St George River Modeling Report
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Executive Summary

A study of the St George River in Warren and Thomaston by DEP and stakeholders involved collection of water quality data and the development of a water quality model.

Water Quality Data

(For details, consult the St George River Data Report, MDEP, Nov 1999)

1. During the summer of 1999 water quality data was collected by DEP and stakeholders in a ten-mile stretch of the St George estuary to establish baseline water quality, and check compliance with required statutory dissolved oxygen criteria. The estuary was sampled at eight locations. Pollutant load sources, which included five tributary locations, and the Warren S. D. were also sampled.

2. The three sampling runs were conducted on the following dates and discharge conditions for the Warren S.D.: July 20-23, zero discharge; August 3-6, historical average discharge (66,000 gpd); August 16-20, conditions approximating design flow and current licensed flow (151,000 gpd) (actual flow 142,000 gpd).

3. The estuary failed to meet the regulatory requirement (class SB dissolved oxygen criteria of 85% of saturation) in all three sampling runs. Daily minimum dissolved oxygen levels as low as 75% to 80% of saturation occurred in four of the sampling locations in the upper estuary. Moderately elevated algae levels (as chlorophyll a) occurred at these locations also.

4. The lower early morning dissolved oxygen levels observed in the data set with Warren at full discharge, when compared to zero discharge, were primarily caused by two factors. (1) The dissolved oxygen at the ocean boundary was about 0.6 ppm lower when Warren was at full discharge. (2) The estuary was sampled at ebb tide during full discharge and high tide during zero discharge. Lower early morning dissolved oxygen is ordinarily expected at ebb and low tides and higher early morning dissolved oxygen at high tide.

Water Quality Model

1. The WASP model (Water Quality Analysis Simulation Program), version 4.32, was used by Maine DEP as a basis to develop a water quality model of the St George estuary.

2. The transport (model simulation of water movement) was calibrated by adjusting the model dispersion rates until the salinity predicted by the model matched salinity measured in the estuary. The dispersion rates were initially calculated from the model volume exchanges that were required to match the travel time of the estuary.

3. The model was calibrated chemically to the three data sets collected in the summer of 1999. Calibration plots of carbonaceous BOD, total dissolved nitrogen, total phosphorus, chlorophyll a, and dissolved oxygen reveal a satisfactory fit of the model to the data.

4. Both the data and model prediction show that the buildup and growth of algae occurs predominately in the first four miles below head of tide, where flushing is very slow. After building up to peak concentrations in the first two miles, a rapid decline in algae occurs due to settling, dieoff, and tidal dilution.

5. A sensitivity analysis reveals that (1) the atmospheric reaeration rate, (2) the sediment oxygen demand rate, and (3) the algae growth and respiration rates are the most important parameters affecting the model's prediction of dissolved oxygen. The model response to algae as chlorophyll a is very sensitive to a number of parameters, including (1) the algae growth, respiration, and settling rates, (2) sediment nutrient flux rates, (3) dispersion rates, and (4) the ratio of nitrogen to carbon.

6. A component analysis at drought flow conditions reveals that (1) sediment oxygen demand, (2) diurnal impacts from algae, and (3) carbonaceous BOD decay are the most important factors affecting dissolved oxygen depletion in the St George estuary. Nutrients from sediments and ocean boundary water chemistry are the most important factors affecting algae growth. It is estimated through modeling and best professional judgement that baseline conditions are represented by about 50% of the algae levels and dissolved oxygen depletion measured in the St George estuary last summer.

7. The model prediction runs of worst case conditions at high water temperature, neap tide, minimum fresh water inputs, and minimum flushing indicate that existing minimum dissolved oxygen levels is about 6 ppm or 77% of saturation. This is under the regulatory requirement (class SB criteria of 85% of saturation) by 0.6 ppm or 8% of saturation. The lowest dissolved oxygen recorded in the intensive survey data was 5.9 ppm. It is estimated that baseline dissolved oxygen levels on the St George estuary are somewhere in-between 85% to 90% of saturation.

8. Model runs at worse case drought flow conditions with the Warren S.D. at zero discharge and their current design flow of 0.151 mgd, when compared, indicate differences (<0.1 ppm) in dissolved oxygen that are not measurable and less than model precision. This is due mainly to the large available dilution of wastewater estimated to be in the thousands. However, the model estimates that the Warren S. D. discharge increases algae levels measured as chlorophyll a by 15% and 21%, respectively for effluent flow rates of .151 and .232 mgd, respectively. The chlorophyll a predicted by the model of 8 to 10 ppb approaches levels of mild bloom conditions. The highest tidally averaged chlorophyll a over three days in the intensive data was 7.9 ppb.

9. To diminish algal growth both point source and non-point source nutrient controls are recommended.

10. Sources of non-point source pollution should be investigated in the watershed and best management practices (BMP's) should be implemented, where feasible. Efforts should begin on tributaries first, in particular, on the Mill River. Both impacts from non-point sources and improvements after implementing non-point source controls can be more easily observed in the tributaries.

11. The licensing action for Warren uses a strategy to discharge more flow in the non-summer when water quality non-attainment is not an issue. This makes possible restricting the Warren discharge to .10 mgd in the summer, which represents a 1/3 reduction in current design flow and will limit potential nitrogen discharges to the St George estuary. The license results in equal summer mass loads of BOD and TSS from current licensed levels and a decrease in historic discharge levels of BOD and TSS. Model runs at worse case drought flow conditions with Warren at .10 mgd predict that the chlorophyll a attributable to the Warren discharge should be reduced to less than 1 ppb and less than 10% of the total chlorophyll a. The dissolved oxygen depletion attributable Warren is predicted to be not measurable (< .1 ppm) and less than model precision. It can be concluded that the Warren discharge, as licensed, will not cause or contribute to the existing dissolved oxygen non-attainment.

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Introduction

The St George River (Georges River) is located in the central coastal area of Maine in Knox and Waldo counties. The drainage area of the Georges River is 182 square miles in Warren and 258 square miles at its mouth. The area of interest is a ten-mile tidal segment that originates at head of tide in Warren and ends in Cushing near Fort Point. The classification of the river here is SB requiring minimum dissolved oxygen levels of 85% of saturation.

A DEP study began in the spring of 1999 involving various stakeholders of the St. George River such as the Warren Sanitary District (SD), Georges River Tidewater Association, Thomaston PCD, Dept. of Marine Resources, and Woodard and Curran. Three data sets, each of four to five consecutive days were collected in July and August. The plant discharge from the Warren Sanitary District was controlled in each data set as follows: survey 1 (7/20 - 23) zero discharge; survey 2 (8/3 - 6) historic discharge 66,000 gpd ; survey 3 (8/16 – 20) design discharge 151,000 gpd. Dissolved oxygen, temperature, and salinity; nutrients, BOD, chlorophyll a, sediment oxygen demand, secchi depth, and point and non-point source inputs were measured at a number of locations and times. For details, one should consult The St George River Data Report (MDEP, Nov 19,1999).

Non-attainment of class SB dissolved oxygen criteria of 85% of saturation was measured in all three surveys, primarily in four sample locations in the upper portion of the estuary. In addition, moderately elevated algae as chlorophyll a was observed during the late morning sampling runs at the same locations. The proposal to build a new state prison facility that would tie in to the Warren WWTP has initiated this study to assure that any increased loading of pollutants to the estuary would not significantly contribute to the non-attainment of dissolved oxygen criteria. This report describes a mathematical modeling effort undertaken by DEP as a follow-up to the sampling effort to determine the cause of dissolved oxygen depletion and growth of algae in the estuary. Various possible pollution sources such as loadings from the sediment bottom area, ocean and landward boundaries, and point and non-point sources are considered in addition to the Warren S.D. discharge.

Water Quality Model

The application of mathematical modeling techniques to water quality problems has proven to be a powerful tool in water resource management. As a diagnostic tool it permits the abstraction of a highly complex real world. Realizing that no one can ever detail all the physical phenomena that comprise our natural world, the modeler attempts to identify and include only the phenomena, be they natural or man-made, that are relevant to the water quality problems under consideration. As a predictive tool, mathematical modeling permits the forecasting and evaluation of the effects of changes in the surrounding environment on water quality. Some water quality problems are of such a complex nature that mathematical models provides the only real means for predicting the source of impact and possible management alternatives to correct problems.

The Water Quality Analysis Simulation Program (WASP), version 4.32, is the water quality model that was used for the St. George estuary. WASP is a USEPA supported model with many variable and powerful features that make it especially suited for estuaries. It has the capability to simulate time variable responses for advection, dispersion, point and non-point source loading, and boundary exchanges. Water quality chemistry and transport can be varied in three dimensions. Both of these features are desirable in a system such as an estuary, where the tides often result in environmental complexities.

Any water quality modeling analysis involves two independent components; that of transport, and that of kinetics or chemistry. The transport is a mathematical representation of how the water moves and involves the components of advection and dispersion. The kinetic representation of the model is quite complex and mathematically relates all the relevant factors to dissolved oxygen production and depletion. The flow chart representation of the model (figure 1) details the many processes involved, such as algae growth and respiration, which in turn are driven by light and nutrient interactions, carbonaceous BOD decay, nitrification, atmospheric reaeration, sediment oxygen demand, sediment nutrient sources (fluxes), and the settling of particulate portions of pollutants. The model includes input sections for point and non-point sources of pollution, and upstream (landward) and downstream (ocean) boundaries.

The first step in the development of a water quality model is the breakup of the system into a number of reaches. For the St George estuary the reach breakup from head of tide (Payson Park) to Fort Knox resulted in 63 segments comprised of the following: 47 water column segments; five non-point source inputs as tributaries; one point source input, the Warren S.D. discharge; and 11 bed segments (figure 2). The data reveal that the St George is a well-mixed estuary, and hence the model setup of two water column reaches in the vertical was deemed sufficient. Both the point and non-point source reaches were “dummy segments” (ie, portions of the model created for practical considerations that are not considered real) as were the bed segments (which were only created to receive pollutants that have settled). The tidal area of the Oyster River was divided into three reaches that was linked into the St George estuary at the appropriate location. The fresh water portion of the St George River enters the estuary at the landward boundary and the tidal exchanges enter at the ocean boundary.

The model was set up as a steady state system that was tidally averaged over several days. This type of analysis involving a long-term averaging period is necessary when modeling algae due to the way the WASP computer program is set up and the time considerations of algae buildup, which could involve several days.

Water Quality Model Transport

The summer of 1999 was very dry and very little fresh water was being contributed to the estuary during the sampling period. As a result, advection (flushing induced by fresh water inputs) was small and the major transport mechanism to this system was dispersion (flushing induced by tidal exchanges). The customary method of calibrating dispersion is by matching the model output of salinity to measured values. This method was utilized in addition to another which involved using the model volume exchanges to calibrate the WASP's model estimate of estuary's flushing to a desk top model calculation (modified tidal prism method).

To obtain an initial estimate of dispersion, the model exchanges can be calculated by the dispersion rate, reach cross sectional area, and mixing length. The model travel time can then be estimated by dividing the reach volume by the volume exchange. A trial and error adjustment of the dispersion rate was undertaken on a spreadsheet until the WASP model travel time compared favorably to desktop calculations. This method has the advantage of assigning the lower and higher dispersion rates to slower and faster moving segments, respectively and assigning the appropriate rates to reaches approaching seawater salinity values. Dispersion rates can be overestimated in the most seaward reaches, since order of magnitude multipliers, when applied to the dispersion rate here, often give a satisfactory calibration to salinity.

The following model dispersion rates used in the first (7/21-23) and third (8/17-20) data sets initially gave a good fit of the estimated estuary travel time; 2.4 m^2/sec for the upper 0.5 miles; 15 m^2/sec for miles 0.5 to 2.0, and 35 m^2/sec for the remaining 8.5 miles. When these dispersion rates were input to the WASP, an excellent match of salinity results. Values up to twice these dispersion rates were deemed as a suitable fit, athough salinity for the upper two sample stations is slightly high for twice the dispersion rates (figure 4b). Values of dispersion slightly higher than this (6,50 100, and 70 m^2/sec) were used for the Aug 3-6 data set (figure 4c) which also results in a suitable fit of salinity.

Values twice the initial dispersion rates were used as the calibrated values, due to the better fits obtained with CBOD, chlorophyll a, nutrients and dissolved oxygen at the higher dispersion rates. Another consideration was assuring far field dilution predicted by WASP was larger than near field dilution predict by a plume model, CORMIX.

The WASP model's prediction of far field dilution of Warren S. D. discharge at .151 mgd (figure 4) indicates that the dilution varies in-between 1000 and 2000 in that portion of the estuary above the state prison in Thomaston (upper 6 miles). The prediction of near field dilution using a plume model, CORMIX, predicts a dilution of 951 17 meters from Warren's outfall diffuser. Similar model runs at the recommended summer flow for Warren at .10 mgd predict summer dilutions of 1435 for near field and 1800 to 7700 for far field in the upper 6 miles of the estuary (figure 4a). Hence it can be concluded that a rather large dilution exists for Warren's effluent and its impact to the St George estuary is not expected to be large.

Model Load Inputs

Some of the inputs to the model were directly measured during each intensive survey as flow and concentrations. The measured inputs included the St George River at head of tide, the Oyster River, the Mill River, an unnamed tributary near the Warren S.D., and the

Warren S.D. discharge. Since it was not practical to measure all tributary sources, loadings to the model for those tributary sources not measured were calculated as a flow weighted average from the measured sources. Slightly more than one half of the sub-watersheds within the model boundaries were measured (30 mi^2 measured, 28 mi^2 not measured). The inputs to the model are summarized in table 2.

It was necessary to group the smaller tributaries as four sources to the model, one of which was grouped with the Mill River, due to load constraints of WASP. All of the tributary loads entering the St George estuary during the sampling period were quite small due to the very low flows that were experienced in last summer's extended drought. As a result, the grouping of tributary loads should not result in any significant errors. The ocean boundaries are not true loads into the system and comparative loads were not calculated.

Water Quality Model Chemical Calibration

The chemical calibration of the water quality model involves adjusting parameter rates until the model output for various chemical constituents (dissolved oxygen, BOD, nutrients, and chlorophyll a) matches the measured values for each data set. The parameter rates being calibrated are held constant from data set to data set, but in some cases minor changes must be implemented. In an estuary, in particular, the dynamic and complex nature would result in some variability of these rates.

Table 1 summarizes the parameter rates used to calibrate the water quality model, how these rates compare to suggested literature values, and the logic and considerations used to assign the rates to the model. When comparing the parameter rates amongst the three data sets, all were held constant except for the algal growth rate and organic nitrogen and phosphorus mineralization rate. The algal growth rate was adjusted from 2 to 1.7 per day in the third data set. The organic nitrogen mineralization (recycling) rate was adjusted from .001 to .025 per day in the third data set to account for more nutrient recycling that was apparent in that data set. The phosphorus mineralization rate varied from .10, .15, and .001 per day in the first, second, and third data sets, respectively.

The model calibration plots are included for CBOD, chlorophyll a, total dissolved nitrogen (TDN), total phosphorus (TP), and dissolved oxygen (two plots). This results in six plots for each data set. Since three data sets were collected, there are a total of eighteen plots (figures 5 to 22). The model output is tidally averaged over the course of several days. The calibration plots typically display the average measured data in the AM as unshaded circles and average PM data as shaded circles. High and low error bars depict the range of the measured data. For a good fit of the model to the data, the model output (typically displayed as lines) should ideally fall in-between the average of the AM and PM data (in-between the shaded and unshaded circles). No AM data for nutrients, BOD and chlorophyll a at the key estuary points (half way down, South Warren, near Warren outfall) were collected for the July data set. The calibrations for the July data are considered inferior to the August data sets, but is still included. The model output for this should fall lower than the dark shaded circles, which represent the average low tide data.

The CBOD calibration was initially problematic due to the fact that the laboratory BOD test measures algal respiration that is not included in the model output for CBOD. (The dissolved oxygen depletion for respiration is accounted for in the model in another way.) An adjustment was made to the model output (outside the model), and hence the term "phytoplankton corrected" in the calibration plots. The following equation was used to correct the model CBOD:

CBODc = CBODm + PHYT X 2.67
where 2.67 = oxygen / carbon ratio
PHYT = Model phytoplankton as carbon (ppm)
CBODm = Model CBOD (ppm)
CBODc = Corrected model CBOD (CBOD + respiration)

The calibration plots for corrected CBOD show a good fit of the model to the data at a BOD decay rate of 0.05 per day. This is also the average of the measured laboratory decay rate. The laboratory decay rate is ordinarily considered a lower boundary for the ambient BOD decay rate.

Ambient levels of nitrogenous BOD, although accounted for in the model as ammonia, were too low (usually <1 ppm) to do a NBOD calibration analysis. It is can be concluded that NBOD does not significantly affect dissolved oxygen depletion.

A number of parameter rates are considered in the calibration of chlorophyll a, nitrogen, and phosphorus, all of which are usually calibrated in unison, since each adjustment of the considered parameter rate can effect all three. The data reveals that a rapid buildup of chlorophyll a occurs in the initial portions of the estuary, where the flushing is slow. It takes about 7 tidal cycles to flush the first mile of the estuary. The chlorophyll a then decreases rapidly in the seaward direction as more dilution and tidal dispersion is encountered and normally is at low values at the stations including and below the Warren outfall.

A phytoplankton settling rate of 1.5 meters per day was assigned to the lower reaches of the model, which had the higher measured sediment oxygen demand (SOD) rates. It is deduced that most of the settling of pollutants probably occurs in the lower reaches, which are deeper and have lower tidal velocities and this is supported by the higher SOD rates measured here. For the other nutrient and algal constants, literature default values were usually assigned. The use of default values is the preferred method that generally results in a more defensible water quality model. A good fit of the model chlorophyll a occurs with the observed data in all the data sets.

A consideration not accounted for by the model is the possibility that the algae, which are usually abundant in the Warren S. D. lagoons, act as a "seed" to enhance algal growth in the St George estuary, that would not ordinarily occur. This would be accounted for in the model by assigning a higher algal growth rate, but would not be counted as an impact from the Warren treatment plant in the model prediction run. The only way to determine whether or not this phenomena actually occurs is by collecting water samples from both Warren's treatment lagoons and the estuary and comparing the species of algae. If similar species occur, then it can be deduced that this is probably occurring.

The total dissolved nitrogen (TDN) calibration is satisfactory in all of the data sets. The model's prediction for TDN is sometimes high in some sample locations but within the error of the model and the data's representation of tidally averaged conditions.

The phosphorus calibration reveals a good fit of the model to most data points, except the model TP is slightly lower than measured at the Thomaston sampling station. The calibration of TP is not a critical part of the model, since the algae growth is nitrogen limited. The WASP model simulated the nitrogen limitation of algae very well.

The final two parameter rates left to adjust for the calibration of dissolved oxygen, after the BOD, nutrient, and chlorophyll a calibrations are completed, are the reaeration rate and sediment oxygen demand rates. Since changes in the reaeration rate were found to result in a high model response to dissolved oxygen revealing its importance in the model calibration (discussed later in the sensitivity analysis section), the reaeration rate was assigned by reach. The rate was initially assigned as a maximum of the O Connor-Dobbins formulation and a minimum default of wind induced reaeration as follows:

<u>O Connor Dobbins</u>

$$\mathbf{Ka = 12.85 * V^{.5} / D^{1.5}}$$

where Ka = reaeration rate (1/day)
V = Average tidal velocity in fps
D = Average tidal depth

<u>Wind Induced</u>

$$\mathbf{Ka = 3 / D}$$

Average tidal velocity values were calculated with the tidal prism and other volumetric data. The average reaeration rate initially assigned to the estuary was 0.28 per day and varied from .06 to .70 per day. The model dissolved oxygen was lower than observed values, when using these reaeration rates. Rates double to the initial rates were eventually assigned to calibrate the model dissolved oxygen to observed values.

Sediment oxygen demand rates were measured by USEPA August 3 to 6 at the five sampling locations in the upper estuary (1 mile below Warren to the Thomaston prison). Rates were initially assigned as measured and values interpolated in-between sampling locations. For the lower estuary no SOD data was available. Rates of 0.5 gm / m2-day were assigned to the bottom water column segments. SOD is thought to be low here, due to the high dissolved oxygen readings that typically occur adjacent to the estuary bottom. In the final dissolved oxygen calibration, the SOD rate had to be adjusted 10% lower than measured to achieve a good match of the model dissolved oxygen to the observed data. Slight adjustments to the measured SOD are considered to be justifiable, since the measured SOD is a very small sample size in comparison to the estuary bottom. It is estimated that the reported SOD rates could easily be off by as much as 50%, but MDEP does not typically adjust the SOD rate by more than 20% from measured values.

A large portion of top segments is in contact with the water column of bottom segments and does not experience SOD. However the top segments are always wider than the bottom segments, and hence some of their bottom area is in contact with sediments. A SOD rate should be assigned to top segments. The “true” bottom areas (areas in contact with the river bottom) of top segments were proportioned to the total bottom area of bottom segments and the product of this ratio and the measured SOD could then be applied as the top segment SOD.

Both the sediment nutrient fluxes for bottom segment nitrogen and phosphorus are initially obtained by multiplying the SOD rate by a set ratio (Redfield); 66.05 for ammonium, and 9.17 for phosphate. There is a very large range of acceptable literature values for the nutrient fluxes and adjustments can be made from initial assigned rates as needed in the nutrient calibration. Multipliers of .4 and .5, respectively were applied to the initial ammonium and phosphate flux rates, respectively. Nutrient flux rates for top segments were similarly proportioned by bottom area considerations, as in the assignments of SOD.

The final adjustment to the model is the development of a method to obtain the daily minimum dissolved oxygen. The WASP model outputs dissolved oxygen as a daily average. The daily minimum dissolved oxygen is the item of interest, since dissolved oxygen criteria are typically expressed as daily minimums. An average of the diurnal dissolved oxygen deviations from the three calibration data sets was deemed sufficient for calibration purposes, since the chlorophyll a values that were measured, when comparing data sets, were not significantly different. The chart titled “Diurnal DO Adjustment to Model” (figure 24) was derived from an average of the measured diurnal dissolved oxygen of the three data sets. Adjustments ranged from 0.55 to –0.15 ppm. The adjustment of one-half the diurnal dissolved oxygen range is subtracted from the model output to obtain the daily minimum dissolved oxygen, and added to the model output to obtain the daily maximum dissolved oxygen.

For some of the lower tidally dominated reaches, negative diurnal adjustments were employed. At these locations, the tidal effect exceeds algal respiration. The afternoon dissolved oxygen readings here were lower than the morning readings, due to the low tide conditions in the afternoon. In the absence of significant algae, the lower dissolved oxygen readings typically occur at low tide. In contrast, systems dominated by algae typically have the lowest dissolved oxygen readings in the morning after an entire evening of respiration and the highest readings in the afternoon after extended daytime photosynthesis.

The dissolved oxygen calibration plots display the data as surface (circles) and bottom (squares) readings. Vertically, dissolved oxygen, temperature, and salinity were fairly uniform, indicating a well-mixed estuary. The AM data is also represented by unshaded figures, and PM data shaded figures. Two plots are displayed for each data set; one with the model tidally averaged and a second in AM and PM dissolved oxygen readings. The model results for the former are displayed as surface (solid lines) and bottom (dashed lines) reaches and the latter as AM (dashed lines) and PM (solid lines) dissolved oxygen. The model dissolved oxygen compares excellently in all data sets.

Model Sensitivity Analysis

In a sensitivity analysis, some of the parameter rates can be tested to determine which are more important in the development of the model. The August 16 to 20 data set was used as a basis for the sensitivity analysis runs. Each parameter was multiplied by a factor of 0.5 and 2 and the model output for dissolved oxygen and chlorophyll a was then compared to the original model result (tables 3 and 4). The sensitivity analysis is further summarized as bar column plots, which show the relative difference in dissolved oxygen (figure 23a) and chlorophyll a (figure 23b) at all sample locations for the parameter rate multipliers of 0.5 and 2.0. From this analysis it appears that the most important items in the calibration of the model dissolved oxygen include sediment oxygen demand; the atmospheric reaeration rate, and the algae growth and respiration rates. The BOD decay rate, dispersion rate, and algae settling rate are less important when considering the model calibration of dissolved oxygen.

When considering the model sensitivity to parameter rates in the calibration of chlorophyll a, the model was sensitive to nearly all the parameters tested (algae growth, respiration, and settling; dispersion; nutrient flux rate from sediment, and nitrogen and phosphorus ratios to carbon) with the exception of the half-saturation constants for nitrogen and phosphorus. This sensitivity is expected, since the measured values for chlorophyll a in the St George estuary were often very unstable on any given day indicating that the levels of algae in this system are quite dynamic.

For both dissolved oxygen and chlorophyll a, the sample locations closest to the landward boundary are generally more sensitive to changes in the model parameter rates.

Model Components of Impact

In the component analysis, potential factors to water quality are individually subtracted from the model and the difference in chlorophyll a or dissolved oxygen observed. The relative contribution of various factors to dissolved oxygen depletion and algal growth in the water body can then be determined. The component analysis is first displayed as a table with the model output at all sample locations and then as a series of pie chart percentage comparisons (figures 25 to 29) at three locations in the estuary (South Warren, Near Warren Outfall, 1 Mile below Warren Village). The model prediction run with Warren S.D. at .151 mgd was used as a basis for the component analysis.

When considering dissolved oxygen depletion in the St George estuary at the sample locations of South Warren and near Warren’s outfall, the sediment oxygen demand is the largest source of impact accounting for about one-half, followed by diurnal dissolved oxygen (algae respiration at evening) which accounts for about one-third. Dissolved oxygen depletion from BOD decay is slightly more than 10% of the total and dissolved oxygen depletion from the ocean boundary 5% to 8% of the total. The estimated dissolved oxygen depletion from point and non-point source inputs at drought flow conditions is negligible (figures 24, 25).

When considering the estuary algae (as chlorophyll a) in the upper portion of the estuary, the nutrients in the sediments are the largest source (49% to 56%), followed by the ocean boundary (21% to 28%), and point and nonpoint source inputs (21 – 23%) (figures 26 – 28).

It is often difficult to separate natural components of impact from man made pollution in rivers or estuaries. If components are grouped into natural and uncontrollable origins, some rough estimates can be provided for baseline conditions, based upon modeling and best professional judgement. It should be recognized that there is much error associated with the baseline estimates, but it is intended to demonstrate that some portion of apparent degradation is not controllable. For the most part, water chemistry collected at the landward and ocean boundaries indicated low levels of pollution and can be considered natural. Both the sediment rates used for oxygen demand and nutrient fluxes are on the lower 10% of range of recommended literature values and SOD rates measured on the St George are typical or possibly slightly lower than SOD rates measured in other Maine estuaries. Hence the sediment on the St George is not largely effected by pollution.

Most of the non-point source inputs come from the upstream boundary which is characterized by low pollution levels. When the algae component of NPS is added to the ocean boundary component of algae, it can be concluded that about one-third of the algae comes from natural sources. If one-half of the sediments are considered to be of natural or uncontrollable origin (see SOD in paragraph below), than slightly over one-half of the source of algae on the St George is of natural or uncontrollable origin. It is estimated that at least 50% of the algae here probably represents a good baseline condition.

When considering baseline dissolved oxygen levels, BOD levels measured in the estuary are low and are typical of natural systems. If the BOD, ocean boundary, one-half the SOD, and one-half of the diurnal components (see algae in paragraph above) are added, a sum of about 60% results. It is estimated that at least 50% of the dissolved oxygen depletion here is a good representation of baseline conditions. The use of one-half the SOD rate as a baseline value results in an average SOD of about 0.5 mg/ft2-day, which is consistent with values typically assigned by MDEP for lowly impacted estuaries.

Model Prediction Runs

The August 16-20 data set was used as a basis to set design conditions for the model prediction run. This data set contained the lowest boundary dissolved oxygen conditions, higher water temperatures than the July data set, and represented the closest tide conditions to a neap tide. In the model "worse case" prediction runs, the fresh water inputs are set at 7 day 10 year low flow (7Q10) conditions and point sources are set at full licensed loads. Tidal conditions are set at neap tide or the time during the monthly tidal cycle when the prism volume is the lowest. Low fresh water inputs and neap tide represent conditions of the slowest flushing of pollutants from the estuary. Water temperatures are adjusted to the warmest temperatures reached in the summer. Warmer water represent a worse case due to lower saturation values of dissolved oxygen, increased biological activity resulting in higher rates of BOD decay and higher sediment oxygen demand, and increased algal activity.

It should be recognized that the model predictions of worse case are conditions that occur very infrequently (a week once every ten years). Due to model uncertainty, an important consideration is assuring that an adequate margin of safety (MOS) is provided. The MOS may be expressed implicitly (through conservative assumptions or explicitly (as loadings set aside). MDEP's implicit approach to MOS involves the use of such conservative assumptions as 7Q10 flow, neap tide and maximum loading from point sources all occurring simultaneously.

There are no long term flow gaging records located on the St George River that can be used to calculate a 7Q10 flow. Prior estimates by MDEP based upon a USGS regression equation (Parker, Sept 1977) resulted in an estimate of 17 cfs for 7Q10 flow at Payson Park. This estimate is considered unreliable due to the constraints of the regression equation. This equation is restricted to unregulated watersheds. Some flow regulation occurs on the St George River from a series of lakes located in the upper part of the basin. The regression equation has a standard error of 68%.

The Sheepscot River, a nearby watershed with similar characteristics to the St George River, experienced a low flow recurrence interval in-between 5 to 10 years last summer. It is estimated that something close to a ten-year low flow was experienced on the St George River last summer. The flow measured in the latter part of the summer at Payson Park was used as an estimate of 7Q10 on the St George River. This results in a 7Q10 flow of about 10 cfs at Payson Park. The model component analysis has indicated that the landward boundary input is not a significant part of the model, so the exact calculation of 7Q10 is not critical to the model.

A different diurnal adjustment (figure 29a) was made to the model prediction runs than that used for the calibration data (figure 23). A linear regression was calculated to the largest diurnal dissolved oxygen range observed over a three day sampling period and a three day average chlorophyll a observed at individual sampling locations. The diurnal dissolved oxygen adjustment is made by use of the chlorophyll a predicted by the model, and obtaining the diurnal adjustment off the regression plot (figure 29a). The minimum dissolved oxygen predicted by the model is obtained by the difference of the daily average dissolved oxygen (model output) and the diurnal adjustment.

It was initially deduced that a relationship of diurnal dissolved oxygen to chlorophyll a was desirable in the model prediction runs, due to the possibility of a higher chlorophyll a predicted by the model under worse case conditions than what was observed in the calibration data sets. It was also necessary to obtain a "worse case" diurnal adjustment. Both the timing of the sampling in the tidal cycle and time of day were not always reflective of the desired times to obtain the total diurnal range. Hence a worse case rather than an average diurnal adjustment was deemed necessary in the model prediction run. (The fit of the regression line to the data is poor, despite extensive analysis by MDEP. This could indicate that for the small differences of chlorophyll a predicted by the model at worse case from the 1999 data, no reliable prediction of diurnal DO is possible. The regression curve will still be used as a MOS for model predictions.)

The design conditions that were used in the model prediction runs are summarized in table 6. The model prediction runs are made with Warren at current design flow (.151 mgd) and compared to model prediction runs at zero discharge in Table 7. The values in this table are those values in the estuary that can be attributed directly to the Warren discharge. The maximum differences in the estuary of TDN and CBOD (.01 and 0.3 ppm, respectively) predicted by the model are small. A maximum difference of 1.3 ppb is predicted in chlorophyll a which represents about 15% of the total peak chlorophyll a (9.8 ppb) predicted by the model at the sample location one mile below Warren village (SGE2). The maximum difference in the estuary of daily minimum dissolved oxygen is predicted to be only 0.03 ppm.

As requested by Warren S.D. personnel, another model run is provided with Warren S. D. at .232 mgd. The differences in TDN and CBOD of .02 and 0.4 ppm, respectively are small. A maximum difference of 1.9 ppb is predicted in chlorophyll a which represents about 21% of the total peak chlorophyll a (10.4 ppb) predicted by the model at the sample location one mile below Warren village (SGE2). The difference in daily minimum dissolved oxygen is predicted to be only 0.02 ppm.

In both (.151 and .232 mgd) of the model prediction runs, the dissolved oxygen lost through diurnal effects involving increased respiration from algae is offset by the higher daily average dissolved oxygen predicted by the model due to the extra daytime photosynthesis occurring as a result of the higher algae levels in the estuary. The dissolved oxygen values that are being offset are very small (<0.1 ppm). It can be concluded that the nutrients and BOD being discharged by Warren have a negligible effect on dissolved oxygen. The differences in D.O. attributable to Warren predicted by the model are less than both measurement and model precision.

The chlorophyll a levels that are attributable to both the Warren discharge and other sources are reason for concern, since levels predicted by the model are approaching bloom conditions.

Plots of the model prediction run are provided showing the various components of dissolved oxygen depletion throughout the estuary (figure 29) and a comparison of the model prediction run dissolved oxygen to required minimum class SB dissolved oxygen criteria of 85% of saturation (figure 30). The model predicts that minimum dissolved oxygen on the St George estuary is about 6 ppm and does not meet regulatory requirements (class SB dissolved oxygen criteria of 85% of saturation) but, on the average, is within 0.6 ppm (7% of saturation) of minimum criteria. This is consistent with what was measured last summer. A single daytime reading of 5.9 ppm was recorded at SGE7 (South Warren) on August 17.

This model prediction includes estimates for high tide in the AM and may not be reflective of a true worse case; low tide in the AM. The minimum dissolved oxygen could be slightly lower under this scenario. However, the dissolved oxygen readings for a three day intensive survey undertaken in August of 1993 by MDEP in which low tide was in the AM does not have three day average readings under 6 ppm. The dissolved oxygen readings for a three day intensive survey undertaken in August of 1990 by MDEP in which high tide was in the AM contains dissolved oxygen readings in the mid 5 ppm range. This older data is reflective of other historic pollutant sources, which have been reduced, so it may be difficult to conclude anything definitive from this data. But it also hasn't necessarily been established that the lowest dissolved oxygen occurs at low tide in the AM rather than high tide in the AM (although this is what one would expect for a default worse case condition).

There is a high degree of uncertainty involved in estuarine modeling, due to the many complexities, which naturally occur in these systems. From work undertaken on other estuaries in Maine, DEP has learned that sediments are ordinarily the largest source of impact in tidal systems. The settling of particulate matter is a natural process in estuaries, which serve as sinks to rivers. Non-point and point sources of pollution can result in increased sediment impacts that wouldn't ordinarily occur in natural systems. Although non-point source pollution can be reduced by implementing best management practices, not all of the sediment of non-point source origin is controllable in a populated watershed. It is very difficult to accurately determine the natural, point source, and non-point source components of estuarine sediments (rough estimates of natural sources are provided earlier in this report).

Due to the mentioned uncertainty, unresolved issues, and the current non-attainment status of the St George estuary, the licensing of the Warren facility should proceed cautiously. To prevent the occurrence of algae blooms, both point source and non-point source nutrient controls are recommended.

The licensing action for Warren uses a strategy to discharge more flow in the non-summer when water quality non-attainment is not an issue. This makes possible restricting the Warren discharge to .10 mgd in the summer, which represents a 1/3 reduction in current design flow and will limit potential nitrogen discharges to the St George estuary. This results in equal summer mass loads of BOD and TSS from current licensed levels and a decrease in historic discharge levels of BOD and TSS.

Model prediction runs are made for Warren at historic (.06 mgd) and proposed summer (.10 mgd) flows and compared to zero discharge at maximum and average effluent nitrogen concentrations (table 8). The results indicate that the chlorophyll a attributable to Warren at worse case drought flow conditions are probably somewhere in-between 0.5 and 1 ppb or 6% to 10% of the total. The D.O. levels attributable to Warren are estimated to be < .02 ppm, which is under measurement and model precision. The levels of chlorophyll a attributable to Warren will be cut in half when compared to early prediction runs at higher effluent flow. This extra MOS is deemed necessary due to the uncertainty of predicting dissolved oxygen in a moderately eutrophic estuarine environment, and to assure that the Warren discharge does not cause or contribute to existing D.O. non-attainment.

Discussion

Although the modeling analysis indicates that non-point source (NPS) inputs are insignificant to the St George estuary seasonally, this isn't necessarily the case, if considered on an annual basis.

During drought flow conditions such as those experienced last summer, NPS loads from tributaries are generally small and are not expected to have a major impact. It is likely that non-point source impacts are experienced in the sediment rather than water column. During higher flow periods, NPS loads to the estuary are much larger and the settling of nutrients and other organic material may be contributing to the sediment problem, which has been identified as a major source of pollution. The St George River has recently been listed by MDEP as one of the priority non-point source (NPS) watersheds. It is possible that the source of pollution from the sediments could be reduced if NPS controls are implemented throughout the watershed. However some of the sediment accumulation in the estuary is either of natural origin or uncontrollable and the expectation of eliminating non-attainment of dissolved oxygen through non-point and / or point source controls may not prove to be feasible.

The model worse case prediction of dissolved oxygen is about 77% of saturation. Earlier it was estimated that at least one- half of the dissolved oxygen deficit (11% of saturation) could be from natural or uncontrollable causes. Hence a baseline dissolved oxygen level for the St George is probably somewhere between 85% and 90% of saturation. Given that all of the non-point source pollution may not be controllable, the difficulty in meeting the 85% of saturation dissolved oxygen criteria is illustrated.

The tributary data taken last summer often had evidence of large levels of non-point source pollution which included elevated CBOD, nutrients, chlorophyll a, bacteria, and low dissolved oxygen. The Mill River had the most evidence of non-point source pollution. It is recommended the BMP's be implemented throughout the watershed, but first on tributaries of the St George River, where the current impacts or future improvements are more easily measurable. Sanitary surveys to check for illegal overboard discharges or failing septic systems may also be necessary.

The DEP has learned through many years of sampling estuaries in Maine that the current SB dissolved oxygen criteria of 85% of saturation is difficult to meet in central and southern Maine. Of all the estuaries DEP has sampled in this portion of Maine, not more than 10% to 20% have met the class SB dissolved oxygen criteria. Despite DEP's findings, the majority of the St George estuary (everything below the Thomaston state prison) meets the 85% of saturation criteria. The water quality problems are generally limited to the upper four miles of estuary during the summer period.

There are many factors that influence dissolved oxygen in estuaries. Substrate composition , flushing, and physical factors such as depth and the bottom area to volume ratio are as important as the pollutant loads going into the estuarine system. Estuaries of southern and central Maine often have predominately silt and clay substrates that result in more nutrient and organic oxygen consuming materials when compared to the eastern Maine estuaries. The southern and central estuaries also have lower tidal prisms that promote slower flushing of pollutants. The upper St. George estuary can be characterized as a slowly flushed estuary.

Graphs (figures 4a, 4b, 4c) of measured dissolved oxygen in the St George River Data Report illustrate lower dissolved oxygen during the third data set (Warren at full discharge) when compared to the first data set (Warren at zero discharge). Many have attributed the lower dissolved oxygen readings to the Warren discharge. However, the DEP deduces that the lower early morning dissolved oxygen levels observed in the data set with Warren at full discharge, when compared to zero discharge, were primarily caused by two factors: (1) The dissolved oxygen at the ocean boundary was about 0.6 ppm lower when Warren was at full discharge; (2) The estuary was sampled at ebb tide during full discharge and high tide during zero discharge (see figures 31 to 33).

Lower early morning dissolved oxygen is ordinarily expected at ebb and low tides and higher early morning dissolved oxygen at high tide. At high tides, the estuary is cleansed with ocean water of higher dissolved oxygen and sediment impacts are less due to the deeper water depth (higher volume to bottom area ratio). Conversely as the depth is reduced sediment oxygen demand becomes more significant leading to decreasing dissolved oxygen at ebb tide and the lowest dissolved oxygen at low tide.

The cleansing action of the ocean was reduced somewhat in the third data set when compared to the first, since the dissolved oxygen of the former was lower by about 0.6 ppm. The lower dissolved oxygen at the ocean boundary can be explained by higher ocean water temperature typically experienced in mid August and possibly the respiration or die-off of algae blooms which occasionally migrate from the ocean. A model runs shows that this reduction in dissolved oxygen at the ocean boundary results in about a 0.2 ppm lowering in D.O near the sag point location (figure 34).

Figures

Tables

Responses to Public Comment