Effects of the Addition of Multi-Slip Docks On Reservoir Flushing and Water Quality: Hydrodynamic Modeling; Aquatic Impact; Regulatory Limits

John E. Edinger, *Consultant in Environmental Hydrology, 63 Crestline Rd., Wayne, PA 19087. E-mail: jeedgr@aol.com (Corresponding Author)*

James L. Martin, *Professor, Department of Civil and Environmental Engineering, Mississippi State University, P.O. Box 9546, Mississippi State, MS 39762. E-mail: jmartin@cee.msstate.edu*

Abstract: *Numerous multi-slip docking facilities are planned for placement along the shoreline of Tims Ford Reservoir located on the Elk River in south central Tennessee, USA. These multi-slip docking facilities will occupy different kinds of shoreline configurations including coves, mouths of small tributaries, and other regions of limited flushing. Placement of the multi-slip docking facilities will limit the amount of local flushing that will take place in the vicinity of the multi-slip docking structures. Very few of the multi-slip docking facilities have been built to date, therefore comparative simulations of flushing need to be performed for conditions without and with the proposed multi-slip docking structures. This report describes the results of comparative simulations using computational hydrodynamic and transport models. The analysis shows that there will be reduced flushing in over 92% of the proposed multi-slip docking locations. The reduction in flushing will worsen water quality conditions. The analysis and results of flushing estimates are compared to flushing guidelines used by some US State regulatory agencies and international guidelines used by ANZECC (2000).*

The comparative analysis of flushing allows evaluation of the changes in water quality including coliforms, dissolved oxygen, algal densities and sedimentation that will take place along the shoreline and in the vicinity of the multi-slip docking facilities. The magnitude of the probable changes due to construction of the multi-slip docking facilities for coliforms, dissolved oxygen and algal densities is greater than the seasonal changes in these water quality constituents as observed over the years in Tims Ford Reservoir. In addition, flushing and the changes in algal densities could be compared to the ANZECC (2000, Sec. 8.1.9.1) algal growth guideline. The change in water quality will not be limited to the multi-slip docking areas alone. Many of the local changes that will take place at the individual multi-slip docking facilities will affect water quality throughout 67% of the area of the reservoir. In particular the increased algal densities will generate seed for spores and cysts that will spread throughout the reservoir by attachment to sediment and decaying algae. The increase in benthic spores and cysts will increase the likelihood of the occurrence of algal blooms in the years following construction of the multi-slip docking facilities.

Key Words: Water resources, marinas, mathematical models, sitting regulations, aquatic impacts, environmental studies.

1. Introduction

The construction of multi-slip docking facilities typically results in an increase of local flushing time with consequent impacts on water quality both around the facility and potentially in adjacent ambient waters. The design of such facilities should include minimization of pollution sources and maximization of flushing (Brown 1993). An assessment the impacts of multi-slip docking facilities on flushing and water quality is often required prior to construction, such as to obtain state water quality certification required by Section 401 of the US EPA Clean Water Act. A water quality certification is the mechanism by which the State evaluates whether an activity may proceed and meet water quality standards. For example, prior to Massachusetts Office of Coastal Zone Management approval of marina projects under the law (Massachusetts OCZM 2001), it is expected that design considerations include marina flushing, water quality, habitat, and shoreline stream bank stabilization. The Delaware Department of Natural Resources and Environmental Control (DNREC 2006) requires that applicants for new marinas or expansions of existing marinas provide a

"documented and valid assessment of the potential water quality impacts of the design, construction, and operation of the proposed marina, specifically, the assessment must explicitly address faecal coliform and dissolved oxygen surface water quality standards,"

based on appropriate modelling, monitoring, and data analysis. In Florida, the St. John's River Water Management District (SJRWMD), in order to provide reasonable assurance that water quality standards will not be violated, requires data or hydrographic studies to document the flushing time of the water at the docking facility and generally requires a flushing time of less than or equal to four days. As an additional water quality consideration for docking facilities (>10 slips), the SJRWMD guidance for assessment of flushing recommends reducing a test dye concentration to 10% of the initial value in 4 days for a dye test carried out at an individual marina. Although methodologies and specific regulations vary, the need to examine marina flushing has been the rule, rather than the exception, in State water quality regulations for over 20 years. Internationally, the ANZECC (2000, Sec. 8.1.9.1) guideline specifically requires that flushing times be less than the doubling time of algal densities.

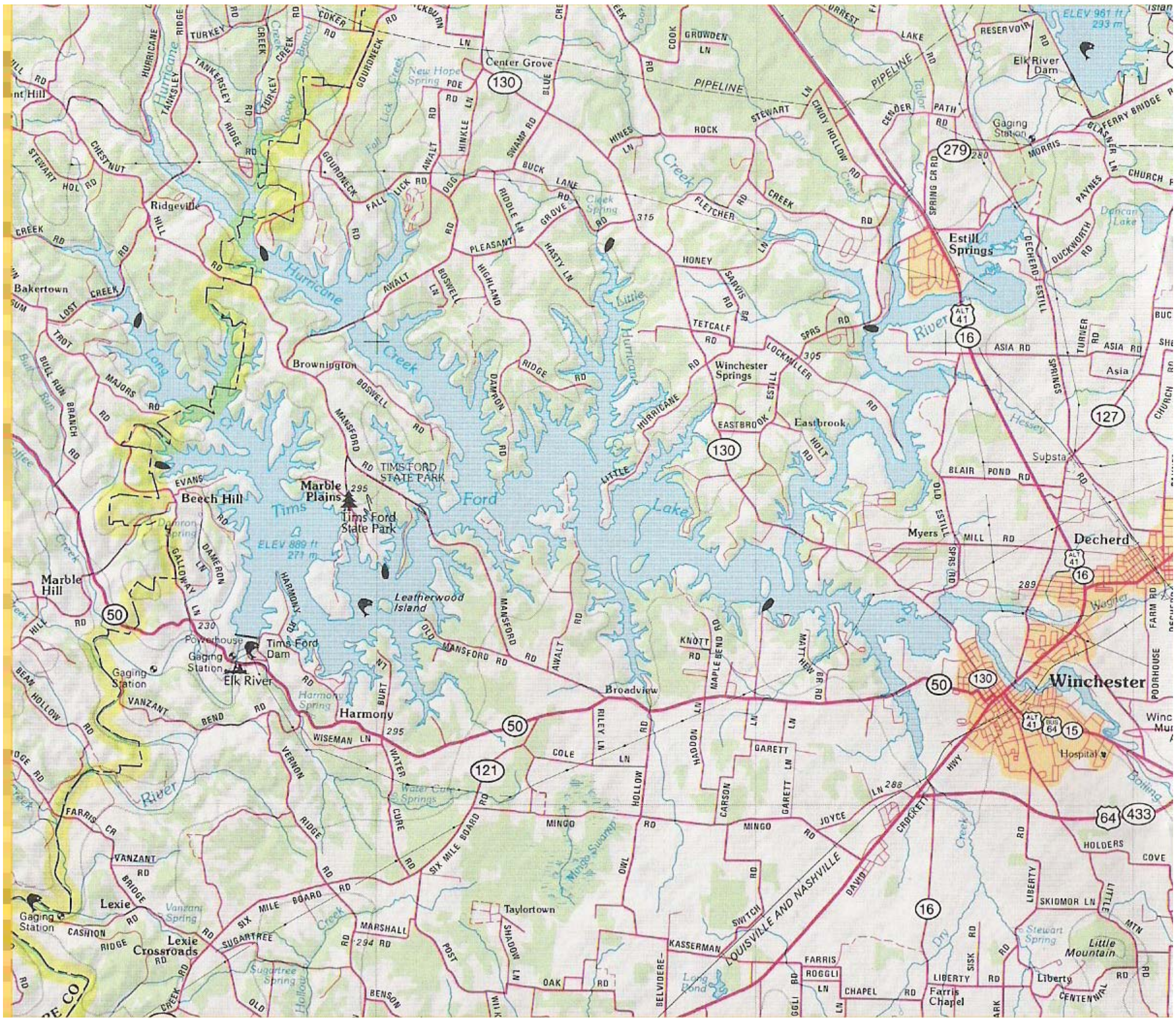
Evaluation of the flushing time and water quality impacts of docking facilities may be estimated using data and or models. Comparative model studies are performed where there is little or no data available to carry out fully parameterized water quality modelling, such as in the analysis of new or proposed docking facilities. Generally, a comparative study evaluates the effect of a perturbation by comparing the results of model simulations with and without the perturbation imposed. Comparative studies may form the basis for permit decisions and used in litigation. For example, comparative analyses were used in an arbitration case between a power buyer and supplier where power plant operations were limited by water quality conditions (Edinger 2004). Comparative analyses also were part of two recent successful water quality issue proceedings concerning Gulf Island Reservoir and Dam on the Androscoggin River in Maine (Edinger 2005, Edinger 2007).

In this paper a comparative study is presented of the impacts of 41 multi-slip docking facilities planned for placement along the shoreline of Tims Ford Reservoir located on the Elk River in south central Tennessee shown on Map 1. The proposed multi-slip docking facilities are relatively evenly spaced along the shoreline of the reservoir and will occupy different kinds of shoreline configurations including coves, mouths of small tributaries, and other regions of limited flushing. The study compares the flushing rates from the overall Tims Ford water body and at individual shoreline locations by running simulations using a three-dimensional hydrodynamic and transport model without the shoreline multi-slip docking facilities, and comparing the results against simulations that included the shoreline multi-slip docking facilities. Methods for the evaluation of flushing time and water quality impacts are presented.

2. Methods

2.1 Hydrodynamic Model

The time-varying three-dimensional hydrodynamic and transport model applied in this study was



Map 1. *Tims Ford Reservoir configuration showing main inflow and major tributary arms.*

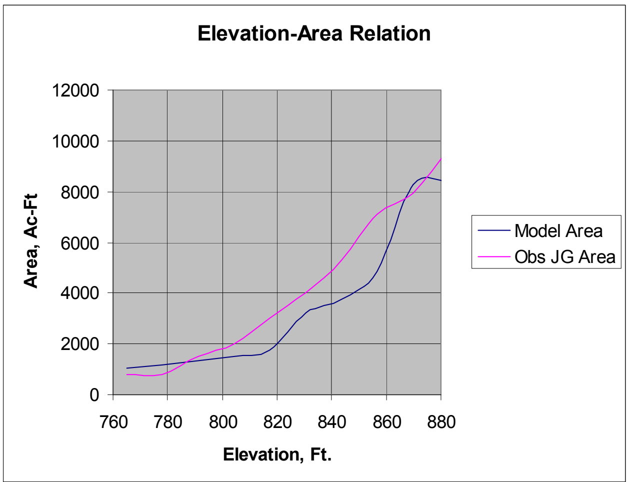
GLLVHT (the Generalized Longitudinal, Lateral, and Vertical Hydrodynamic and Transport model) as presented in Edinger (2002). This model was originally developed by Edinger and Buchak (1980, 1985). Details of the formulation of the GLLVHT model are given in Edinger and Buchak (1995). The model includes horizontal and vertical momentum, the barotropic and baroclinic components of the horizontal pressure gradient, vertical shear, constituent transport and an equation of state. All of the dispersion coefficients used in the model are internally computed from known relationships. GLLVHT is a finite difference model that uses an implicit solution technique. The implicit solution technique allows large computational time steps on the order of minutes. This efficiency permits the computations to be done on ordinary personal computers. The application of GLLVHT is described in Edinger (2002) and Martin et al. (2006). GLLVHT was applied using the bathymetry and inflows to Tims Ford Reservoir.

2.1.1 Tims Ford Reservoir Model Bathymetry

The bathymetry or water depths throughout Tims Ford Reservoir were evaluated by Gordon (1974). Using maps available at that time, the reservoir hypsographs were developed to give the planar area of the reservoir at each elevation from the lowest depth in the reservoir to the normal maximum operating elevation of 888 feet above sea-level. The surface area at the maximum normal operating surface elevation was found to be 10,600 acres. The area-elevation was then integrated vertically to give the cumulative reservoir volume at each elevation from the lowest elevation point on the reservoir floor up to the maximum normal operating elevation. The reservoir volume at the maximum normal operating surface was found to be 530,000 acre-feet.

The three-dimensional bathymetric grid required by the hydrodynamic and transport model (Edinger 2002) was derived from a number of sources. The shoreline of the reservoir at the maximum normal operating elevation was developed from the map presented in Gordon (1974) and the few elevations given with it. The rest of the model grid bathymetry was developed from the "Tims Ford Lake Recreation and Fishing Guide with Topography."

The resulting three-dimensional bathymetric grid consisted of 1,028 surface cells, and a total of 7,203 volume cells. The grid resolution was 200 by 200 meters with two meter thick layers. The model grid hypsographs of planar elevation versus reservoir elevation and cumulative volume versus reservoir elevation are compared to the hypsographic data presented in Gordon (1974) in Figure 1. It is seen that the three-dimensional model grid hypsographs conform favorably to those presented in Gordon (1974).



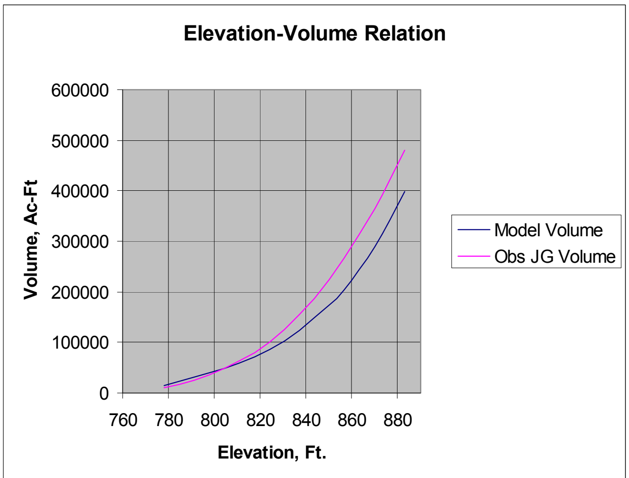


Figure 1. *Comparison of Model Digital Bathymetric Hypsographs with TVA Data*

2.1.2 Tims Ford Inflow Rates

Tims Ford Reservoir was evaluated by Dycus and others (1999) for aquatic health and water quality conditions. For that study, the reservoir was evaluated at a surface area of 10,600 acres, a mean annual inflow rate of 980 cubic feet per second (cfs) and an overall reservoir hydraulic residence time of 270 days. The mean annual inflow and the hydraulic residence time give a volume of 525,000 acre-feet. The surface area and volume of the reservoir from Dycus and others (1999) agree favourably with those provided by Gordon (1974) and to those computed from the three-dimensional model grid. Gordon (1974) gives the total drainage area into Tims Ford Reservoir of 529 square miles which gives an inflow of 1.85 cfs/mi^2 for the mean annual flow.

For three-dimensional modelling of Tims Ford Reservoir, the total inflow rate given in Dycus and others (1999) needed to be apportioned among its major Elk River inflow and the major tributary arms of the reservoir. As shown by Gordon (1974) the Tims Ford Reservoir main inflow is the Elk River below Woods Reservoir which is at the northeastern corner of Map 1. The area drained via the Elk River into Tims Ford Reservoir is 263 square miles. This leaves 266 square miles of drainage area to be distributed among the other reservoir tributaries. The reservoir has two large tributary arms: Lost Creek and Hurricane Creek. It has three smaller tributary arms of interest in the multi-slip docking facility study: Little Hurricane Creek, Winchester Creek and Boiling Springs Creek. From the map provided in Gordon (1974) Lost Creek and Hurricane Creek each appear to occupy 25% of the remaining drainage area of 266 square miles. The three smaller tributary arms each appear to occupy 16.6% of the remaining drainage area. The resulting drainage areas and mean annual inflow rates for each of the inflows to Tims Ford Reservoir at 1.85 cfs/mi^2 are therefore apportioned as shown in Table 1. The totals in Table 1 differ slightly from those in the references due to rounding the proportion of drainage area to each of the inflows.

The three dimensional hydrodynamic and transport model (Edinger 2002) requires an initial temperature profile to represent thermal stratification and

***Table 1** Tims Ford Inflow Drainage Areas and Flows*

Inflow	*DA, Mi2*	*Inflow, cfs*	*Inflow m3/s*
Elk River	263.0	486.6	13.8
Lost Cr.	66.5	123.0	3.5
Hurricane Cr.	66.5	123.0	3.5
Little Hurr. Cr.	44.2	81.8	2.3
Winchester Cr.	44.2	81.8	2.3
Boiling Spr. Cr.	44.2	81.8	2.3
Totals	528.6	978.0	27.7

inflow temperatures. Dycus and others (1999) give in their Appendix B diagrams of the seasonal temperature isopleths for the vertical distribution of temperature at Elk River Dam shown on the southern edge of Map 1. It shows very little variation in temperature stratification from early June through mid-September. The three-dimensional model is initialized for the temperature profiles for Tims Ford given in Dycus et al. (1999). The river inflow temperatures were set at the surface temperatures in the model so that there will be little change in temperature over the sixty day simulation period.

2.1.3 Multi-Slip Docking Area Representation
The three dimensional model in Edinger (2002) was applied to simulate detailed reservoir flow patterns first without representation of multi-slip docking structures and then with a representation of the multi-slip docking structures and the shoreline region encompassing them. Multi-slip docking structures are represented in the model as extensions from the shorelines that behave as partial barriers to flow. The vertical extent of the shoreline extension to represent dock structures requires evaluation to determine their effects on flushing and water quality. The US Army Corps of Engineers report, "Engineering and Design - Environmental Engineering for Small Boat Basins" (Brown 1993) presented an early evaluation of the processes involved. It outlined the factors affecting water quality that should be included when developing permitting procedures for small boat docks and basins. The report shows that almost any small boat dock has related to it, or in effect creates, some type of natural or man-made cove, basin or backwater tributary.

Multi-slip dock structures were examined and members of the Coastal Modeling Experts list maintained by the University of Delaware were asked to assess the problem. Donohue (2007) stated based on his experience that:

"Most multi-slip docking facility docks float with less than 12 inches of draft. There are usually underwater structures like stiffening truss work and fairleads that may extend 6 to 8 feet below the water line depending on the dock size. The only other environmental problems some attribute to docks is the inhibition of wind driven surface flows and the flushing of waters in a slough or cove. The reality of the latter is more related to individual circumstances than some sort of general rule or certainty."

The key elements here are that the effective hydraulic interference of a multi-slip docking facility depends upon: (1) the underwater structures beneath it; (2) the structure's location in a slough or cove; and (3) individual site circumstances rather than a general rule. The use of the three-dimensional hydrodynamic and transport modelling is designed to take care of items (2) and (3), and as indicated there will be interference with flow to more than just the draft of the floating dock.

Most of the 41 docks were at least the length of a 200 meter grid cell and were spaced more than a grid cell apart along the shoreline on Map 1. The three-dimensional model vertical layer thickness was set at 2 meters and the shoreline extensions representing the multi-slip dock sides was also set for a depth of 2 meters with a fraction of the surface layer flows toward or away from the shoreline extensions deflected as allowed in the model formulation (Edinger 2002, Sec. 2.1.11).

2.2 Dye Simulations
Each volume cell in the three dimensional model was initialized with a "virtual dye" concentration of 1,000 ppb. No dye was included in the inflows; hence the dye concentration in each volume cell will decrease over the simulation period due to the un-dyed inflows and the resulting circulation through the reservoir. The output of the model was set to obtain the dye concentration in each of the

cells where the multi-slip docking facilities will be located. The simulation was first run without the multi-slip docks in place. A second simulation was then conducted with the multi-slip docks in place. Both runs simulated a 60 day period of stratified summertime water conditions.

2.3 Estimation of Flushing Rates

A theoretical estimation of reservoir flushing time can be computed for comparison with model predictions. The flushing rate may be computed from time requirements to remove a dye from a specified volume of the reservoir. For a reservoir with a fixed inflow and outflow rate, Q_r, and volume V_r, the average rate of change in dye concentration (C) will be:

$$V_r \frac{dC}{dt} = -Q_r C \qquad 1$$

from which it is expected that the decrease in average dye concentration at the end of the simulation time (T_{sim}) would be:

$$C(T_{sim}) = C_o * \exp\left[-\frac{Q_r}{V_r} T_{sim}\right] \qquad 2$$

where C_o is the initial virtual dye concentration. A flushing rate can also be defined as $K_r = Q_r/V_r$.

2.4 Individual Model Flushing Rates and Times

A flushing rate, K_{nd}, can also be defined for individual cells within the reservoir where $C_{nd}(T_{sim})$ is the dye concentration at the end of the simulation for that individual cell. Here K_{nd} is the flushing rate with no model shoreline extensions representing multi-slip docking facilities. The individual cell flushing rate can be computed as:

$$K_{nd} = -\frac{Ln\left(\frac{C_{nd}(T_{sim})}{C_o}\right)}{T_{sim}} \qquad 3$$

If V_{dk} is the volume of the model cell containing the multi-slip docking facility, a flow rate (Q_{nd}) can be estimated for that model cell as:

$$Q_{nd} = K_{nd} V_{dk} \qquad 4$$

If shoreline extensions are placed around one or two of the model cells containing the multi-slip docking facility and its embayment and the dye simulation is re-run to obtain the dye concentration with the multi slip docking facilities at the end of simulation $C_{wd}(T_{sim})$, then similar relationships apply giving:

$$K_{wd} = -\frac{Ln\left(\frac{C_{wd}(T_{sim})}{C_o}\right)}{T_{sim}} \qquad 5$$

and for a flow rate with multi-slip docking facilities (Q_{wd}):

$$Q_{wd} = K_{wd} V_{dk} \qquad 6$$

2.5 Estimating Changes in Water Quality

The numerous fisheries, biological and water quality studies carried out on Tims Ford Reservoir, including Butkus (1990), Dycus, et al (1992), Dycus and Meinert (1992), Fehring (1993), Meinert and Dycus (1993), Fehring and Meinert (1993), Scoff, et al (1996), Dycus and Meinert (1998) and Dycus (1999), were based on examining one or more of the following water quality parameters: coliform, dissolved oxygen, phytoplankton, and sediments. The effects of multi-slip docking facilities and changes in local circulation on each of these water quality parameters can be studied using the changes in flow rates and flushing through the multi-slip docking regions. The changes in water quality can be determined from simple difference computations without running extensive simulations beyond those performed for the flushing rates in the multi-slip docking regions. The water quality difference computations without and with multi-slip docking regions are based on the water quality models given in Edinger (2002) that were derived from numerous other water quality studies.

2.5.1 Simple First Order Decay Relation for Coliforms

The water quality change for a simple first order decay relation, for example, coliforms, can be derived from a constituent balance for a cell whose flows were determined from the dye simulation formulations used to derive Equation 4 and Equation 6 respectively. The constituent balance can be written by determining the amount of material flowing out of the cell from the amount flowing into it minus that lost by first order decay. The constituent balance with no multi-slip docking facilities would be:

$$Q_{nd} C_{nd} = Q_{nd} C_{oo} - R_d V_{dk} C_{nd} \quad 7$$

where C_{nd} is the constituent concentration with no multi-slip docking facilities flushing out of the model cell, C_{oo} would be the background of the constituent concentration entering the multi-slip docking facility area from off shore and R_d is the constituent decay rate (coliform dye-off for example). Note that when dividing through by the volume, V_{dk}, the balance can be written more conveniently as:

$$C_{nd} = \frac{K_{nd}}{K_{nd} + R_d} C_{oo}$$

$$C_{wd} = \frac{K_{wd}}{K_{wd} + R_d} C_{oo}$$

$$K_{nd} C_{nd} = K_{nd} C_{oo} - R_d C_{nd} \quad 8$$

giving:

$$\frac{(C_{wd} - C_{nd})}{C_{nd}} = \frac{\left[\left(\frac{K_{wd}}{K_{wd} + R_d}\right) - \left(\frac{K_{nd}}{K_{nd} + R_d}\right)\right]}{\left(\frac{K_{nd}}{K_{nd} + R_d}\right)} \quad 9$$

Similarly, with multi-slip docking facilities, the constituent concentration becomes:

10

and the difference with docks in comparison to without docks becomes:

11

This comparison conveniently eliminates the arbitrary C_{oo} and for descriptive purposes can be expressed as a percentage. First order decay rates for many water quality constituents including coliforms are given in Edinger (2002; Table 10-1).

2.5.2 Effects on Dissolved Oxygen

The change in dissolved oxygen without and with multi-slip docking facilities can best be evaluated using the dissolved oxygen deficit (DOD) which is the depression of dissolved oxygen below saturation at a given water temperature. Its evaluation requires first formulating the biochemical demand (BOD) and then using that demand as one process in the dissolved oxygen deficit balance along with the flux of DOD and its re-aeration from the surface (Edinger,2002; Ch. 12).

$$BOD_{nd} = K_{nd} \frac{BOD_{oo}}{(K_{nd} + R_{bod})}$$

Without multi-slip docking facilities in place, the BOD relationship would be:

$$K_{nd} BOD_{nd} = K_{nd} BOD_{oo} - R_{bod} BOD_{nd} \quad 12$$

$$DOD_{nd} = \frac{R_{bod} K_{nd}}{(K_{nd} + R_{bod})(K_{nd} + R_{re})} BOD_{00}$$

where R_{bod} is the rate of BOD decay and BOD_{oo} is the background BOD. This relationship gives:

$$DOD_{wd} = \frac{R_{bod} K_{wd}}{(K_{wd} + R_{bod})(K_{wd} + R_{re})} BOD_{00} \quad 13$$

The DOD relationship would be:

$$K_{nd} DOD_{nd} = K_{nd} DOD_{oo} + R_{bod} BOD_{nd} - R_{re} DOD_{nd} \quad 14$$

$$\text{Fraction change in Dissolved oxygen} = \frac{(DOD_{wd} - DOD_{nd})}{DOD_{nd}}$$

where R_{re} is the surface re-aeration rate. The dissolved oxygen depression is in addition to any background dissolved oxygen depression below saturation that exists in the reservoir, and hence DOD_{oo} can be set to zero. Substituting from Equation 14 for BOD_{nd} gives the relationship for DOD_{nd} of:

15

Similarly, the relationship for DOD with docks can be written as:

16

Each of these could be evaluated separately for a unit value of BOD_{oo} (ie, $BOD_{oo} = 1.0$) to give the change in DOD from the no dock case to the case with multi-slip docking facilities as:

17

Note that if Equation 17 and Equation 16 were placed into Equation 15, the background BOD_{oo} would be eliminated.

2.5.3 Potential Aquatic Plant, Slime and Algal Density Change Due to Flushing Rates

Dock shading is known to affect shoreline plant growth (Sanger and Holland 2002). This becomes an important factor when trying to maintain existing shoreline grasses, or to build up valuable shoreline vegetation for erosion protection, fish spawning habitat, and ascetic attraction. The amount of shading and a possible assessment of its effect on plant growth can be evaluated from the orientation of the dock facilities to the sun and the extent of the shading footprint.

The underwater structural features of floating docks as well as boats kept within the water provide extensive surface area for the growth of slimes and attached algae. The seriousness of this problem can be judged by how quickly a boat bottom will foul up before it requires vigorous cleaning, or the extent to which complex docks with boat lifts are used. The growth of slimes on underwater structural features of a dock and algal growths can be evaluated on a comparative basis from the fundamental relationships governing the growth of algae.

Algal densities along with their dissolved oxygen production and respiration vary hourly, daily and seasonally and are very difficult to characterize over a full summer season. A characterization of algal carrying capacity of lakes and reservoirs was developed by Reynolds and Marbely (2002). Their evaluation requires knowing the seasonal inflow rate of nitrogen and phosphorous nutrients and the seasonal inflow rate to the water body. It also allows examining the effects of varying mineral and light conditions. Their evaluation applies to the whole reservoir and it is doubtful that it could be used to determine the effects of changes in flushing rates through a volume of the reservoir surrounding a docking facility. Additionally, the detailed nutrient inflow data required is often unavailable.

$$\frac{dC_p}{dt} = \left[G_p(N,P,I) - D_d - D_r\right] * C_p - K_{dg} * C_p^2$$

Density dependent grazing is used in the evaluation of aquatic vegetation growth and decay (Gentleman et al 2000). It is now being recognized that algal blooms and similar rapid growth of other aquatic biota is more related to cysts and spores in sediments and attached to water contact surfaces (McGillicuddy et al 2003). The bloom mechanisms have been incorporated into combined hydrodynamic and water quality numerical modelling (Edinger et al, 2003).

It is possible to reduce the relationships given in Edinger et al (2003) describing the temporal variations in algal densities to a long term steady-state estimate by examining the balance between algal growth and zooplankton grazing using the time varying algal relationship of:

$$K_{nd}*C_{pnd} = K_{nd}*C_{poo} + K_{phy}*C_{pnd} - K_{dg}*C_{pnd}^2$$

$$K_{dg}*C_{pnd}^2 + (K_{nd} - K_{phy})*C_{pnd} - K_{nd}*C_{poo} = 0$$

$$K_{dg}*C_{pwd}^2 + (K_{wd} - K_{phy})*C_{pwd} - K_{wd}*C_{poo} = 0$$

18

where $G_p(N,P,I)$ = The phytoplankton growth rate as limited by concentrations of nitrogen and phosphorous constituents and by light, D_d = The phytoplankton death rate, D_r = The phytoplankton respiration rate, K_{dg} = zooplankton density dependent grazing rate.

$$C_{pnd} \frac{\left[-(K_{nd} - K_{phy}) + ((K_{nd} - K_{phy})2 + 4K_{nd}*K_{dg}*C_{poo})\right]}{2K_{dg}}$$

The $G_p(N,P,I)$ can be evaluated more simply by algal growth rates and death rates over a long period of time as given in Edinger (2002; Table 13-3). Letting

$$K_{phy} = [Gp(N,P,I) - D_d - D_r] \qquad 19$$

then the algae transported through a multi-slip docking location with no facility in place is described as:

20

or

$$C_{poo} = \frac{K_{phy}}{K_{dg}} \qquad 21$$

and with multi-slip docking facilities:

22

In order to determine the difference in algal densities in the multi-slip docking areas, it is necessary to have an estimate of background algal density C_{poo} through the season and first evaluate Equation 21 and Equation 22 separately for C_{pnd} and C_{pwd}. The advantage of this approach is that all the rate processes of flushing, algal kinetics and density dependent grazing are included.

The solution to the quadratic Equations 21 and 22 is:

23

and a similar solution can be written for C_{pwd}.

The C_{poo}, or background algal density at a location without docks can be considered a "carrying capacity" value based on the algal density rate processes similar to the phytoplankton carrying capacity developed by Reynolds and Marbely (2002) based on nutrient loadings for the whole lake or reservoir. A good definition would be the C_{poo} resulting from the algal rate parameters alone with no flushing as background. From Equation 22 or Equation 23 with K_{nd} or K_{wd} set to zero, it would be evaluated from either C_{pwd} or C_{pnd} as:

$$C_{swd} - C_{snd} = \left[\frac{K_{wd}}{(K_{wd} + R_v)} - \frac{K_{nd}}{(K_{nd} + R_v)}\right] C_{soo} \qquad 24$$

which is the C_{poo} that results from the balance between algal growth and zooplankton grazing. It is sufficient to allow determining the change in algal density without and with multi-slip docking facilities as $(C_{pwd} - C_{pnd})/C_{pnd}$ similar to that used in the other water quality relationships. Almost any algal like slime that attaches to multi-slip docking understructure will be limited by a balance between growth rate and grazing. It is

$$\text{Diff. in settling rate } (kg/m^2/yr) = (C_{swd} - C_{snd}) * V_s (m/yr)$$

when this balance is upset that additional seed for spores and cysts get spread throughout the reservoir and trapped into the sediment to become the source for vegetative cellular material which generates algal blooms (McGillicuddy et al. 2003, Edinger et al. 2003).

2.5.4 Application to Changes in Sedimentation

The simple first order decay can be used to approximate the change in bottom sediment concentration under a multi-slip docking facility by defining the first order decay rate as $R_v = V_s/D_{dk}$ where V_s is the settling rate for the chosen sediment size and D_{dk} is the water depth at the multi-slip docking facility location. The sediment analysis can be performed over a range of expected sediment sizes using Stokes law to determine settling velocity. The change in the amount settled for each sediment size will vary depending on the flushing rates without and with the docks.

From the simple first order relation for coliforms, the difference in sediment concentrations within the multi-slip docking regions would be:

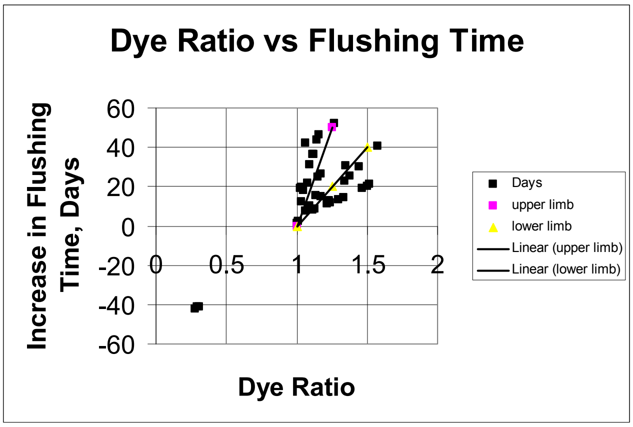


***Figure 2.** Relationships between Cwd/Cnd Ratio and Change in Flushing Time with Two Limbs*

25

The C_{soo} for reservoir suspended and settling sediment typically is of the order of magnitude of 1.5 kg/m^3 and using this as a background value, the difference in sedimentation rates through the multi-slip docking regions with and without the facilities can be estimated as:

26

3. Results and Discussion

3.1 Hydrodynamic Simulation

The dye flushing results determined with the hydrodynamic simulations are that the final dye concentrations with the multi-slip docking facility is higher than without them at 38 of the 41 proposed multi-slip docking facility locations included in the model. The ratio of the final dye concentration in the simulations with docks to that without docks (C_{wd}/C_{nd}) quantifies the degree to which a particular dock structure alters the circulation. When this ratio is greater than unity there will probably be a decrease in water quality at the multi-slip docking facility location due to reduced flushing around the docks, and the greater the ratio the greater the potential water quality problems. Figure 2 shows values of the C_{wd}/C_{nd} ratio are greater than one (i.e., flushing is reduced by docks) for over 92% of the planned multi-slip docking facility locations.

Changes in water quality in the multi-slip docking regions would also affect water quality throughout the remainder of the lake. The relationship between the dye ratio, C_{wd}/C_{nd}, and the increased flushing time given in Figure 2 shows the flushing time bifurcates into two branches when $C_{wd}/C_{nd} > 1$ indicating that for certain locations the increased residence time is higher than at other locations for a given value of the ratio. Figure 2 demonstrates that the increased residence time is as much a function of location and shoreline within the reservoir where the multi-slip docking facility is located on the lake as it is a function of the facility being in that location.

$$\Delta t = \frac{Ln\left(\frac{C_{nd}}{C_{wd}}\right)}{K_{wd}}$$

3.2 Estimating Reservoir Flushing Rates

For the overall lake, K_r has the value of 1/270 per day. Using Equation 2 starting with the initial dye concentration of C_o = 1,000 ppb over the 60 day simulation time, the theoretical dye concentration throughout the lake with no multi-slip docking should be 800 ppb. The average dye concentration over the 41 shoreline multi-slip docking sites from the model simulation was 683 +/- 323 ppb computed from only 41 shoreline multi-slip docking sites out of a total of 7,023 model cells. The model simulation value is within less than one standard deviation difference of the theoretical value indicating that the model simulation results are quite reasonable.

3.3 Individual Model Flushing Rates and Times

The multi-slip docking volume flow rate and flushing rate at each of the locations were used in estimating the changes in water quality within the multi-slip docking facility volumes, where the increase or decrease in local flushing time with the multi-slip docking facilities was derived from the above flushing rates. The increase in time is defined as the time it would take for C_{wd} to reduce to the concentration with no docks, C_{nd}, at a rate of K_{wd}. This increase in time is derived from Equation 5 where C_{wd} is substituted for C_o as:

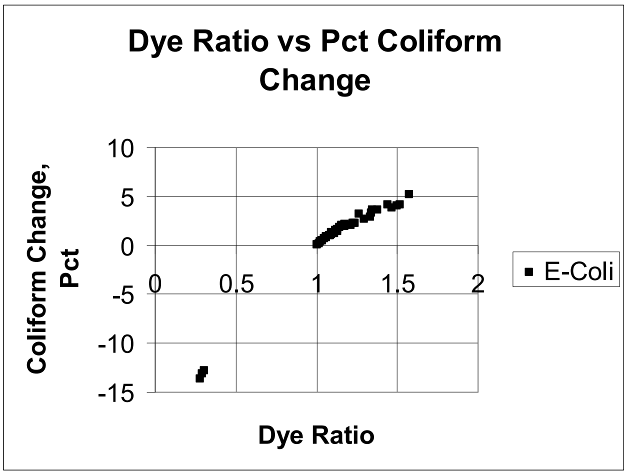


Figure 3. Relationships between Cwd/Cnd Ratio and Change in Coliforms

27

All but three, or 85%, of the 41 multi-slip docking facilities show increases in flushing times ranging from an average of 17 days up to a maximum of 52 days.

3.4 Estimating Changes in Water Quality

3.4.1 Simple first order decay relation for Coliforms

The results for coliforms without and with the multi-slip docking facilities were computed from

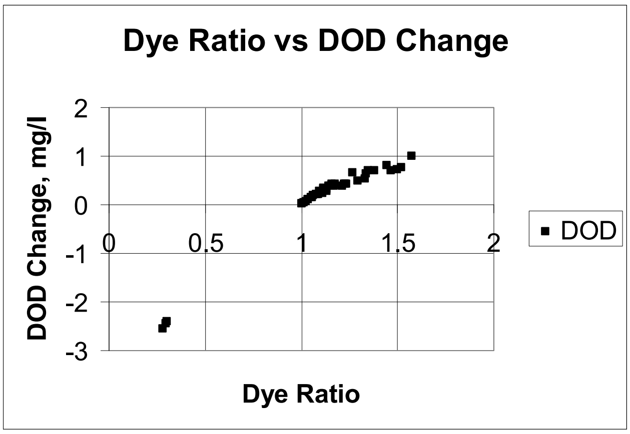


Figure 4. *Relationships between Cwd/Cnd Ratio and Change in DOD*

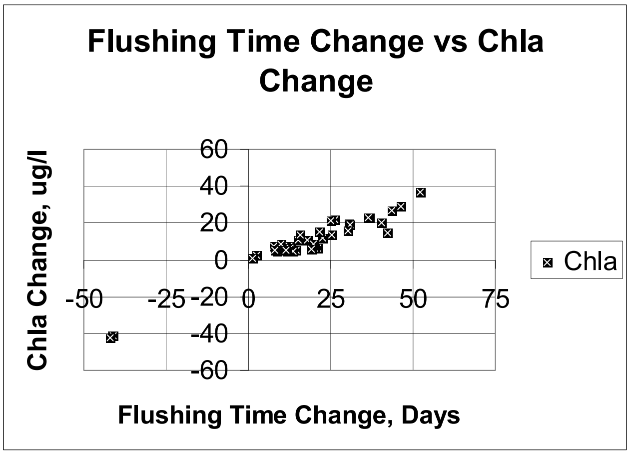


Figure 6. *Relationships between Flushing Time and Change in Phytoplankton.*

Equation 11 and compared to results for coliform mean, maximum and minimum values in Tims Ford Reservoir as sampled through the year in 1998. The magnitudes of the increases in coliforms with the multi-slip docking can be compared with the data using the statistical normalized range of results defined as (Max – Min)/Mean as a basis for judging the severity of the multi-slip docking additions. The normalized range statistic is used for comparison because most of the available water quality data are summarized using the mean, maximum, and minimum values. The normalized range for coliforms with the multi-slip docking in place will be about five times as great as that recently observed in Tims Ford Reservoir.

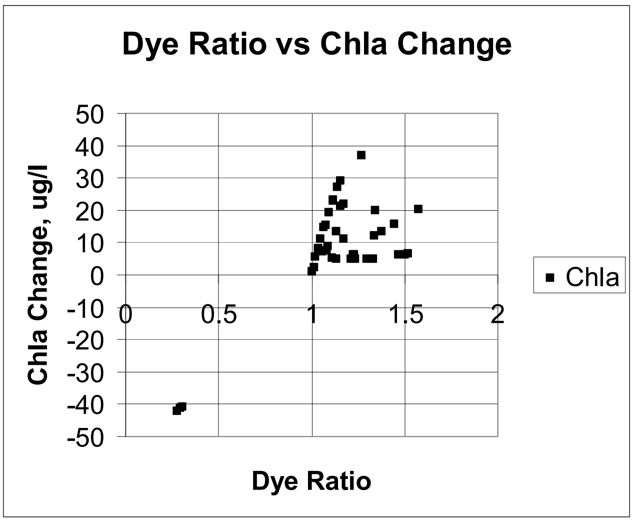


Figure 5. *Relationships between Cwd/Cnd Ratio and Change in Phytoplankton*

The relationship between the change in coliforms without and with the docks, and the dye ratio, C_{wd}/C_{nd}, is given in Figure 3. It shows that the change in coliform density will be almost proportional to the increased dye ratio.

3.4.2 Dissolved Oxygen

The results for DOD, changes in dissolved oxygen without and with docks and a comparison to observed results showed that the depression in dissolved oxygen with the multi-slip docking facilities in place would be up to 5 times the seasonal normalized change in dissolved oxygen presently observed in the reservoir. Figure 4 gives the relationship between the C_{wd}/C_{nd} ratio and the change in DOD. Figure 4 indicates that the change in DOD is almost directly proportional to the increase in the dye ratio.

3.4.3 Potential Aquatic Plant, Slime and Algal Density Change Due to Flushing Rates

Changes in algal densities without and with docks were compared to observed data results. Mean, maximum, and minimum algal densities among the docks as computed were about the same magnitude of the mean, maximum, and minimum algal densities computed from observed data over a year indicating that the simulations are producing realistic algal densities using algal model default parameters given in Edinger (2002, Table 10-1). The range of algal densities with the docks in place was estimated to be 2 to 3 times the range of algal densities presently observed throughout a year and with the docks it is expected that the algal problems will get worse.

Figure 5 shows the relationship between the C_{wd}/C_{nd}

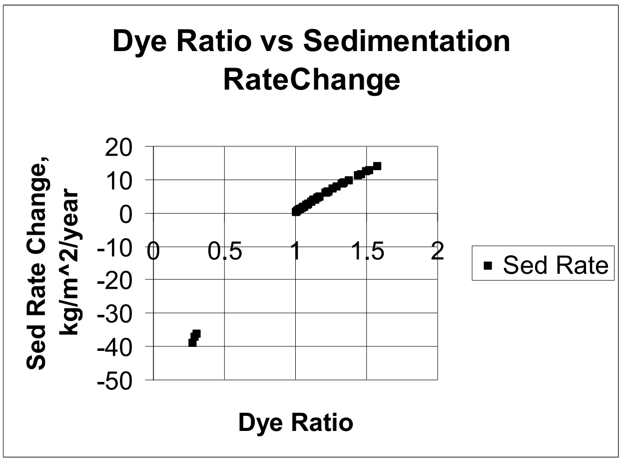


Figure 7. *Relationships between Cwd/Cnd Ratio and Change in Settling Rate*

ratio and change in algal densities with the addition of the docks. Like Figure 2, the change in algal densities is bifurcated indicating that some of the change is due to the addition of the docks themselves, and some of the change is due to the location of the docks within the reservoir. Figure 6 shows that the change in algal densities is more directly related to the increased flushing time which, similar to Figure 2, is related to location throughout the reservoir.

3.4.4 Application to Changes in Sedimentation

Not all the sediment will be lost within a multi-slip docking region, but some will be carried out into the remainder of the lake transporting with it the seeds from the phytoplankton and attached aquatics that settle to the bottom of the reservoir and grow to the spores and cysts that release vegetative cellular material that results in algal blooms (McGillicuddy et al. 2003, Edinger et al. 2003).

Analysis of the increase in sedimentation rates without and with docks showed that the sedimentation rate will increase with a variance (Standard Deviation/Mean) by about a factor of 5. The variance for the dye tracer ratio for comparison is about 0.2, indicating that there is a wider variation in the increase in sedimentation rates at different locations throughout the reservoir. Figure 7 shows that the increase in sedimentation is proportional to the C_{wd}/C_{nd} dye ratio.

3.4.5 Application of Different Dock Flushing Criteria to Proposed Tims Ford Docks

The State of Florida has a specific guideline for flushing at individual multi-slip docking facilities (SJRWMD 2005). The guideline is to reduce the test dye concentration to 10% of the initial value in 4 days for a dye test carried out at an individual marina. This test is different from the change in the concentration of dye of the whole lake used previously, where the latter can be replenished as it is flushed away from a marina location. It provides an independent analysis of the marinas relative to an independent criterion that is used elsewhere to determine if there will be water quality problems at the multi-slip docking facility.

The application of the Florida guideline requires dying each individual multi-slip docking facility alone and comparing the dye concentration within the facility to the initial dye concentration at the end of four days. Each individual multi-slip docking facility was initialized with a dye concentration of 1,000 ug/l and the remaining dye concentration at the end of 4 days was determined. The multi-slip docking facilities dye concentration at the end of four days showed that only 9 of the facilities examined, or less than 20%, might have satisfied the Florida individual marina facility flushing criteria of having a dye concentration of 100 ug/l or less at the end of 4 days. Most of the 9 multi-slip docking facilities that would satisfy the Florida marina flushing criteria are located along the eastern shoreline of Map 1 where the original channel of the main inflowing Elk River is located.

State of Florida officials point out that the flushing guideline is only one criterion for marina and dockage facility siting (Lazar, 2005) and other local conditions need to be considered. However, even by this simple criterion close to 80% of the proposed multi-slip docking facilities for Tims Ford reservoir will have water quality problems due to poor flushing. The international ANZECC (2000, Sec. 8.1.9.1) guideline for flushing required to minimize algal densities can be applied using Figure 6. Figure 6 shows that doubling the flushing times more than doubles the change in algal densities at most of the individual docks.

4. Summary

Analyses of the potential water quality impact of marinas are usually required prior to construction, such as for determining whether violations of state water quality standards would occur prior to the issuance of state certifications under section 401 of the Clean Water Act. Since the facilities do not yet exist, a comparative analysis can be used whereby conditions are compared with and without the facility in place. In this paper, a comparative analysis was demonstrated for a set of 41 multi-slip docking facilities planned for placement along the shoreline of Tims Ford Reservoir, located on the Elk River in south central Tennessee. The comparative study was based on the application of the publicly available three-dimensional Generalized Longitudinal, Lateral, and Vertical Hydrodynamic and Transport (GLLVHT) model given in Edinger (2002) based on earlier formulations of GLLVHT by Edinger and Buchak (1980, 1985, 1995). The comparative analysis of flushing based on the hydrodynamic model application allowed evaluation of the changes in water quality including coliforms, dissolved oxygen, algal densities and sedimentation that will take place along the shoreline and in the vicinity of the multi-slip docking facilities.

The comparative analysis showed that there will be reduced flushing in over 92% of the proposed multi-slip docking locations and that the increased flushing time will worsen water quality conditions as indicated by comparison to US State of Florida Guidelines and international ANZECC Guidelines. The analysis suggested that the change in water quality will not be limited to the multi-slip docking areas alone, and that local changes will ultimately affect water quality throughout 67% of the area of the reservoir. In particular the increased algal densities will generate seed for spores and cysts that will spread throughout the reservoir by attachment to sediment and decaying algae. The increase in benthic spores and cysts will increase the likelihood of the occurrence of algal blooms following construction of the multi-slip docking facilities.

The reports on data for coliforms, dissolved oxygen and algal densities given in Dycus and others (1992, 1999) indicate that water quality in Tims Ford Reservoir is generally unacceptable for recreational use of the reservoir. The model simulation results showed that the magnitude of the probable changes in these water quality parameters with the docks in place was greater than the observed seasonal changes in these water quality constituents over a year of available data by factors of 3 to 5 mostly due to reduced flushing or increased flushing time further indicating that the docks would have a significant impact on the reservoir.

References

Brown, W.D. (1993). Engineering and Design: Environmental Engineering for Small Boat Basins. *Department of the Army EM 1110-2-1206* U.S. Army Corps of Engineers. CECW-EH-W Washington, DC 20314-1000 Manual No. 1110-2-1206 31 October 1993.

Butkus, S.R. (1990). Evaluation of the Water Quality in the Releases from Thirty Dams in the Tennessee River Valley. *TVA; Water Resources* TVA/WR/WQ--90/17. Delaware. 1993. Appendix X: Marina Regulations State of Delaware Marina Regulations Adopted: March 29, 1990 Amended: February 22, 1993.

Donoghue, C.M. (2007). Discussion of blockage of shoreline flows by floating docks. *In U of Del. Coastal Sites Communications*.

Dycus, D.L. and Meinert, D. L. (1992). Reservoir Monitoring – 1991 Summary of Vital Signs and Use Impairment Monitoring on Tennessee Valley Reservoirs. *Tennessee Valley Authority Resource Group River Basin Operations Water Resources*. July 1992.

Dycus, D.L. Meinert, D.L. and Baker, T.F. (1999). Aquatic Ecological Health Determinations for TVA Reservoirs -- 1998 – An Informal Summary of 1998 Vital Signs Monitoring Results and Ecological Health Determination Methods. *TVA; Water Management*. August 1999.

Edinger, J. E. and Buchak, E.M. (1980). Numerical Hydrodynamics of Estuaries, in P. Hamilton and K. B. Macdonald (eds.), *Estuarine and Wetland Processes with Emphasis on Modeling*, Plenum Press, New York, New York, pp. 115–146.

Edinger, J. E. and Buchak, E. M. (1985). Numerical Waterbody Dynamics and Small Computers, *Proceedings of ASCE 1985 Hydraulic Division Specialty Conference on Hydraulics and Hydrology in the Small Computer Age*, Aug. 13–16, American Society of Civil Engineers, Lake Buena Vista, FL.

Edinger J. E., and Buchak, E. M. (1995). Numerical Intermediate and Far Field Dilution Modelling. *Journal of Water, Air and Soil Pollution* 83: 147-160, 1995. Kluwer Academic Publishers, The Netherlands.

Edinger, J. E., Buchak, E. M. and Kolluru, V. (1998). Flushing and Mixing in a Deep Estuary. *Journal Water, Air and Soil Pollution*. 102: 345-353, 1998. Kluwer Academic Publishers, The Netherlands.

Edinger, J.E. (2002). Waterbody Hydrodynamic and Water Quality Modeling. *Three dimensional hydrodynamic and transport modeling. A workbook with 3-D model CD ROM*. 215 pgs. ASCE Press, Reston, VA.

Edinger, J.E., Dierks, S. and Kolluru, V.S. (2003b). Density Dependent Grazing in Estuarine Water Quality Models. *Water, Air and Soil Pollution*, Kluwer Academic Publishers, the Netherlands.

Edinger, J.E., Boatman, C.D. and Kolluru, V.S. (2003). Influence of Multi Algal Groups in the

Calibration of a Water Quality Model. *ASCE Estuarine and Coastal Waters: Proceedings from the Fall 2003 Conference.*

Edinger, J.E. (2004). Hydrothermal and Water Quality Studies for the Arbitration of a Power Purchase Arrangement For Battle River Under Section 45.95(1) of the *Electric Utilities Act* between: ATCO Electric Ltd., and EPCOR, Ltd., Calgary, Cda. February-June, 2004.

Edinger, J.E. and Buchak E.M. (2005). Control of Reservoir Algal Blooms through Discharge Drawdown *Prepared for* Preti Flaherty Beliveau Pachios & Haley LLC Augusta, Maine 04332 J. E. Edinger Associates, Inc., 63 Crestline Rd, Wayne, Pennsylvania 19087, February 2005. Submitted as part of the record in the Maine 2005 legislative proceedings and as an appendix to the pre-filed direct testimony in the Androscoggin River permit appeals proceeding of 2005.

Edinger, J.E. (2006). Waterbody Hydrodynamic and Transport Case Studies Using the ASCE Introgllvht Model and Updates. Project applications and new routines. Prepared for Workshop Presentations. June 2006. Wayne, PA.

Edinger, J.E. (2007). Pre-filed Testimony On Behalf Of Livermore Falls Wastewater Treatment Facility And The Towns Of Livermore Falls And Jay before the State of Maine Board of Environmental Protection in the Matter of Town of Livermore Falls and Town of Jay, Androscoggin County, Maine. Appeal Of Publicly Owned Treatment Works MPDES No. ME0100315 and Wastewater Discharge License Renewal No. W002654-5l-G-R, filed February 28, 2007.

Edinger, J.E. and Krallis, G.A. (2007). Hydrothermal Modeling Studies of Cooling Tower Alternatives. *Journal of Energy Engineering, ASCE*, Vol. 133, No. 1, March 2007, Pgs. 1-7.

Fehring, J.P. (1993). Bacteriological Conditions in the Tennessee Valley, *Fourth Annual Report Reservoir Monitoring – 1992*. Tennessee Valley Authority, Resource Group, Water Management, Chattanooga, Tennessee. May 1993 (Revised August 1993).

Gentleman, W., Leising, A., Frost, B., Murry, J. and Strom, S. (2000). Dynamics of Food-Web Models with Multiple Nutritional Resources: A Critical Review of Implicit Assumptions. *JGOFS SMP Workshop*, School of Oceanography, University of Washington, Seattle, Washington.

Gordon, J. (1974). Tims Ford Reservoir-Elk River Data Report 1963-1973. *TVA Special Projects Staff, Water Quality Branch*, Chattanooga, Tenn. May 1974.

Lazar, Ann (2005). Office of Submerged Lands and Environmental Resources Florida Department of Environmental Protection.

Martin, J.L, Edinger, J. E. Higgins, J. M. and Gordon, J. A. (2006). Energy Production and Reservoir Water Quality: A Guide to the Regulatory, Technical, and Theoretical Basis for Required Studies. *Report of the Energy Engineering Division Environmental Effects Committee*. 345 pgs. ASCE Publications, Reston, VA. Massachusetts. 2005. Chapter 5: New and Expanding Marina Regulations. Commonwealth of Massachusetts DNR.

McGillicuddy, D.J., Signell, R.P., Stock, C.A., Keafer, B.A., Keller, M.D., Hetland, R.D., and Anderson, D.M. (2003). A Mechanism for Offshore Initiation of Harmful Algal Blooms in the Coastal Gulf of Maine. *Journal of Plankton Research*. Vol. 95. Number 9. Pgs. 1131-1138. 2003.

Reynolds, C.S. and Marbely. S.C. (2002). A Simple Method for Approximating the Supportive Capacities and Metabolic Constraints in Lakes and Reservoirs. *Fisheries Biology* (2002) 47, 20, 1183-1188.

Sanger, D.M. and Holland. A. F. (2002). Evaluation of the Impacts of Dock Structures on South Carolina Estuarine Environments. Marine Resources Research Institute, Marine Resources Division, South Carolina Department of Natural Resources, P.O. Box 12559 Charleston, SC 29422.

Scoff, E.M., Gardner, K.D., Baxter, D. S. and Veager, B. L. (1996). Biological and Water Quality Responses in Tributary Tailwaters to Dissolved Oxygen and Minimum Flow Improvements Implementation of the Reservoir Releases Improvements Program and Lake Improvement Plan. *Environmental Compliance, Tennessee Valley Authority, Resource Group, Water Management,* Norris, Tennessee October 1996.

SJRWMD (2005). Applicant's Handbook: Management and Storage of Surface Waters. *St. Johns River Water Management District, Palatka, FL*. U.S. Army Corps of Engineers. CECW-EH-W Washington, DC 20314-1000 Manual No. 1110-2-1206 31 October 1993.

Virginia (1988). Regulation: Pertaining to the Siting of Marinas or Community Facilities for Boat Mooring, Virginia Marine Resources Commission "Criteria for the Siting of Marinas or Community Facilities for Boat Mooring". *Regulation 4* VAC 20-360-10 ET SEQ. August 1988.

Notation

The following symbols are used in this paper:
$_{nd}$ = subscript to indicate condition no docking facilities in place,
$_{wd}$ = subscript to indicate condition with docking facilities in place,
$_{oo}$ = subscript to indicate background conditions,
BOD = Biochemical oxygen demand,
C = Concentration,
C_o = Initial concentration,
Cp = Phytoplankton concentration,
Cs = Sediment concentration,
$C(T_{sim})$ = Individual cell dye concentration at the end of the simulation (T_{sim}),
D_d = Phytoplankton death rate,
DOD = Dissolved oxygen deficit,
D_r = Phytoplankton respiration rate,
G_p = Phytoplankton growth rate as limited by concentrations of nitrogen (N),
phosphorous (I), and light (I),
K = First order decay rate,
K_{dg} = Zooplankton density dependent grazing rate,
K_{phy} = Phytoplankton net growth rate,
K_r = Reservoir flushing rate,
Q = Flow rate,
Q_r = Outflow rate,
R_{bod} = Rate of BOD decay,
R_d = Constituent decay rate (coliform dye-off for example),
R_{re} = Surface reaeration rate,
T_{sim} = Simulation time,
V_{dk} = Volume of the model cell containing the multi-slip docking facility,
V_r = Reservoir volume,
V_s = Settling velocity.