was absorbed into the layers near the surface.

While less than 20 parameters have a possible impact on temperature, over 60 play a potential role in the prediction of DO concentration. The DO sensitivity analysis was completed in a similar manner to temperature. However, the results from the DO sensitivity analysis were not as well-defined as those obtained for temperature. For example, the observed impact of a change in a certain variable could be an increase in DO in the first year and no effect during the second year.

These differences indicated a change in reservoir characteristics from year one to year two, which was consistent with the inflow pattern – large amounts during the first part of year one and then no inflow besides runoff until the last half of year two (Fig. 10). A table similar to that created for the temperature sensitivity analysis was thus not appropriate for DO, i.e. a general statement concerning what occurred during stratification and destratification could not be made. However, a group of variables that appeared to have the greatest impact on DO was identified. These parameters consisted of variables that affected sediment oxygen demand (SOD), algal processes, and detritus and dissolved organics concentrations and decay.

SOD determined how much oxygen demand was exerted in each cell by the sediment in contact with that cell. Algal coefficients related to growth determined increases in DO, while those related to respiration and mortality affected the oxygen consumed. Variables used for detritus and dissolved organics impacted the amount and rate of oxygen consumption during decay. Also, the meteorological data had an impact on DO, but to a lesser degree than it had on temperature.

Calibration

Using the results from the sensitivity analysis, calibration of the model to field data was carried out. The field data spanned from June 3rd, 1996 to August 28th, 1997. For calibration, a subset of this period was chosen so that the remaining days could be used to verify the model. In choosing the subset, it was important that the reservoir behavior varied during the selected time. Therefore, the time from September 1996 to January 1997 was selected for calibration purposes. This time period included the months prior to destratification in February. The process of moving toward destratification allowed a number of characteristics to be matched: surface temperature decrease, surface mixed layer increase, and hypolimnetic DO depletion.

Due to the impact that temperature had on the various processes affecting DO (e.g. decay and algal growth) calibration of temperature was completed first. The method used for calibration entailed varying the most sensitivity parameters in a systematic fashion until the predicted temperature matched the observed profiles. Calibration runs were analyzed for “goodness-of-fit” by visual inspection of the predicted profiles versus the field data (Fig. 11) and by calculating the sum of squares for the residual values. The field data during the calibration period for the station closest to the dam, SH10, and the station furthest from the dam, SH40, were used for these purposes. These two stations had a total of 402 data points. The base case had a sum of squares value of 471 $°C^2$, while the best case for the temperature calibration decreased this value to 275 $°C^2$.

Some of the parameters that were calibrated to fit the temperature data also impacted the predicted DO. Therefore, the best fit values obtained for the temperature calibration were used as the base case for the DO calibration. Certain reservoir characteristics varied significantly between years one and two – filling at the beginning of year one, then no inflow except for runoff until the last half of year two (Fig. 10). These changing characteristics meant that a true calibration and verification was not possible for DO since the major factors driving the depletion of DO changed between years one and two. The more limited objective of the DO calibration was therefore to match the observed depletion in both years without the benefit of an independent data set for the verification stage. The matched time series graphs (Figs. 12-13) are discussed in the following two sections.

Verification

After calibration, the parameter values obtained (Table 6) were used to verify the model. Verification can also be thought of as confirmation that the model adequately describes reservoir behavior in order to make reasonable predictions (Butkus 1990). It is not expected that the model will fit the field data as closely for the entire simulation period as it did for the calibration subset.

The field data for the station closest to the dam, SH10, and the station furthest from the dam, SH40, were used for verification. Temperature verification occurred by plotting predicted temperature profiles versus field data profiles for various days throughout the simulation period (Figs. 14-15) and by plotting time series graphs of the predicted and actual values at various depths (Figs. 16-17). As previously stated, instead of calibrating DO to a subset of the simulation period, it was calibrated to the complete range of field data. The verification procedure employed for temperature was not applicable for DO, although time series graphs for predicted and actual DO concentrations, similar to those for temperature, are plotted for discussion purposes in Figs. 12 and 13.

Discussion

The results of the temperature and DO calibration will be discussed in this section. However, before these topics are explored, other general findings from the research that had an impact on the model's capability to simulate temperature and DO will be discussed.

General Results

Three-dimensional phenomena in two-dimensional models

In reality the dynamics of a reservoir are three-dimensional. Therefore, when a one- or two-dimensional model is used to predict water quality in a reservoir, the results represent a simplification of what actually occurs. The three-dimensional features in Spring Hollow that are lost when using the two-dimensional BETTER model include the local flow fields generated by point discharges and withdrawals.

Spring Hollow Reservoir versus typical hydropower reservoirs

The BETTER model was created to predict water quality in hydropower reservoirs. Differences exist between Spring Hollow, which is a drinking water reservoir, and the typical hydropower reservoir modeled using the BETTER model. Some of the unique features of Spring Hollow are listed below:

- Spring Hollow is steep with slopes ranging approximately from 0.15 to 0.28
- it has a point discharge as the main water source instead of upstream inflows
- instead of turbine releases or surface spillways, outflows in Spring Hollow occur as point withdrawals at four discrete locations
- since no bottom outflow exist in Spring Hollow, no bottom through-flow exists in the reservoir
- the reservoir is new and had inconsistent flow patterns during the first two years
- Spring Hollow has long residence times (up to four years depending on the inflow and outflow pattern at the time).

These differences highlighted limitations in the model's capability to represent various processes occurring in Spring Hollow and were not realized until the model had been applied to the reservoir. Some of these limitations are examined in the following sections.

Mixing and Flow

Water in the hypolimnion of a reservoir is typically characterized by constant temperature and should therefore experience some degree of mixing since no stabilizing density gradients exist. Water at the bottom-most part of the hypolimnion does not necessarily circulate to the top of the hypolimnion, but to some degree, mixing within the hypolimnion should occur as a result of the water momentum. Once the water is set in motion, it should continue moving in the same direction until a force, such as a density gradient, dam wall, or side of an impoundment, redirects it. This process should continue until the water is either withdrawn from the hypolimnion or the reservoir destratifies. When the reservoir destratifies the entire body of water mixes from top to bottom.

Spring Hollow does not have a large or constant inflow of water. When water was pumped into the reservoir, the largest amount pumped in during a single day was less than one fiftieth of the reservoir volume. The water withdrawn at the dam was more constant than the water pumped into the reservoir. However, the largest amount of outflow for a given day was much smaller comprising only one thousandth of the reservoir volume.

Since the flow of water in the model is driven by advection, the inflows and outflows have a major impact on how the model represents water movement. Due to the lack of substantial inflows or outflows, Spring Hollow did not have large amounts of water moving through it. Since the model does not include the momentum term when determining flow patterns, the water that is located away from the inflows and outflows has no driving force moving it. The model therefore treats this water as stagnant, when the water should experience some degree of mixing.

Temperature and Dissolved Oxygen Results

Temperature

The predicted temperatures closely match the observed temperatures (Figs. 14-17). Spring Hollow is a warm monomictic reservoir in that it is stratified during the summer months and mixes during the winter months. The model accurately predicted the onset of thermal stratification in the spring and thermal destratification or turnover in the winter. The model also captured the deepening of the surface mixed layer, although the slope of the thermocline and the temperatures at the point sources and releases (Figs. 11 and 14) were not accurately matched.

The thermocline in Spring Hollow has a gradual transition between the epilimnion and the hypolimnion. It is thought that the gradual thermocline seen in the reservoir is partly due to the influent water. In reality, if the influent water is warmer than the surrounding water at the discharge level (1300 foot), then it will migrate toward the surface to an elevation of equal temperature and density. During this movement upward, it is speculated that heat transfer will occur between the warmer influent water and the surrounding water either by convective cooling or by an entrainment-detrainment process. This exchange of heat could cause a gradual temperature transition between the deeper water and the surface water.

The BETTER model inserts the influent water into the layer at the discharge elevation. This water is instantaneously mixed together. If the new layer temperature causes density instability, i.e. is warmer or cooler than the layers above or below it, then the appropriate surrounding layer will be mixed with it. This process of checking density instability and instantaneous mixing will continue until stability is met. Since the inflow to Spring Hollow is small relative to the water volume, it does not cause a large temperature or density difference between layers, and if it does, then mixing with a few of the surrounding layers will re-establish density stability quickly. Therefore, the influent water did not have a great effect on the thermocline in the model.

The gradual thermocline in the reservoir could also be attributed to dispersion since there is not a large advective force, such as a tributary inflow, driving the flow of water. In reality, due to the lack of advective movement, it is assumed that solar radiation had more opportunity to penetrate deeper and warm the water to greater depths. An explanation for why the model was not able to capture this phenomenon is because water mixing in the model is handled via advection instead of diffusion.

The area around the outlets also caused difficulty for the model. The model has variables that determine the withdrawal zone for turbine releases and the inflow placement; however, no similar variables exist to determine vertical spread for point sources or releases. To simulate the vertical spread of releases, each withdrawal gate was divided into four smaller withdrawals located at different elevations next to the actual release elevation. This modification allowed the model to extract water from more than one layer, and thus, reduced the effect of releases, which was to increase the temperature and decrease the DO in the layer of withdrawal. An attempt to vertically spread the discharge into the reservoir did not improve the temperature or DO simulation. Therefore, the pump discharge remained at 1300 foot, which caused a slight increase in temperature at that elevation (Fig. 11 and 14).

Dissolved Oxygen

Unlike temperature, the predicted DO concentrations did not accurately match the field observations. In the first year, the pattern matched in that the model predicted a gradual hypolimnetic decline in DO similar to that observed in the field. A deepening of the epilimnion was also predicted in a similar manner to what actually happened. Also, the timing for predicted turnover coincided with field data. However, problems arose when comparing the predicted DO with the field data for the second year.

The differences in the predicted values for the first and second years could be caused by the inconsistent inflow pattern in Spring Hollow (Fig. 10) and the model's limitation to accumulate settled organic material. The average inflow for the first 162 days of model simulation was 22 cfs per day. After day 162, the only inflow to the reservoir was local runoff, which averaged 1.2 cfs per day, with an occasional storm event. Not until day 450 did the reservoir receive pump discharge water from the river again, and this flow only averaged 5 cfs per day. The sensitivity analysis indicated that the inflow from the pump discharge and the SOD had the largest effects on DO. Since the quantity and timing of pump discharge into the reservoir were known, and the concentration of oxygen consuming constituents in the influent water was not available, the SOD became the main variable to alter.

In the model, a SOD value of 2.0 was used in columns 1 and 2, the columns closest to the dam, a SOD value of 1.0 was used for column 3, and a SOD value of 0.5 was used for column 4, the most upstream column (Table 6). This spatial variation was adopted because the majority of the inflow entered the reservoir halfway through column 3. It is thought that the majority of the water then traveled toward the dam, passing through columns 2 and 1 before reaching the outlet. Therefore, a greater amount of detritus would have settled to the bottom in columns 1 and 2, than in 3 which in turn had more settled detritus than column 4.

Since the model uses a constant SOD for each segment and ignores accumulation of settled organic material at the bottom, the organic material that settles out in the first year was not added to the SOD for the second year. It is therefore thought that the SOD could have been changing over time due to the inconsistent inflow patterns. To simulate this potential variation, the model's computer code was altered to include a multiplication factor for the SOD value. During the first year, the multiplication factor was increased linearly from zero to one, which caused the modeled DO depletion to occur slower. At the beginning of the second year the multiplication factor started at two and decreased linearly to a value of one, which allowed for DO depletion to begin when the reservoir began to stratify again.

The spatial and temporal variation of SOD yielded DO patterns that were similar to those observed in the field (Figs 12-13). Although no evidence could be found to support the claim that SOD increases linearly in the first year and decreases linearly in the second year, the following speculative reasons are advanced: Spring Hollow was a new reservoir and had large inflows until June of the first year. Thus, increasing amounts of organic material were being introduced into the reservoir where they had time to settle and accumulate in the sediment. Organics in the sediment could also accumulate from the death, settling, and subsequent decay of algae. This increasing amount of organic material in the sediment could justify the increase in SOD over time during the first year. For the second year, it is thought that the settled detritus from the first year added to the SOD for the second year. However, the effect of the previous year's settled detritus would decrease over time, and therefore SOD decreased as the second year progressed.

Conclusion

Reservoir modeling can be an important tool for making water resource management decisions. Despite some structural limitations, the BETTER model provided useful insight into the characteristics of Spring Hollow Reservoir. The influent water flow rate and detritus and dissolved organics concentrations appear to have a major impact on the amount and rate of DO depletion. The water quality of the Roanoke River therefore dictates to a considerable degree the conditions found in the reservoir. For optimal water quality conditions in the reservoir, a monitoring system in the Roanoke River should be installed with filling carried out when water quality in the river is optimal. Due concern would still have to be given to meeting the volumetric flow requirements for storage. The sediment oxygen demand also appears to have a substantial effect on DO and should be monitored more closely in the future.

This research also provided information on possible improvements for modeling Spring Hollow. From the sensitivity analysis, the meteorological data was shown to greatly influence both temperature and DO patterns. A weather station located at the reservoir would permit collection of more accurate values of the forcing variables, leading to greater confidence in the interpretation of the model predictions. Another aspect to keep in mind concerns monitoring programs. Ideally, sampling spanning at least two complete years would have been best. This would have allowed the calibration to be completed using data collected during one year and verification to be performed with data from the other.

The BETTER model has been used in the past to simulate the water quality and the impact of various management techniques in hydropower reservoirs. However, in applying the model to Spring Hollow, a drinking water reservoir, some structural limitations of the model were found. For reservoirs such as Spring Hollow where through-flow is not the driving force for mixing, a model that employs the momentum equation might result in greater hydrodynamic accuracy. Also, the point sources and releases might have been more accurately represented using a model designed to capture these features.

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Appendices

1. Field data (including water quality data recorded by the Sonde and collected using the kemmerer) for 50 days spanning from March 1996 to September 1997.
2. Withdrawal data for Spring Hollow Reservoir from June 1996 to September 1997.
3. Data for the pump discharge into Spring Hollow Reservoir from January 1996 to June 1996 and from March 1997 to September 1997.
4. Roanoke River water quality data on pumping days.
5. Roanoke airport meteorological data from January 1996 to September 1997.
6. Streamflow data for Roanoke River at Lafayette, VA.
7. Table of geometry used (surface area, conveyance area, and volume).
8. Graphs for DO sensitivity analysis.
9. Graphs for various temperature and DO calibration runs.
10. Fortran program used to determine sum of squares value used in calibration stage.
11. Charts of parameter values used and corresponding sum of squares value for temperature and DO calibration runs .
12. BETTER fortran code and required files.
13. Input geometry file.
14. Fortran code used to create the input inflow file.
15. Files used to create the input inflow file.
16. Input inflow file.
17. Plotting package files.
18. BETTER fortran code with first attempt of coupling bubble plume model.
19. Input files and code related to coupled model.