2. UMR-LP MODEL DEVELOPMENT

This chapter provides a discussion of the model development process for the linked ECOMSED/RCA framework for simulation of hydrodynamic, sediment transport, and water quality dynamics. Specific discussion is provided for model selection, the conceptual model framework, and the representation and coding of key processes in both ECOMSED and RCA. This chapter concludes with a discussion of model processing tools/capabilities and implementation.

2.1 MODEL SELECTION

The original model framework for the Upper Mississippi River (UMR) system was developed by HydroQual, Inc. (HQI) in the late 1990s using customized versions of the ECOMSED hydrodynamic / sediment transport model and the Row-Column AESOP (RCA) water quality model. Public domain versions of ECOMSED and RCA and supporting documentation were also available directly from HQI.

The public domain versions of ECOMSED and RCA were evaluated against the original HQI models developed for the UMR to determine which framework would provide the best starting point for modeling activities on this project. In spring 2006, LTI provided a recommendation to MPCA and the SAP that the public domain versions of both models be adopted for use on this project. In addition, it was recommended that the public domain source codes be modified as necessary to reflect UMR-specific enhancements included in the original model framework. These recommendations were accepted by MPCA and the SAP. The rationale for selecting the public domain versions of ECOMSED and RCA to support project modeling activities is provided in the following sections.

2.1.1 Review of HQI Upper Mississippi River Model

A review of the source code files, including various “hardcoded” portions of the original HQI code was conducted. In addition, the HQI UMR ECOMSED and RCA codes were compiled using the Digital Visual Fortran 6.0 compiler. Test simulations for both models were attempted based on the inputs provided for the year 1985. During the process of reviewing, compiling, and testing the source code, several significant concerns were noted related to the UMR codes. Given the difficulties encountered with the existing UMR versions of ECOMSED and RCA, the feasibility of adapting the UMR model to the recent public domain versions of ECOMSED (v1.3 – released in 2002) and RCA (v3.0 – released in 2004) developed by HQI was explored. In addition to reviewing the source code and accompanying documentation for these models, the feasibility of moving to the public domain frameworks was considered.

2.1.2 Comparison of UMR Model to Public-Domain Codes

The following benefits were identified with respect to moving to the public domain versions of ECOMSED and RCA:

- Public domain versions of ECOMSED/RCA are much better documented than the existing UMR versions. The public domain versions are accompanied by user manuals and code comments are more extensive, better organized, and easier to interpret.
- Public domain versions of ECOMSED/RCA were compiled with a modern compiler (Compaq Visual Fortran), which is more effective at identifying and resolving memory allocation errors. The Compaq compiler used by HQI belongs to the same family of compilers used by LimnoTech staff. Preliminary compilation and testing of the public domain codes has been successfully conducted, providing confidence that these codes are free of the errors identified within original source code files.
- Public domain version of ECOMSED uses a "sigma-level" vertical coordinate representation as opposed to the "z-level" representation that was implemented in the original ECOMSED code used for the UMR application. The "sigma" representation generally provides better resolution of near-shore water column response because the same numbers of vertical layers are maintained throughout the model domain. In addition, conducting sensitivity analysis on the vertical grid resolution is more easily accomplished with a "sigma" representation.
- Public domain versions of ECOMSED/RCA provide a better suite of standard output options, which provides significant advantages in processing and interpreting model results. As a result, developing an effective and friendly user interface for the linked modeling framework could be more readily accomplished.
- Finally, the model would be available freely in the public domain, so that future refinement and/or use of the model will not carry any restrictions.

The disadvantage of the public domain versions of ECOMSED/RCA is that both models are missing some of the site-specific code sections that were developed for the original UMR application, including:

- Full linkage of RCA to ECOMSED predictions for cohesive and non-cohesive suspended sediment concentrations;
- Representation within RCA of inorganic phosphorus partitioning to cohesive and non-cohesive suspended sediments present in the water column;
- Miscellaneous code changes in ECOMSED to accommodate lock and dam operations; and
- Miscellaneous code changes to accommodate averaging of state variables across portions of the spatial model domain (e.g., Lake Pepin).

2.1.3 Selected Approach

Based on the information provided above, the project team recommended that the existing UMR models be ported to the public domain versions of ECOMSED and RCA. The rationale for this recommendation was as follows:

- Overall, the team had greater confidence that the public domain versions would allow the modeling objectives to be met in an efficient manner. In particular, the public domain versions could be more readily updated in the future to include other kinetic processes and/or state variables as required by interactions with MPCA, the SAP, and other stakeholders (e.g., coupling a SAV sub-model).
- The public domain version of ECOMSED/RCA represents a framework that is more in line with the current state-of-the-art of advanced eutrophication modeling because of the use of sigma coordinates and the capability to use two different phytoplankton growth models.
- The existence of a comprehensive user's manual and better internal code documentation allows for a more thorough understanding of model capabilities and input/output structures. The availability of documentation is an important feature in terms of maintaining the usefulness of the model application into the future.
- Overall, the level of effort involved in adapting the Upper Mississippi River model to the public domain versions was estimated to be similar to that for troubleshooting and enhancing the original ECOMSED/RCA codes. In addition, converting the UMR model to the public domain version will likely circumvent future problems associated with updating and testing the ECOMSED and RCA source codes.

After this recommendation was accepted by MPCA and the SAP, the project team incorporated the UMR "hardcoding" into the public domain source code and adapted the existing input structures to be consistent with the public domain versions. As verification that the coding changes worked as expected, it was confirmed that the new code largely reproduced the original version's calibrated simulation for the 1985-1996 period.

2.2 OVERVIEW OF MODEL FRAMEWORK

The three-dimensional, fine-scale water quality modeling framework developed for the Upper Mississippi River consists of an ECOMSED hydrodynamic/sediment and a Row-Column AESOP (RCA) water quality model. The two models operate on the same computational grid, and hydrodynamic and sediment transport predictions from the ECOMSED model are linked directly to the RCA model to inform the water quality simulation.

ECOMSED is a state-of-the-art hydrodynamic and sediment transport model capable of computing water circulation patterns, water temperature, salinity, general mixing

and transport, and deposition and resuspension of cohesive and non-cohesive sediments (HydroQual 2002a). Output variables predicted by ECOMSED that are of interest for the UMR framework include local water surface elevation and depth, flow and velocity gradients, water temperature, and suspended concentrations of cohesive and non-cohesive sediments.

The RCA model is a part of a family of generalized water quality models developed by HydroQual, Inc. and known as AESOP (Advanced Ecological Systems Operating Program) (HydroQual 2004). The RCA model framework is capable of simulating water quality dynamics on a fine-scale, multi-dimensional computational grid based on linkage to an external hydrodynamic model application. RCA is specifically designed to interface with the ECOMSED model via a series of binary files generated by the latter model. The general transport fields predicted by ECOMSED (or another hydrodynamic model) are used by RCA to advect and disperse water quality constituents throughout the water column. Likewise, the sediment transport fields provided by ECOMSED, including deposition and resuspension fluxes, are used by RCA to simulate the advection, dispersion, settling, and resuspension of cohesive and non-cohesive sediments.

In the ECOMSED/RCA application developed for the UMR system, the models operate on the three computational grids originally developed by HQI for Pools 2, 3, and 4, respectively. Each pool is simulated independently and flows and constituent loadings passing Lock and Dam No. 2 (LD2) and Lock and Dam No. 3 (LD3) are used as upstream boundary conditions for Pool 3 and Pool 4, respectively. The current application improves on the previous HQI application in a number of ways, including the use of equivalent grids for ECOMSED and RCA. The original UMR application utilized a much coarser three-dimensional grid for the water quality simulation, which required "collapsing" finer-scale ECOMSED predictions to the coarser grid space. The consistent use of a single grid for both the hydrodynamic and water quality not only provides better spatial resolution for the water quality simulation, but also avoids the artificial "smoothing" of information that occurs during the collapsing process.

2.3 HYDRODYNAMIC/SEDIMENT TRANSPORT MODEL (ECOMSED)

The "ECOM" component of the ECOMSED modeling framework is used to simulate multi-dimensional and time-dependent hydrodynamic behavior in the Upper Mississippi River from Lock and Dam No. 1 (LD1) to Lock and Dam No. 4 (LD4). The ECOM module has been applied successfully for a range of sites, including coastal and estuarine water systems. Detailed presentation and discussion of the algorithms used by ECOM to simulate hydrodynamic and thermodynamic behavior are documented in various publications, including the HQI Upper Mississippi River final project report (HydroQual 2002c) and a user's manual developed by HQI for the publicly available version (v1.3) (HydroQual 2002a).

As a complementary module to the "ECOM" hydrodynamic module, the "SED" component of the overall ECOMSED framework may be used to simulate the

transport and fate of cohesive and non-cohesive sediments. Advective/dispersive transport and deposition and resuspension processes are simulated for cohesive sediments, which represent clays, fine and medium silts, and associated organic material. Likewise, transport and deposition/resuspension may be simulated for a non-cohesive sediment class, which typically represents medium to coarse sands, based on formulations developed by van Rijn (HydroQual 2002a). Although bed load transport of non-cohesive sediment is not available as an option in ECOMSED, the model can be configured to represent armoring of the sediment bed due to particle heterogeneity and sorting.

This section provides a detailed discussion of the hydrodynamic and sediment transport components of the ECOMSED model application for the UMR. Specific topics include model domain and segmentation, boundary conditions, and sediment transport processes. Similarities and differences between the revised ECOMSED framework and the original HQI framework are discussed throughout the following sections.

2.3.1 Model Framework Configuration

As discussed in Section 2.1, it was determined in Year 1 that the most efficient and beneficial approach for further ECOMSED model development would be to upgrade the application to the public domain version (v1.3) released by HQI in 2002 (HydroQual 2002a). In addition to being a more recent and more robust version of the model code, the public domain version is associated with more advanced documentation than the original HQI version of the UMR ECOMSED model.

The UMR application utilizes the ECOM "prognostic" mode, which computes the water free surface elevation, the three directional components of velocity, water temperature, and turbulent kinetic energy and mixing length. Although salinity is available as an additional prognostic state variable, this variable is not actively simulated in the UMR application because dissolved solids are not a significant factor affecting water quality response in the UMR/Lake Pepin system.

With the exception of vertical grid representation, which is discussed in Section 2.3.2, the public domain version of ECOMSED is functionally very similar to the original model for the UMR system. Therefore, it was not necessary to make significant alterations to the public domain ECOMSED source code. Minor modifications to the model included adding the necessary code to output 2-hour average predicted flow, temperature, and suspended sediment loading at the lock and dam locations. Results reported for LD2 and LD3 were used to specify boundary conditions for the Pool 3 and Pool 4 simulations, respectively. Other modifications to the public domain model included necessary alterations to the wind-wave module to ensure realistic resuspension behavior in shallow-water areas of Pools 2 and 3.

2.3.2 Model Segmentation

The ECOMSED hydrodynamic model consists of three sub-models representing Pool 2 (including Spring Lake), Pool 3, and Pool 4 (including Lake Pepin). The horizontal grid resolution and bathymetry represented in the updated ECOMSED model application is identical to that used for the original HQI application and is depicted in Figures 2-1, 2-2, and 2-3 for Pools 2, 3, and 4, respectively.

In terms of vertical segmentation, the original HQI model utilized a Cartesian "z"-level grid, while the more recent public domain version of ECOMSED utilizes a "sigma"-level or "stretched" vertical grid. For a "z"-level grid, the water column is divided into layers of either uniform or non-uniform thickness defined by constant upper and lower elevation boundaries. The number of active layers represented across the horizontal model domain varies depending on the water depth, thereby producing a "stair step" configuration with more layers in deeper segments and less layers in shallower segments. In a typical "z"-level application, only the volume of the surface water layer varies as the water free surface elevation fluctuates during the course of a model simulation.

For the "sigma"-level grid used in the public domain version of ECOMSED, a constant number of vertical layers is maintained throughout the model domain, as are the thicknesses of those layers relative to the local water column depth. With this configuration, the actual thickness of each sigma level varies through both horizontal space and time. The algorithms specific to a sigma vertical grid representation are detailed in the ECOMSED version 1.3 user's manual developed by HQI (HydroQual 2002a). The "sigma"-level representation potentially provides a more accurate representation of hydrodynamic behavior and water quality transport by providing a higher vertical resolution in shallower regions of Pools 2, 3, and 4 relative to the original ECOMSED application. Six vertical sigma layers (each representing 16.67% of the total water column depth) are used for Pools 3 and 4, while five layers are specified for Pool 2.

Configuration of the public domain version of ECOMSED to the UMR system included the addition of source code to mimic HQI's customization of the original framework. One of the more significant modifications made to the public domain version was the addition of a routine to extract model-predicted, vertically-averaged output for key variables (averaged over a daily interval) for grid locations representing the outlet of each pool. Simulation output extracted by this routine is used to facilitate the linkage of flow, water temperature, and suspended sediment concentrations at LD2 and LD3 to the upstream boundaries for Pool 3 and Pool 4, respectively. The necessary source code changes were incorporated into the public domain version of ECOMSED to reproduce this approach.

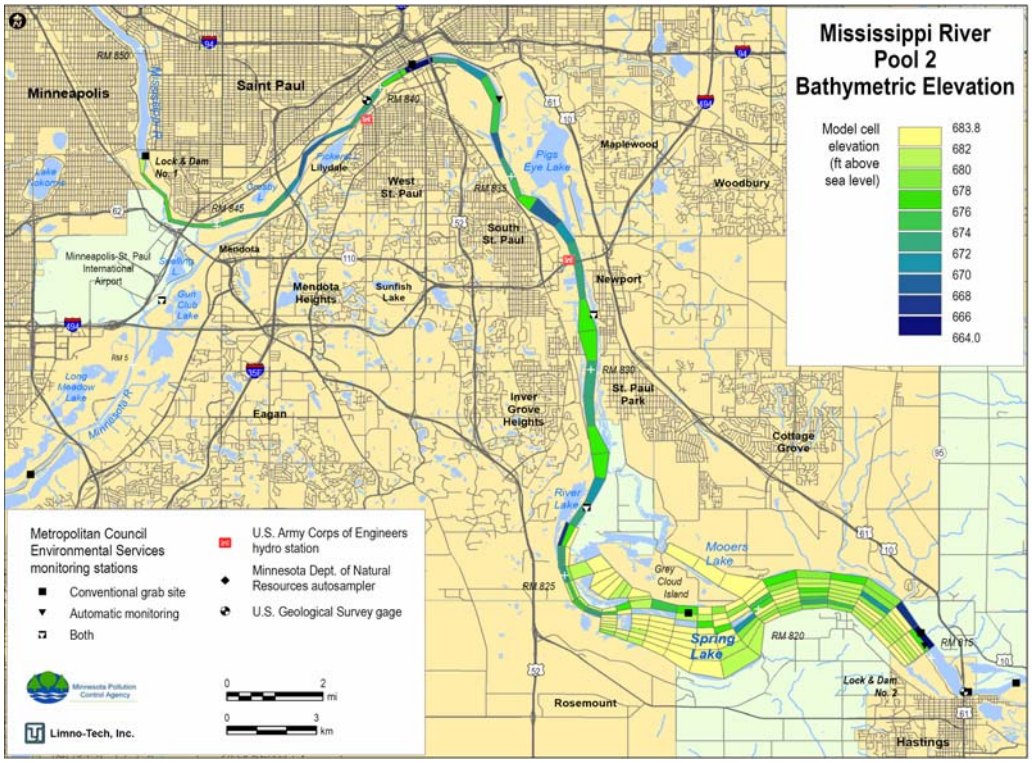

Figure 2-1. ECOM/RCA Model Grid for Upper Mississippi River (Pool 2)

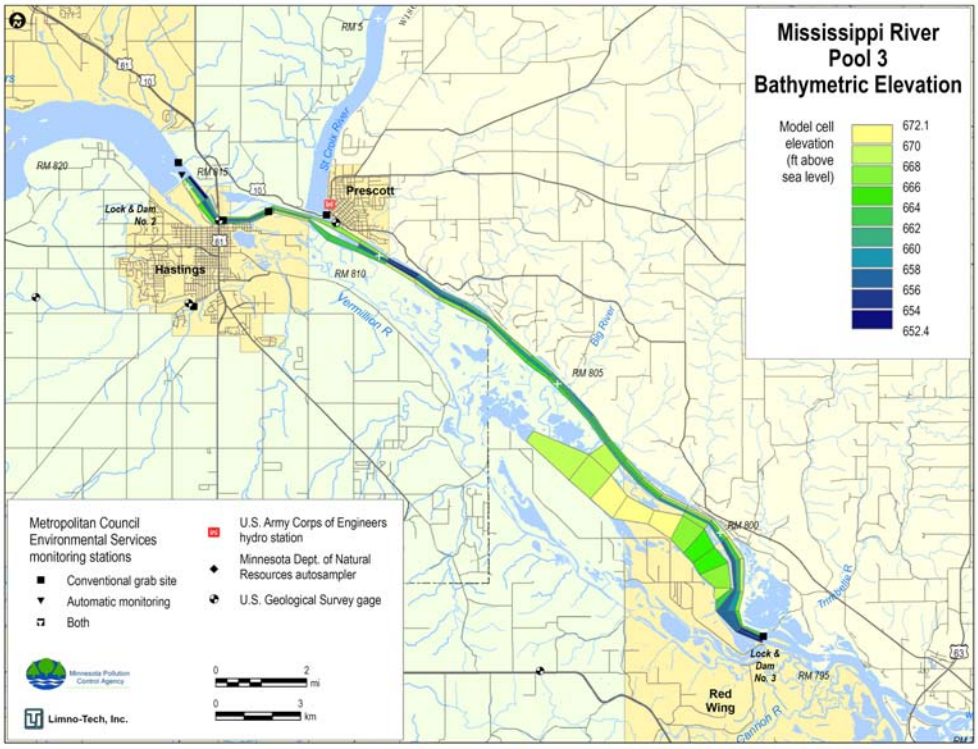

Figure 2-2. ECOM/RCA Model Grid for Upper Mississippi River (Pool 3)

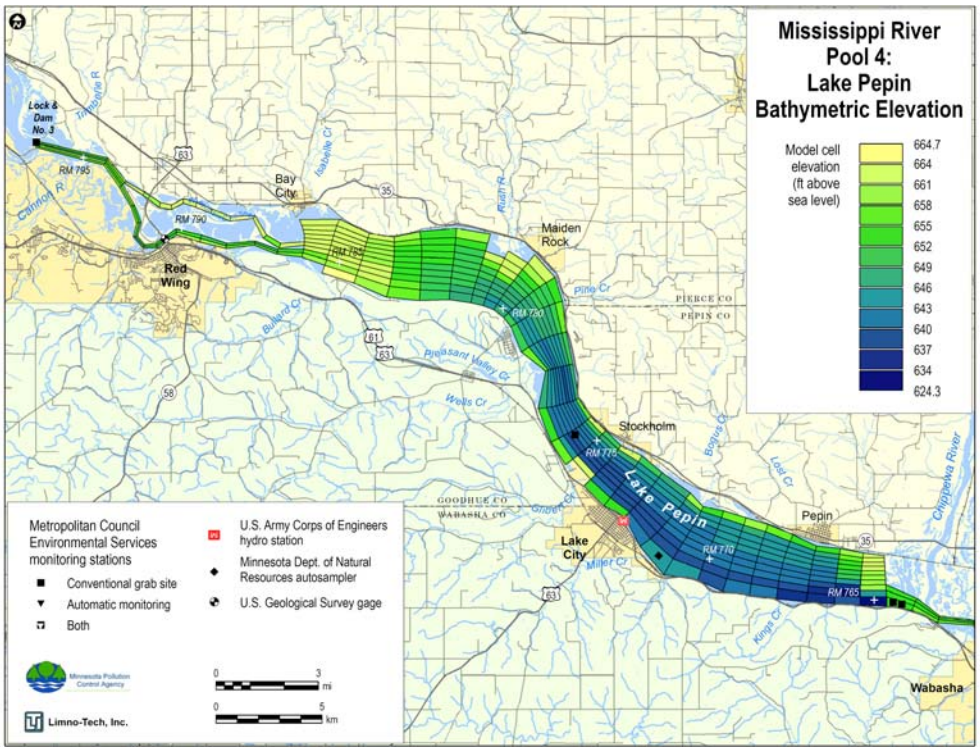

Figure 2-3. ECOM/RCA Model Grid for Upper Mississippi River (Pool 4)

2.3.3 Boundary Conditions

The major classes of boundary conditions used in the ECOMSED model include a set of environmental forcing functions, hydrodynamic and temperature boundary conditions, and suspended sediment boundary concentrations. Each of these boundary condition classes is discussed below.

Environmental Parameters

The environmental boundary conditions for the UMR application consist of forcing functions (i.e., time series) representing hourly input data for a series of atmospheric variables and fractional ice cover. Atmospheric variables for which ECOMSED requires an input forcing function include:

- Wind speed and direction;
- Solar radiation;
- Air temperature;
- Relative humidity;
- Barometric pressure; and
- Cloud cover.

The atmospheric forcing functions represented in the updated ECOM modeling framework are based on hourly datasets for the 12-year calibration and confirmation periods covering 1996-2006 and 1985-1995, respectively. Ice cover was represented on a daily basis and was assumed to extend from December 1st through March 31st for each winter period. Meteorological functions used for the 1985-1995 period were generally the same as those used in the original HQI model application. The forcing functions for the later 1996-2006 period were developed based on the same data sources used for the 1985-1995 period. Additional discussion of boundary conditions for environmental parameters is provided in Section 3.2.

Hydrodynamic & Sediment Transport

The hydrodynamic boundary conditions required by ECOM include forcing functions for incoming flows from upstream, tributary/watershed, and point sources, as well as a downstream water level boundary condition for each pool simulation. In addition, constant or time-variable boundary conditions must be specified at these locations for water temperature and suspended sediment concentrations. Upstream and tributary inflow boundary locations include:

- Upper Mississippi River at LD1 (upstream inflow entering Pool 2 at river mile [RM] 848);
- Minnesota River (entering Pool 2 near RM 845);
- MCES Metropolitan WWTP (Metro Plant) effluent (entering Pool 2 near RM 836);
- St. Croix River (entering Pool 3 near RM 811);
- Cannon River (entering Pool 4 near RM 795);
- Vermillion River (entering Pool 4 near RM 795);
- Rush River (entering Pool 4 near RM 780); and
- Chippewa River (entering Pool 4 near RM 764).

As discussed previously, the upstream boundary conditions for Pool 3 and Pool 4 inflows, water temperature, and suspended sediment concentrations, are input based on ECOMSED predictions of flow and constituent loadings at the upstream lock and dam control structures.

Of the tributary systems described above, only the Minnesota River supplies a significant quantity of non-cohesive suspended sediments to the UMR system, and only during high-flow events associated with significant watershed surface runoff and erosion (HydroQual 2002c). Therefore, a boundary concentration series was developed to represent the presence of non-cohesive suspended sediment in this tributary during such events.

The downstream water level boundary conditions were specified as a “clamped” water level/stage forcing function in the original HQI application for Pools 2, 3, and

4. A potential disadvantage of the clamped condition is that it does not allow long-wave energy to radiate out of the model domain at the grid boundary location(s); rather, this type of boundary condition "reflects" this energy component back into the "upstream" model domain. For the newly configured ECOMSED application, the use of the clamped condition was effective in simulating outflow conditions for Pool 4. However, the use of the clamped condition to represent the outlet characteristics of Pools 2 and 3 caused unrealistic lock and dam behavior during low-flow conditions during the 1987-1989 period. Specifically, wide fluctuations in the flow rate at the lock and dam boundary locations were observed on an hourly time scale. To eliminate this problem, an open radiation boundary condition option (as developed by Reid and Bodine) was used in place of the clamped condition for Pools 2 and 3. The open boundary condition allows long-wave energy (e.g., due to periodic wind surface stresses) to pass through the downstream boundary, thereby preventing the undesirable flow fluctuations observed for the clamped condition.

The hourly water level boundary conditions used for 1985-1995 were identical to those developed by HQI for the original model application. Water level boundary conditions were developed by LTI for the 1996-2006 period using available USACE data at lock and dams 2, 3, and 4.

2.3.4 Sediment Transport Processes

The simulation and accounting of sediment bed properties is a critical component of the SED sediment transport module. ECOMSED requires the specification of sediment type (i.e., cohesive or non-cohesive) and other physical properties, including particle size distribution and deposition- and erosion-related process coefficients. Exchange between the water column and the underlying sediment bed may occur through settling/deposition and resuspension processes. A detailed treatment of these sediment transport processes is provided in the HQI user's manual for ECOMSED version 1.3 (HydroQual 2002a). The rate of mass deposition to the bed for cohesive and non-cohesive suspended solids is dictated by a particle settling rate, the local water column suspended sediment concentration, and a probability of deposition term. Resuspension of cohesive or non-cohesive material from the sediment bed to the overlying water column may result from elevated shear stresses caused by either elevated near-bed velocities during high-flow events and/or wind-generated waves. The sediment type assigned to each horizontal model grid was consistent with the original model developed by HQI.

During development and testing of the updated UMR ECOMSED model, some potential errors and inconsistencies were discovered in the public domain wind-wave routines that resulted in excessive resuspension of cohesive sediment in some areas of Pools 2 and 3. These issues were corrected in Year 2 to allow for accurate, realistic simulation of wind-induced resuspension of bottom sediments during model calibration and application.

Complete documentation of the sediment transport algorithms in ECOMSED and supporting theory is provided in the user's manual (HydroQual 2002a). A detailed

discussion of UMR-LP model sediment transport parameterization is provided in Chapter 4.

2.4 WATER QUALITY MODEL (RCA)

The Row-Column AESOP (RCA) model is used as the computational framework to simulate water quality response in the UMR from LD1 to LD4. The basic RCA framework includes a suite of state variables to represent carbon, nitrogen, phosphorus, and algal dynamics, and it is configured to interface directly with the ECOMSED model, including linkage of hydrodynamic and water temperature results. In addition to simulation of water column processes affecting water quality, the RCA framework includes a coupled sediment diagenesis sub-model that simulates the cycling of detrital material and nutrients in the surface sediments and subsequent impacts on near-bed sediment oxygen demand and release of dissolved nutrients, including dissolved inorganic phosphorus. Detailed documentation of the RCA water quality modeling framework, including the sediment diagenesis sub-model, is provided in the HQI Upper Mississippi River final project report (HydroQual 2002c) and a user's manual developed by HQI for the publicly available version 3.0 (HydroQual 2004).

2.4.1 Model Framework Configuration

The original RCA UMR application developed by HQI in the 1990s was based on a version of the framework customized specifically for the UMR system. This customized version of RCA was linked to the customized ECOMSED model, which is described in Section 2.3. The RCA framework was modified in a number of ways for the current UMR application to better represent sediment transport processes and distribution of inorganic phosphorus (i.e., orthophosphate) in the water column.

In 2004, HQI released a public domain version of RCA (version 3.0), including complete documentation and a standard set of eutrophication state variables and associated kinetic routines (HydroQual 2004). As discussed in Section 2.1, it was decided early in Year 1 that the most efficient approach would be to transition the RCA modeling framework to the public domain version along with the ECOMSED components. The benefits of transitioning the UMR model application to the public domain RCA framework are significant and are summarized in Section 2.1. Key modifications made by HQI to the original UMR RCA framework and the approach taken in integrating those customizations into the base public domain RCA framework are summarized below.

Linkage to ECOMSED

The base public domain version of RCA provides a hydrodynamic linkage to ECOMSED; however, it does not include a linkage to the sediment transport results generated by that model. As part of the original UMR application, HQI configured the ECOMSED and RCA models to exchange relevant concentration and rate information for cohesive and non-cohesive suspended sediment, including water

column boundary concentrations, settling and deposition rates, and resuspension mass fluxes. Because suspended sediment is treated conservatively in the water column (neglecting exchange with the sediment bed), it is possible to directly simulate suspended sediment as explicit state variables using the information provided via the ECOMSED linkage. This linkage setup is beneficial because it allows the user to run sensitivity analyses on sediment boundary conditions and settling, deposition, and resuspension rates without re-running the ECOMSED model. The public domain RCA framework was updated to be consistent with the original UMR framework in regards to the sediment transport linkage. A schematic illustrating the ECOMSED/RCA linkage is provided in Figure 2-4.

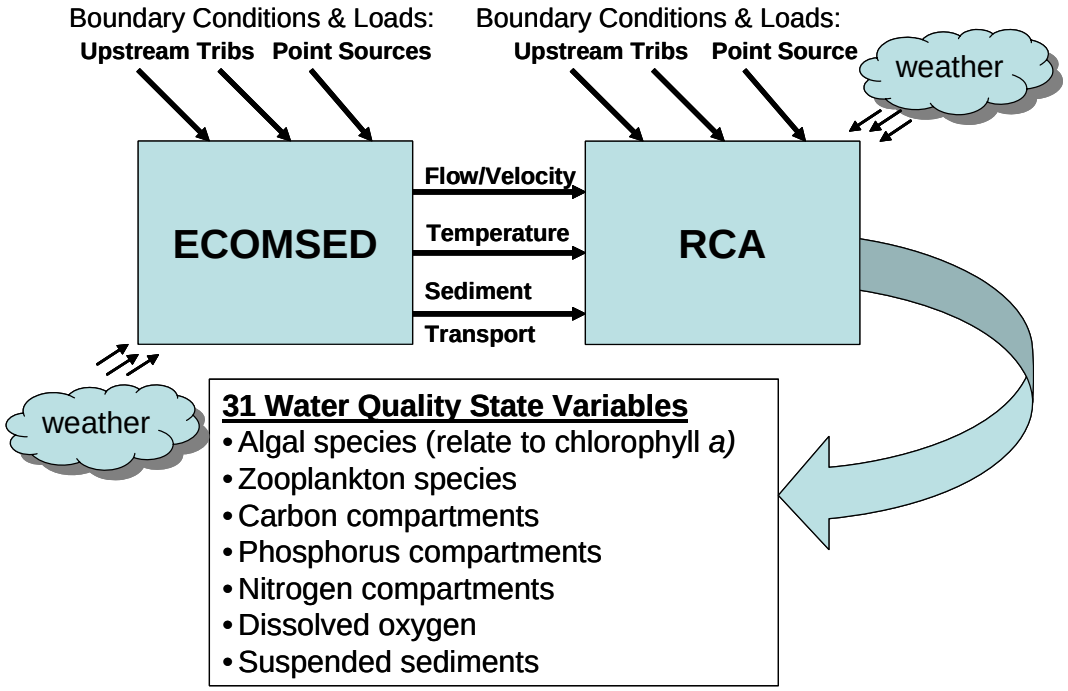

Figure 2-4. ECOMSED-RCA Linkage Schematic

Inorganic Phosphorus Dynamics

The base public domain version of RCA does not represent the adsorption of dissolved inorganic phosphorus (DIP) to non-volatile (i.e., cohesive and non-cohesive) suspended sediments. HQI configured the original UMR framework to simulate partitioning of DIP to cohesive and non-cohesive suspended sediments because this process plays an important role in phosphorus cycling within the UMR system due to the high turbidity levels and deposition rates in Spring Lake and Lake Pepin. The local suspended solids deposition rate and the local particulate inorganic phosphorus (PIP) concentration are used to compute the mass flux of particulate inorganic phosphorus to the sediment bed for use in the coupled sediment diagenesis sub-model. The public domain RCA framework was updated to be consistent with the original UMR framework.

Light Extinction

The previous light extinction algorithm used by HQI for the original UMR RCA application was replaced in favor of a formulation developed by Dr. Robert Megard, using coefficients revised by LTI. The relevant equations and coefficients are presented in Section 2.4.5.

Inorganic Carbon Chemistry

The original HQI application included a complete set of state variables and kinetic processes to simulate components of inorganic carbon chemistry, including total inorganic carbon (TIC), dissolved organic carbon (DOC), and calcium carbonate (CaCO3). Ultimately, the inorganic carbon "sub-model" is computationally expensive and has no impact on other systems represented in the original UMR model (it is assumed that DIP does not adsorb to CaCO3 precipitate). As a result, the inorganic carbon systems and processes were not incorporated into the revised public domain version of RCA.

Zooplankton Dynamics

Biological data for Lake Pepin indicate that zooplankton may have a significant impact on phytoplankton dynamics; however, zooplankton were not included as state variables in the original RCA code for the UMR system. Instead, zooplankton grazing was included essentially as a forcing function based on the measured zooplankton biomass profile during 1996. This grazing function was held constant throughout the 12 year calibration period for the original model, thus not allowing zooplankton biomass to respond to changes in nutrient loads and the resulting phytoplankton production.

As part of the RCA model development process, LTI developed an algorithm to facilitate including zooplankton as state variables in the RCA water quality model, thus allowing appropriate feedback between phytoplankton and zooplankton and associated nutrient cycling. The zooplankton algorithm is based on the Chesapeake Bay Model zooplankton algorithm (Cerco and Noel, 2004) and the AQUATOX model (Park, et al., 2004), with the only significant modification being the inclusion of a growth rate reduction based on the stoichiometry of zooplankton prey (Sterner, 1997). The zooplankton algorithm simulates biomass and nutrient cycling of three groups of zooplankton: cladocerans, copepods, and microzooplankton (e.g., rotifers). The Chesapeake Bay Model simulates mesozooplankton (cladocerans plus copepods) and microzooplankton, but site-specific data for Lake Pepin indicate that cladocerans and copepods compose the mesozooplankton community, with slightly different seasonal dynamics for each group. Therefore, cladocerans and copepods are represented as separate mesozooplankton sub-groups. The zooplankton algorithm, which is described in detail in Section 2.4.5, has been developed to efficiently interact with other applicable state variables and algorithms in the RCA model.

2.4.2 Model Segmentation

The original RCA framework developed by HQI in the 1990s used a water quality grid that was coarser than the computational grid used by the ECOMSED hydrodynamic/sediment transport model. This grid reduction was likely necessitated by long simulation runtimes and/or storage space issues associated with the original RCA calibration and application efforts. However, there are notable disadvantages associated with using a reduced water quality grid for the Upper Mississippi River, including 1) the complex linkage required to properly "collapsing" ECOMSED results to the reduced RCA grid, and 2) loss of resolution in the water quality model for nearshore areas where sudden transitions may exist between deep and shallow zones. An ideal linkage would consist of a one-to-one correspondence between the ECOMSED and RCA model segmentations, thereby avoiding these pitfalls. Since the original model development work took place, significant advances have been made in the availability and affordability of high-end personal computers. Present-day computing power makes it feasible to run the RCA framework at the same spatial grid scale (both horizontal and vertical) as the ECOMSED framework, and this was the approach adapted when configuring and revising the public domain RCA framework. Figures 2-1 through 2-3 depict the horizontal segmentation scheme employed for the revised modeling framework.

2.4.3 Boundary Conditions

Boundary concentration forcing functions must be specified in the RCA model for each simulated water quality system at each boundary location defined for the ECOMSED model. For the UMR application, time-varying water quality boundary conditions are input for:

- Upper Mississippi River at LD1 (Pool 2);
- Minnesota River (Pool 2);
- St. Croix River (Pool 3);
- Cannon River (Pool 4);
- Vermillion River (Pool 4);
- Rush River (Pool 4); and
- Chippewa River (Pool 4).

In addition to tributary boundary conditions, nutrient mass loadings were input to the RCA model for MSP urban/suburban loads, minor tributaries to Pool 4, and the following wastewater treatment plants that discharge directly to the UMR-LP system: Metro Plant, Rosemont, Eagles Point, Empire, Hastings, Prescott, Red Wing, and Lake City. The development of tributary and point source water quality boundary conditions is discussed in detail in Chapter 3.

2.4.4 Eutrophication State Variables

The revised RCA framework includes thirty-one eutrophication state variables, as listed in Table 2-1.

Table 2-1. Upper Mississippi River RCA Water Quality State Variables

System No	System ID	System Description	Units
1	SAL[1]	Salinity	ppt
2	PHYT1	Blue-green algae	mg-C/L
3	PHYT2	Diatom class	mg-C/L
4	PHYT3	Summer assemblage class	mg-C/L
5	RPOP	Particulate Organic Phosphorus - refractory	mg-P/L
6	LPOP	Particulate Organic Phosphorus - labile	mg-P/L
7	RDOP	Dissolved Organic Phosphorus - refractory	mg-P/L
8	LDOP	Dissolved Organic Phosphorus - labile	mg-P/L
9	PO4T	Total Inorganic + Algal Phosphorus	mg-P/L
10	RPON	Particulate Organic Nitrogen - refractory	mg-N/L
11	LPON	Particulate Organic Nitrogen - labile	mg-N/L
12	RDON	Dissolved Organic Nitrogen - refractory	mg-N/L
13	LDON	Dissolved Organic Nitrogen - labile	mg-N/L
14	NH4T	Total Ammonia + Algal Nitrogen	mg-N/L
15	NO23	Nitrite + Nitrate	mg-N/L
16	BSI	Biogenic Silica	mg-Si/L
17	SIT	Total Available Silica	mg-Si/L
18	RPOC	Particulate Organic Carbon - refractory	mg-C/L
19	LPOC	Particulate Organic Carbon - labile	mg-C/L
20	RDOC	Dissolved Organic Carbon - refractory	mg-C/L
21	LDOC	Dissolved Organic Carbon - labile	mg-C/L
22	EXDOC	Dissolved Organic Carbon - algal exudate	mg-C/L
23	REPOC[1]	Particulate Organic Carbon - reactive	mg-C/L
24	REDOC	Dissolved Organic Carbon - reactive	mg-C/L
25	O2EQ	Aqueous SOD	mg-O^2/L
26	DO	Dissolved Oxygen	mg-O^2/L
27	SS1	Suspended Solids, fine	mg/L d.w.[2]
28	SS2	Suspended Solids, coarse	mg/L d.w.[2]
29	ZOO1	Cladocerans	mg-C/L
30	ZOO2	Copepods	mg-C/L
31	ZOO3	Microzooplankton	mg-C/L

[1]The [SAL] and [REPOC] systems are not actively simulated in the current UMR-LP model.
[2]Refers to "dry weight."

Of the thirty-one variables shown in Table 2-1, only salinity [SAL] and reactive particulate organic carbon [REPOC] are not actively simulated in the UMR application. As discussed in the previous sub-section, cohesive [SS1] and non-cohesive [SS2] suspended sediment are modeled explicitly within the RCA framework using boundary concentration and water-sediment exchange process rates provided via the linkage to ECOMSED. The basic relationships between the RCA state variables and other quantities of interest are provided in the below sub-sections for phytoplankton, zooplankton, carbon, nitrogen, and phosphorus components.

Biological Components

The RCA model simulates phytoplankton and zooplankton biomass on a carbon basis (mg-C/L). Algal-bound carbon is provided directly by the combination of the [PHYT1], [PHYT2], and [PHYT3] systems. For simplicity, [AlgC], [AlgP], and [AlgN] can be used to represent phytoplankton biomass expressed in carbon, phosphorus, and nitrogen equivalents, respectively:

$$[Alg\,C] = [PHYT1] + [PHYT2] + [PHYT3] \tag{2-1}$$

$$[Alg\,P] = \frac{[PHYT1]}{\left(R_{C:P,\,PHYT1}\right)} + \frac{[PHYT2]}{\left(R_{C:P,\,PHYT2}\right)} + \frac{[PHYT3]}{\left(R_{C:P,\,PHYT3}\right)} \tag{2-2}$$

$$[Alg\,N] = \frac{[PHYT1]}{\left(R_{C:N,\,PHYT1}\right)} + \frac{[PHYT2]}{\left(R_{C:N,\,PHYT2}\right)} + \frac{[PHYT3]}{\left(R_{C:N,\,PHYT3}\right)} \tag{2-3}$$

In Equations 2-2 and 2-3, $R_{C:P,\,PHYTi}$ and $R_{C:N,\,PHYTi}$ represent the carbon:phosphorus (C:P) and carbon:nitrogen (C:N) ratios, respectively, for phytoplankton class *i*. The current RCA model varies these ratios per user-defined limits based on whether or not the model predicts nutrient limitations (i.e., "starvation" conditions). The UMR is currently a light-limited system under nearly all hydrologic and meteorological conditions. Therefore, the minimum ratios of 40 mg-C/mg-P and 5.68 mg-C/mg-N specified for all three classes are typically being used.

Similar to phytoplankton carbon, zooplankton-bound carbon can be calculated directly as the sum of the cladoceran (ZOO1), copepod (ZOO2), and microzooplankton (ZOO3) systems. For simplicity, [ZooC], [ZooP], and [ZooN] can be used to represent zooplankton biomass expressed in carbon, phosphorus, and nitrogen equivalents, respectively:

$$[ZooC] = [ZOO1] + [ZOO2] + [ZOO3] \tag{2-4}$$

$$[ZooP] = \frac{[ZOO1]}{\left(R_{C:P,\,ZOO1}\right)} + \frac{[ZOO2]}{\left(R_{C:P,\,ZOO2}\right)} + \frac{[ZOO3]}{\left(R_{C:P,\,ZOO3}\right)} \tag{2-5}$$

$$[ZooN] = \frac{[ZOO1]}{\left(R_{C:N,\,ZOO1}\right)} + \frac{[ZOO2]}{\left(R_{C:N,\,ZOO2}\right)} + \frac{[ZOO3]}{\left(R_{C:N,\,ZOO3}\right)} \tag{2-6}$$

In Equations 2-2 and 2-3, $R_{C:P,\,ZOOi}$ and $R_{C:N,\,ZOOi}$ represent the C:P and C:N ratios, respectively, for zooplankton class *i*. Constant C:P and C:N ratios of 50 mg-C/mg-P and 5 mg-C/mg-N, respectively, were used for all three zooplankton classes in the RCA model application.

RCA tracks algal-bound and zooplankton-bound nitrogen (N) and phosphorus (P) as fractions of the [NH4T] and [PO4T] systems, respectively. In the below equations,

[NH4] and [DIP] will be used to denote dissolved inorganic ammonia and orthophosphate. In Equation 2-8, [PO4SS1] and [PO4SS2] represent inorganic phosphorus adsorbed to cohesive and non-cohesive sediment, respectively.

$$[NH4] = [NH4T] - [A\lg N] - [ZooN] \tag{2-7}$$

$$[DIP] = [PO4T] - \left([PO4SS1] + [PO4SS2]\right) - [A\lg P] - [ZooP] \tag{2-8}$$

Carbon Components

The carbon components represented in the RCA framework can be summarized by Equations 2-9 through 2-11 (all quantities have units of mg-C/L). As discussed previously, inorganic carbon components (i.e., TIC, DIC, CO2, and CaCO3) are not explicitly represented in the current RCA UMR-LP model because this sub-system does not significantly influence the processing and recycling of nutrients that principally drive the UMR system response.

- *Total Organic Carbon (TOC):*

$$\begin{aligned}[TOC] = &([RPOC] + [LPOC]) + ([RDOC] + [LDOC]) \\ &+ ([REDOC] + [EXDOC]) + [A\lg C] + [ZooC]\end{aligned} \tag{2-9}$$

- *Particulate Organic Carbon (POC):*

$$[POC] = [RPOC] + [LPOC] + [A\lg C] + [ZooC] \tag{2-10}$$

- *Dissolved Organic Carbon (DOC):*

$$[DOC] = [RDOC] + [LDOC] + [REDOC] + [EXDOC] \tag{2-11}$$

Nitrogen Components

The nitrogen components represented in the RCA framework can be summarized by Equations 2-12 through 2-17 (all quantities have units of mg-N/L). It should be noted that particulate inorganic nitrogen (PIN) is not represented in the framework.

- *Total Nitrogen (TN):*

$$\begin{aligned}[TN] = &([RPON] + [LPON]) + ([RDON] + [LDON]) \\ &+ ([NH4] + [NO23]) + [A\lg N] + [ZooN]\end{aligned} \tag{2-12}$$

- *Total Organic Nitrogen, non-algal (TON):*

$$[TON] = ([RPON] + [LPON]) + ([RDON] + [LDON]) \tag{2-13}$$

- *Particulate Organic Nitrogen (PON):*

$$[PON] = [RPON] + [LPON] + [Alg\,N] + [ZooN] \quad (2\text{-}14)$$

- *Dissolved Organic Nitrogen (DON):*

$$[DON] = [RDON] + [LDON] \quad (2\text{-}15)$$

- *Total Inorganic Nitrogen (TIN):*

$$[TIN] = [DIN] = [NH4] + [NO23] \quad (2\text{-}16)$$

- *Dissolved Inorganic Nitrogen (DIN):*

$$[DIN] = [NH4] + [NO23] \quad (2\text{-}17)$$

Phosphorus Components

The phosphorus components represented in the RCA framework can be summarized by Equations 2-18 through 2-24 (all quantities have units of mg-P/L). It should be noted that in RCA, [DPO4] represents actual dissolved P, [PO4SS1] represents inorganic P (mg-P/L) sorbed to cohesive solids, and [PO4SS2] represents inorganic P (mg-P/L) sorbed to non-cohesive solids.

- *Total Phosphorus (TP):*

$$[TP] = ([RPOP] + [LPOP]) + ([RDOP] + [LDOP]) + [DIP] + ([PO4SS1] + [PO4SS2]) + [Alg\,P] + [ZooP] \quad (2\text{-}18)$$

- *Total Organic Phosphorus (TOP):*

$$[TOP] = ([RPOP] + [LPOP]) + ([RDOP] + [LDOP]) + ([Alg\,P] + [ZooP]) \quad (2\text{-}19)$$

- *Particulate Organic Phosphorus (POP):*

$$[POP] = [RPOP] + [LPOP] \quad (2\text{-}20)$$

- *Dissolved Organic Phosphorus (DOP):*

$$[DOP] = [RDOP] + [LDOP] \quad (2\text{-}21)$$

- *Total Inorganic Phosphorus (TIP):*

$$[TIP] = [PO4] = [DIP] + ([PO4SS1] + [PO4SS2]) \quad (2\text{-}22)$$

(Note: In RCA, [DIP] represents actual dissolved PO_4, [PO4SS1] represents inorganic phosphate (mg-P/L) sorbed to cohesive solids, and [PO4SS2] represents inorganic phosphate (mg-P/L) sorbed to non-cohesive solids.

- *Particulate Inorganic Phosphorus (PIP):*

$$[PIP] = [PO4SS1] + [PO4SS2] \quad (2\text{-}23)$$

- *Dissolved Inorganic Phosphorus (DIP):*

$$[DIP] = [DPO4] \quad (2\text{-}24)$$

2.4.5 Eutrophication Processes

The revised RCA framework includes a fully integrated eutrophication and sediment nutrient flux modeling framework customized specifically for the UMR system. The modeling framework is based on the conservation of mass principle, which says that all mass leaving a given model compartment (i.e., segment) must be accounted for by incoming/outgoing transport and/or gains/losses via simulated transformation processes. The following sub-sections provide an overview of key processes related to phytoplankton production, zooplankton dynamics, and cycling of the carbon, nitrogen, and phosphorus components simulated within the RCA framework.

Phytoplankton

As indicated in Table 2-1, RCA includes three phytoplankton state variables representing the biomass (on a carbon basis) of blue-green algae [PHYT1], winter/spring diatoms [PHYT2], and a summer assemblage [PHYT3]. Viable chlorophyll *a*, the most typical method for measuring total algal biomass is related to the RCA phytoplankton state variables by the following:

$$\{Chla\} = \frac{1000\,ug/mg}{\left(R_{C:Chla,PHYT1}\right)} * [PHYT1] + \frac{1000\,ug/mg}{\left(R_{C:Chla,PHYT2}\right)} * [PHYT2] + \frac{1000\,ug/mg}{\left(R_{C:Chla,PHYT3}\right)} * [PHYT3] \quad (2\text{-}25)$$

where $\{Chla\}$ represents the total viable chlorophyll *a* concentration (µg/L), and $R_{C:Chla,\,PHYT*}$ represents the carbon:chlorophyll *a* ratio for each phytoplankton class (specified as 33 mg-C/mg-Chla for blue-greens and summer assemblage, and 50 mg-C/mg-Chla for winter diatoms). It should be noted that the term "chlorophyll *a*" used throughout this report always refers to the viable (i.e., pheophytin-corrected) chlorophyll *a* concentration.

Net production (S_p, mg/l/day^{-1}) of each phytoplankton class is computed as the difference between gross growth (G_p, day^{-1}) and death (D_p, day^{-1}) via endogenous respiration and zooplankton grazing as shown below:

$$S_p = (G_P - D_P) * P \tag{2-26}$$

where *P* is the initial biomass (mg-C/L) of a given phytoplankton class. Gross production of phytoplankton is computed as the product of a maximum (i.e., saturated) growth rate (day^{-1}) and a correction factor that reflects Michaelis-Menton assumptions regarding potential light, phosphorus, and nitrogen limitations.

The growth rate (G_p) in Equation 2-26 is computed assuming a multiplicative relationship with ambient water temperature, light, and nutrient availability:

$$G_p = G_{P,\max} * \left[G_T(T) * G_I(I) * G_N(N)\right] \tag{2-27}$$

where: $G_{P,max}$ is the temperature-corrected maximum growth rate (day^{-1});

$G_T(T)$ is the effect of temperature on growth rate;

$G_I(I)$ is the effect of light attenuation on growth rate; and

$G_N(N)$ is the effect of nutrient limitation on growth rate.

The temperature correction for maximum growth rate ($G_{P,max}$) is calculated by RCA based on the time and space-variable water temperature predicted by the ECOMSED hydrodynamic model:

$$\begin{aligned} G_T(T) &= e^{-\beta_1 (T_{opt} - T)^2} \qquad \text{for } T \le T_{opt} \\ G_T(T) &= e^{-\beta_2 (T_{opt} - T)^2} \qquad \text{for } T > T_{opt} \end{aligned} \tag{2-28}$$

where T_{opt} (°C) is the optimal temperature, and β_1 and β_2 are shaping coefficients for a particular phytoplankton class. Figure 2-5 shows the maximum growth rate as a function of temperature for the three phytoplankton classes simulated in the current model: blue-greens, diatoms, and summer assemblage. As indicated in this figure, the optimal temperature for winter diatoms (15°C) is considerably lower than that for blue-greens and summer assemblage. Therefore, cooler temperatures in late winter, spring, and fall tend to favor diatom growth, while higher temperatures in the summer favor the growth of summer assemblage and blue-greens.

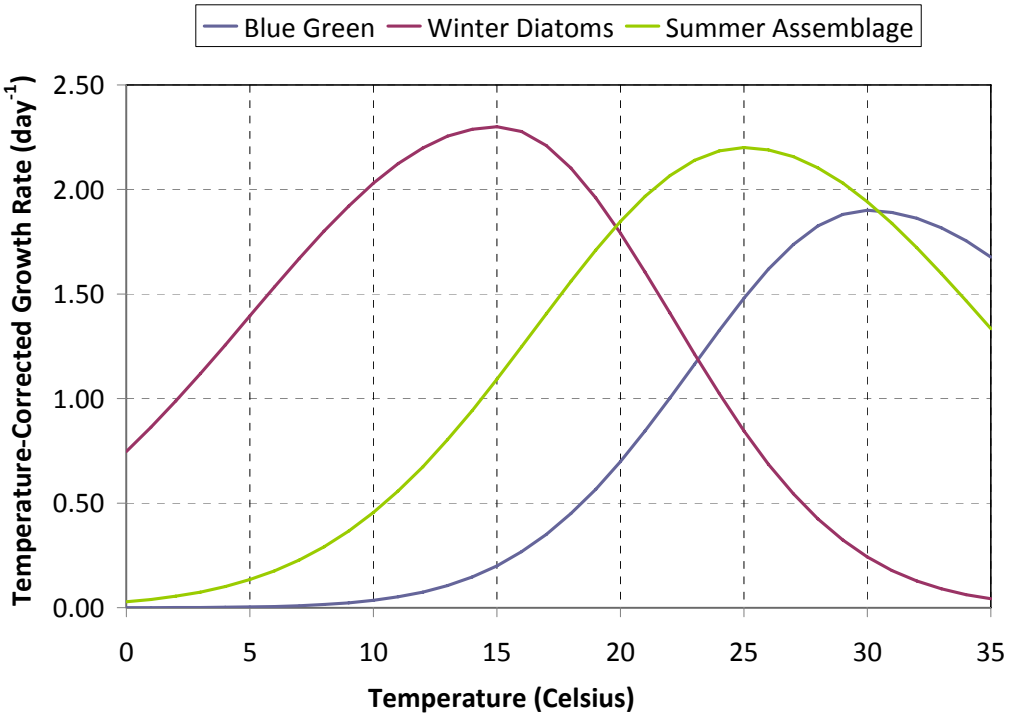

Figure 2-5. Phytoplankton Maximum Growth Rates as a Function of Temperature

Light availability is an important factor governing the growth of phytoplankton in many systems, and it is particularly important in the UMR-LP system where turbidities are generally elevated. Light intensity is at a maximum at the water surface, with attenuation occurring with increasing depth through the water column. Photo-inhibition may occur right at the surface due to light intensities exceeding saturation, while minimal light will be available lower in the water column due to attenuation by non-living suspended solids, dissolved solids, and phytoplankton. The RCA model computes the depth-averaged light reduction factor for growth as:

$$G_I(I) = \frac{2.718}{k_e H}\left[\exp\left(\frac{-I_0(t)}{I_s} * e^{-k_e H}\right) - \exp\left(\frac{-I_0(t)}{I_s}\right)\right] \qquad (2\text{-}29)$$

where: H = thickness of water column segment (m);

k_e = light extinction coefficient (m^{-1});

I_0 = incident light intensity at the segment surface (ly/day); and

I_s = saturating light intensity (ly/day).

The incident light intensity at the water surface ($I_{0,surface}$) is calculated based on the current time of day (t_d), the time of sunrise ($t_{sunrise}$), and the fraction of day experiencing daylight (f):

$$I_{0,surf}(t) = \frac{I_{tot}}{0.635 * f} \sin\left[\frac{\pi(t_d - t_{sunrise})}{f}\right] \quad (2\text{-}30)$$

where I_{tot} is total daily incident solar radiation (ly/day). The light intensity at any point within the water column ($I_0(H)$) is calculated as a function of the incident surface intensity ($I_{0,surf}$), the light extinction coefficient (k_e), and water depth (H):

$$I_0(H) = I_{0,surf} * \exp(-k_e H) \quad (2\text{-}31)$$

The effect of nutrient concentrations on phytoplankton growth are represented in RCA using Michaelis-Menten kinetic functions. The Michaelis-Menten expression is calculated for each nutrient (phosphorus, nitrogen, and silica), and the minimum value is then used to calculate the nutrient correction factor for phytoplankton growth ($G_N(N)$):

$$G_N(N) = MIN\left(\frac{DIN}{K_{mN} + DIN}, \frac{DIP}{K_{mP} + DIP}, \frac{DIS}{K_{mS} + DIS}\right) \quad (2\text{-}32)$$

where K_{mN}, K_{mP}, and K_{mS} are the half-saturation constants (mg/l) and DIN, DIP, and DIS are the inorganic concentrations (mg/l) for nitrogen, phosphorus, and silica, respectively.

The phytoplankton total death or loss rate (D_p) in Equation 2-26 is calculated as the sum of the total respiration rate and the zooplankton grazing rate per Equation 2-33:

$$D_p = k_{PR}(T) + k_{GRZ} \quad (2\text{-}33)$$

where: $k_{PR}(T)$ is the temperature-dependent respiration rate (day^{-1}), including basal/resting respiration and growth-dependent respiration; and

k_{GRZ} is rate of zooplankton grazing on phytoplankton.

Zooplankton grazing rates (k_{GRZ}) are calculated explicitly as part of the zooplankton algorithm introduced by LTI. In addition to growth and death processes described in Equations 2-27 and 2-33, phytoplankton are advected, dispersed, and settled within the model grid. Once phytoplankton biomass has deposited on the sediment bed, immediate death and recycling of the biomass is assumed.

A complete discussion of the phytoplankton algorithms implemented in the RCA model is provided in the RCA Version 3.0 user's manual (HydroQual 2004).

Light Extinction

As discussed previously, the light extinction formulation provided by Dr. Robert Megard was adapted to support RCA model application (Megard 2006). This formulation replaced the light extinction formulation previously used by HQI

(HydroQual 2002c). The Megard formulation directly estimates the Secchi depth (meters) per Equation 2-34:

$$Secchi^{-1} = \left\{ \begin{matrix} 0.18 * ALGS + 0.28 * NLOS + 0.004 * NVSS] \\ + 0.021 * DOC + 0.01 \end{matrix} \right\} \quad (2\text{-}34)$$

where:

NVSS is the total non-volatile suspended solids concentration (mg/L) calculated as:

$$NVSS = [SS1] + [SS2] \quad (2\text{-}35)$$

DOC is total dissolved organic carbon (mg-C/L) calculated as:

$$DOC = [RDOC] + [LDOC] + [\mathrm{Re}\, DOC] + [ExDOC] \quad (2\text{-}36)$$

ALGS is total algal solids (mg-d.w./L) calculated as:

$$ALGS = \frac{[PHYT1] + [PHYT2] + [PHYT3]}{R_{ALGC:DW}} \quad (2\text{-}37)$$

where $R_{ALGC:DW}$ (ratio of algal carbon to total biomass) is assumed to be 0.4; and

NLOS is the total non-living (i.e., non-algal) organic solids concentration (mg-d.w./L) computed by:

$$NLOS = \frac{[RPOC] + [LPOC]}{R_{POC:DW}} \quad (2\text{-}38)$$

where $R_{POC:DW}$ (the carbon: dry weight ratio) is assumed to be 0.3 (due to the significant fraction of allochthonous solids derived from tributary watersheds). It should also be noted that volatile suspended solids (VSS) can be calculated by summing the *ALGS* and *NLOS* variables.

The coefficients presented in Equation 2-34 were based on MCES data obtained for three sites in Lake Pepin, five sites in Pools 2 and 3, and additional sites from the Minnesota and St. Croix rivers.

As part of the water quality model calibration, it was determined that the calibration to available Secchi depth data would benefit from revised coefficients computed based on all available MCES water quality data for the 1985-2006 period. The revised set of coefficients is provided in Equation 2-39, which is identical in form to Equation 2-34:

$$Secchi^{-1} = \left\{ \begin{matrix} 0.125 * ALGS + 0.106 * NLOS + 0.023 * NVSS \\ + 0.080 * DOC + 0.01 \end{matrix} \right\} \quad (2\text{-}39)$$

Within the RCA framework, the light extinction coefficient (K_e, m^{-1}) is calculated from the Secchi depth (obtained by Equation 2-39) by Equation 2-40:

$$K_e = \frac{A}{Secchi} \tag{2-40}$$

where *A* is the Secchi constant. The Secchi constant typically falls within the range 1.5-1.8 and is generally site-specific (Wetzel et al. 1991). A factor of 1.5 was used based on an analysis of 155 paired measurements of light attenuance and transparency measured by the USACE in Lake Pepin, where the mean (± 95% confidence interval) at four sampling sites was 1.46 (± 0.05) (R.O. Megard, personal communication).

Zooplankton

The zooplankton algorithm simulates the dynamics of three groups of zooplankton: cladocerans, copepods, and microzooplankton (e.g., rotifers). Cladocerans and copepods are represented as separate groups because Lake Pepin data indicated that these two classes exhibit slightly different seasonal dynamics. The UMR RCA zooplankton algorithm as summarized below is based on the Chesapeake Bay Model (CBM) zooplankton algorithm (Cerco and Noel, 2004), with the following modifications:

1. Three zooplankton groups are represented in UMR RCA algorithm as compared to the single mesozooplankton group and the microzooplankton group included in the CBM.

2. Calculations of carbon and nutrient assimilation rates for all three zooplankton groups were refined to ensure conservation of mass when differences exist between zooplankton and prey stoichiometries.

3. A relationship between mesozooplankton grazing efficiency and non-volatile suspended solids concentration was introduced to represent the potential for high turbidities to negatively impact mesozooplankton growth rates.

The governing principles for the zooplankton algorithm are conservation of mass and homeostatic zooplankton (constant biomass stoichiometry). The governing equation for net growth (S_z, day^{-1}) of zooplankton group *z* is given by:

$$S_z = GR_z - \left(BM_z + MZ_z + \frac{PR_z}{Z_z} \right) \tag{2-41}$$

where:

GR_z is the zooplankton growth rate (day^{-1});
BM_z is the zooplankton basal metabolism rate (day^{-1});
MZ_z is the zooplankton mortality rate (day^{-1});
PR_z is the rate of predation on zooplankton (mg-C/L/day); and
Z_z is the zooplankton biomass per unit volume (mg-C/L);

Zooplankton Growth Terms

The zooplankton growth rate (GR_z) for zooplankton group *z* is calculated per Equation 2-42:

$$GR_z = EZ_z * (1 - RF_z) * (1 - CEX_z) * \frac{GZ_z}{Z_z} \quad (2\text{-}42)$$

where:

EZ_z is the assimilation efficiency;
RF_z is the fraction of assimilated prey lost to respiration;
CEX_z is the stoichiometric excess of carbon available from all prey sources (mg-C/L); and
GZ_z is the grazing rate (mg-C/L/day).

The fraction of assimilated prey lost to respiration (RF_z) was specified as a constant value for microzooplankton. However, for the mesozooplankton groups, this efficiency parameter was represented as a Monod-type function of the simulated non-volatile suspended solids (NVSS) concentration:

$$RF = RFZ + (RFMZ - RFZ) * \left(\frac{NVSS}{KRFZ + NVSS} \right) \quad (2\text{-}43)$$

where:

RFZ is the minimum fraction lost to respiration;
RFMZ is the maximum fraction lost to respiration;
KRFZ is the half-saturation constant (mg/l); and
NVSS is the non-volatile suspended solids concentration (mg/l).

The dependence of the assimilation efficiency on NVSS was introduced in the model because 1) it was necessary to have the mesozooplankton growth rate be less in Pools 2 and 3 relative to Lake Pepin to achieve a good fit to the zooplankton biomass data, and 2) the literature provides support for this phenomenon (Thorp and Mantovani 2005).

The grazing (i.e., prey uptake) rate is calculated as:

$$GZ_z = \left(\frac{CPREY_z}{KHC_z + CPREY_z} \right) * RMAX_z * fT_z \quad (2\text{-}44)$$

where:

$CPREY_z$ is the total available prey biomass (mg-C/L);
KHC_z is the prey density at which the grazing rate is halved (mg-C/L);
$RMAX_z$ is the maximum ration of prey to zooplankton biomass (mg-C prey/mg-C zooplankton/day); and
fT_z is the effect of temperature on grazing.

The overall availability of prey ($CPREY_z$) is calculated as the sum of the available prey for each individual source. Phytoplankton, refractory/labile POC (RPOC/LPOC), and microzooplankton serve as prey for the mesozooplankton groups (cladocerans and copepods). Microzooplankton also utilize phytoplankton and RPOC/LPOC, as well as refractory/labile DOC (RDOC/LDOC). The availability of a specific prey source is calculated as:

$$CPREY_{z,x} = Max\left(C_x - CT_{z,x}, 0\right) \quad (2\text{-}45)$$

where:

$CPREY_{z,x}$ is the available concentration for prey source x (mg-C/L);
C_x is the actual prey biomass per unit volume (mg-C/L);
$CT_{z,x}$ is the zooplankton group-specific concentration below which prey source x will not be utilized (mg-C/L).

The effect of temperature on grazing (fT_z) is calculated by Equation 2-46a or 2-46b, depending on whether the ambient water temperature is below or above the optimum grazing/growth temperature:

$$fT_z = \exp\left[-KBETAZ1_z * \left(T - TOPT_z\right)^2\right] \quad (2\text{-}46a)$$

$$fT_z = \exp\left[-KBETAZ2_z * \left(TOPT_z - T\right)^2\right] \quad (2\text{-}46b)$$

where:

$TOPT_z$ is the optimal grazing temperature (degrees C);
T is the water temperature (degrees C); and
$KBETAZ1_z$ and $KBETAZ2_z$ are coefficients representing the effect of temperature on grazing below and above the optimal temperature.

Conceptual diagrams showing the carbon and nitrogen flow associated with zooplankton growth dynamics are provided in Figure 2-6 and Figure 2-7, respectively. Although not included here, the phosphorus diagram is fully analogous to the nitrogen diagram in Figure 2-7.

Zooplankton: Stoichiometric Considerations

Prior to computing the grazing and growth rates and the associated uptake and recycling of nutrients, the zooplankton stoichiometry is compared against the aggregate prey stoichiometry to determine whether carbon, nitrogen, or phosphorus is the limiting factor for growth. Unless the aggregate prey stoichiometry is perfectly consistent with the zooplankton stoichiometry, one of the quantities will be limiting. The fractions of prey nutrient that "wasted" following uptake can be expressed as a "stoichiometric excess" quantity of either carbon (CEX_z), nitrogen (NEX_z), or phosphorus (PEX_z). Three scenarios are possible:

1. C-Limited: If carbon is determined to be limiting, then the stoichiometric excess of carbon (CEX_z) is zero, and the stoichiometric excesses of nitrogen (NEX_z) and phosphorus (PEX_z) are calculated per Equation 2-47a and 2-47b:

$$NEX_z = 1 - \left(\frac{NCRZ_z}{NCRP_z} \right) \quad \text{(2-47a)}$$

$$PEX_z = 1 - \left(\frac{PCRZ_z}{PCRP_z} \right) \quad \text{(2-47b)}$$

2. N-Limited: If nitrogen is determined to be limiting, then the stoichiometric excess of nitrogen (NEX_z) is zero, and the stoichiometric excesses of carbon (CEX_z) and phosphorus (PEX_z) are calculated per Equation 2-48a and 2-48b:

$$CEX_z = 1 - \left(\frac{NCRP_z}{NCRZ_z} \right) \quad \text{(2-48a)}$$

$$PEX_z = 1 - \left(\frac{PNRZ_z}{PNRP_z} \right) \quad \text{(2-48b)}$$

3. P-Limited: If phosphorus is determined to be limiting, then the stoichiometric excess of phosphorus (PEX_z) is zero, and the stoichiometric excesses of carbon (CEX_z) and nitrogen (NEX_z) are calculated per Equation 2-49a and 2-49b:

$$CEX_z = 1 - \left(\frac{PCRP_z}{PCRZ_z} \right) \quad \text{(2-49a)}$$

$$NEX_z = 1 - \left(\frac{PNRP_z}{PNRZ_z} \right) \quad \text{(2-49b)}$$

The stoichiometric ratios used in Equations 2-47 through 2-49 include:

$NCRZ_z$ is the zooplankton N:C ratio; $NCRP_z$ is the prey N:C ratio
$PCRZ_z$ is the zooplankton P:C ratio; $PCRP_z$ is the prey P:C ratio
$PNRZ_z$ is the zooplankton P:N ratio; and $PNRP_z$ is the prey P:N ratio.

As indicated in Equation 2-42, only the stoichiometric excess of carbon (CEXz) can limit the zooplankton growth rate. Stoichiometric excesses of nitrogen and phosphorus only affect the fraction of prey nutrients that are assimilated into zooplankton biomass and the fraction of nutrients that are recycled to the water column.

Zooplankton: Loss Terms

The zooplankton algorithm includes loss terms for basal metabolism (BM_z), mortality (MZ_z), and predation by fish (PR_z). Relevant equations for these processes are outlined below.

The basal metabolism rate (BM_z, day^{-1}) is calculated per Equation 2-50:

$$BM_z = BMREF_z * \exp\left[KTB_z * \left(T - TREF_z\right)\right] \quad (2\text{-}50)$$

where:

$BMREF_z$ is the zooplankton metabolic rate at the reference temperature;
KTB_z is the is the effect of temperature on the metabolic rate (degrees C^{-1});
$TREF_z$ is the reference temperature (degrees C).

The zooplankton mortality rate (MZ_z, day^{-1}), is represented as a function of dissolved oxygen (DO) concentration and temperature, where Equation 2-51a applies when DO concentrations are greater than the critical concentration, and Equation 2-51b applies for when DO is less than the critical concentration:

$$MZ_z = MZREF_z + \frac{e^{(T-TMax_z)}}{2} \quad (2\text{-}51a)$$

$$MZ_z = MZREF_z + \frac{e^{(T-TMax_z)}}{2} + MZERO_z * \left(1 - \frac{DO}{DOCRIT_z}\right) \quad (2\text{-}51b)$$

where:

$MZREF_z$ is the zooplankton reference mortality rate (day^{-1});
$TMax_z$ is the maximum tolerable temperature (degrees C);
$MZERO_z$ is the mortality rate at zero DO (day^{-1});
DO is the dissolved oxygen concentration (mg/L); and
$DOCRIT_z$ is the threshold below which DO-induced mortality occurs (mg/L).

While microzooplankton are too small to be preyed upon by fish, fish are the primary predator for meozooplankton, (and copepods in particular). The predation rate (PR_z, day^{-1}) on the mesozooplankton groups is included as an empirical forcing function:

$$PR_z = \alpha * \exp\left[KTPR_z * \left(T - TPR_z\right)\right] * \left(Z_{1,2} * Z_z\right) \quad (2\text{-}52)$$

where:

α is the predation constant (L/mg-C/day);

$KTPR_z$ is the effect of temperature on predation rate (day^{-1});
TPR_z is the reference temperature for predation (degrees C);
$Z_{1,2}$ is the total mesozooplankton concentration (mg-C/L); and
Z_z is the cladoceran (1) or copepod (2) concentration (mg-C/L).

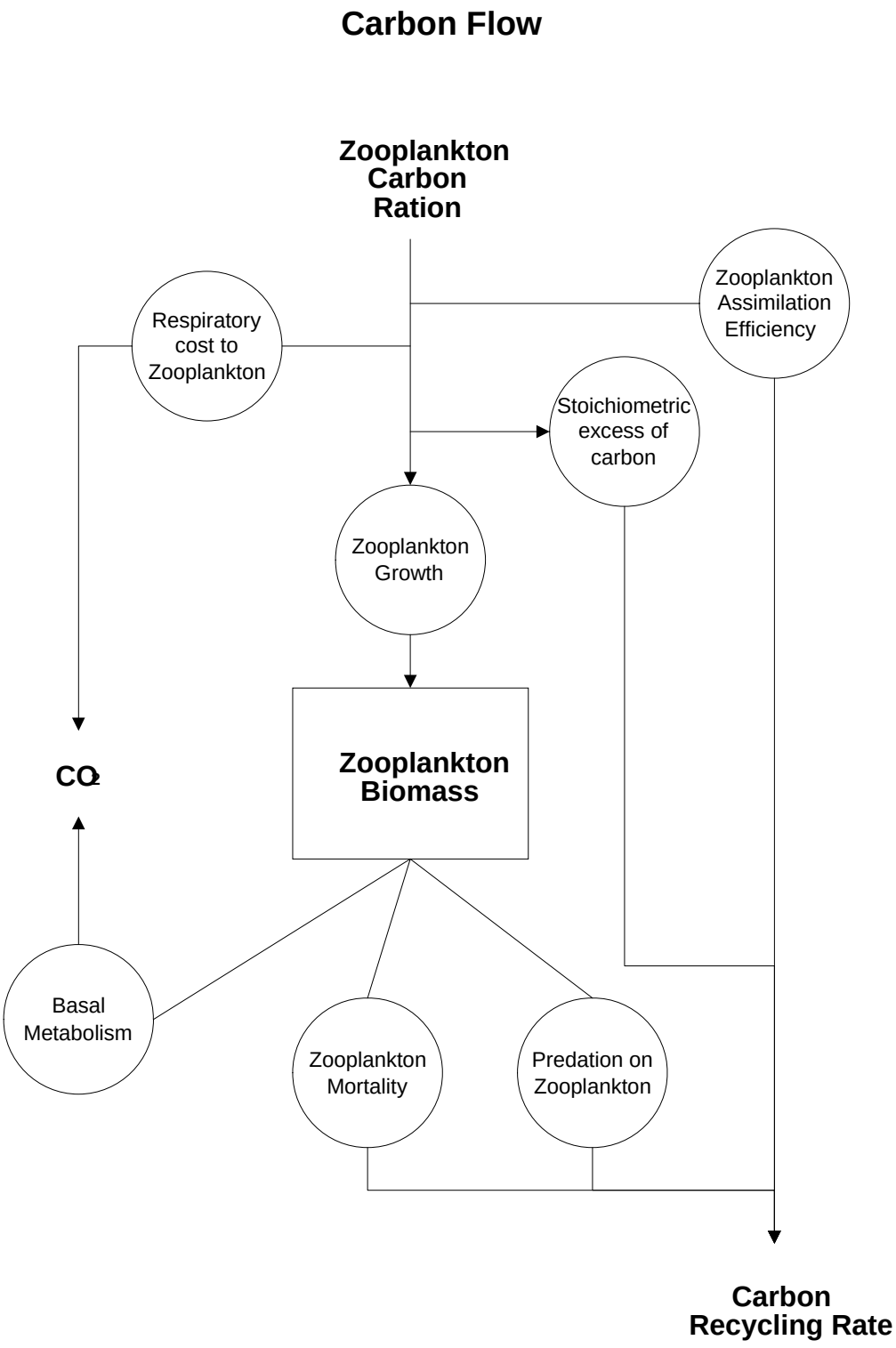

Figure 2-6. Carbon Cycling Associated with Zooplankton Dynamics

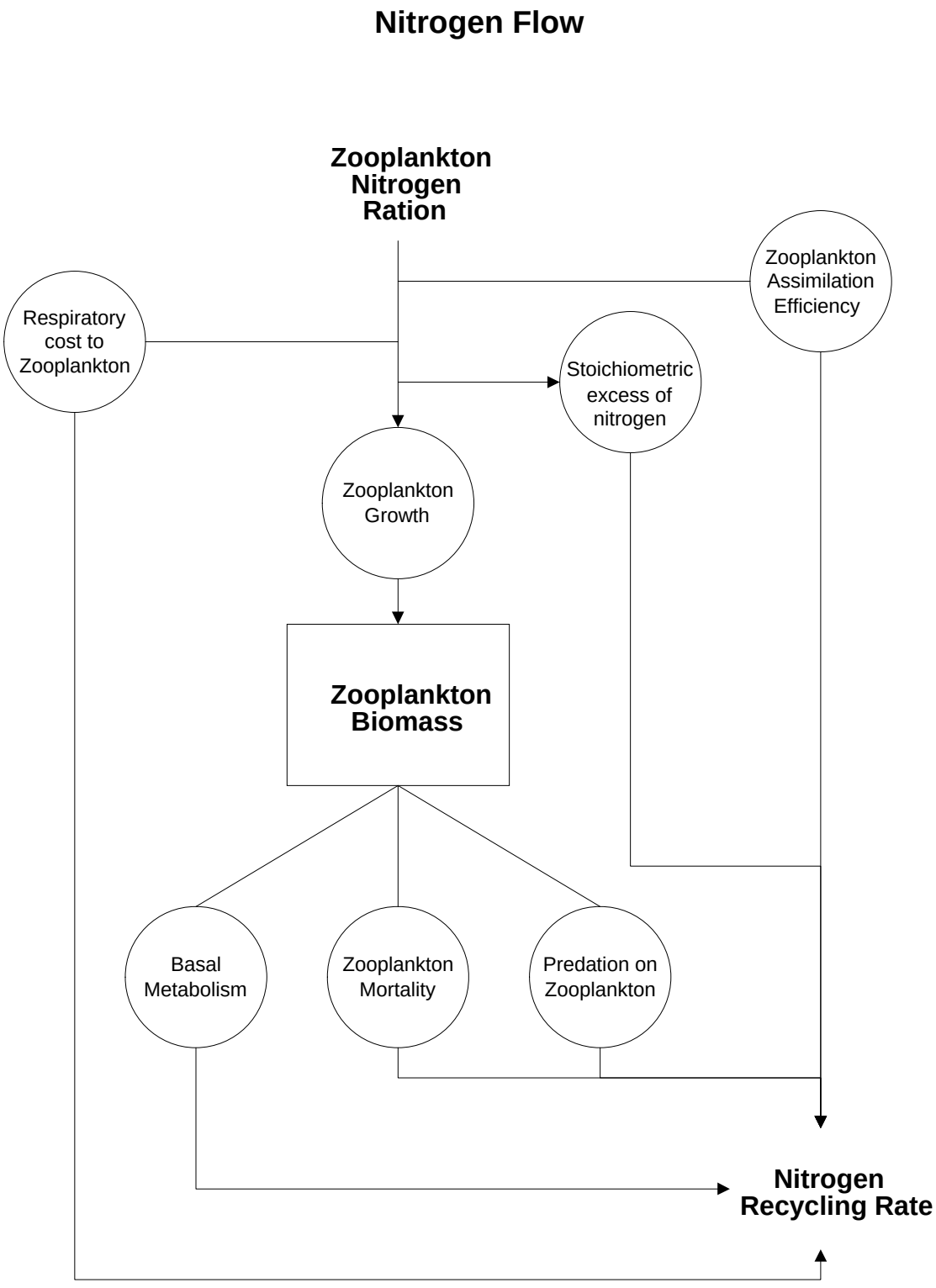

Figure 2-7. Nitrogen Cycling Associated with Zooplankton Dynamics

Carbon, Nitrogen, & Phosphorus Cycling

A set of simplified schematics illustrating carbon, nitrogen, and phosphorus kinetics and cycling in the water column and surface sediments are provided in Figures 2-8 through 2-10. Dissolved inorganic silica and biogenic silica, which are not depicted here, are also simulated within RCA. A complete discussion of carbon and nutrient dynamics is provided in the HQI UMR final project report (HydroQual 2002c) and the RCA Version 3.0 user's manual (HydroQual 2004).

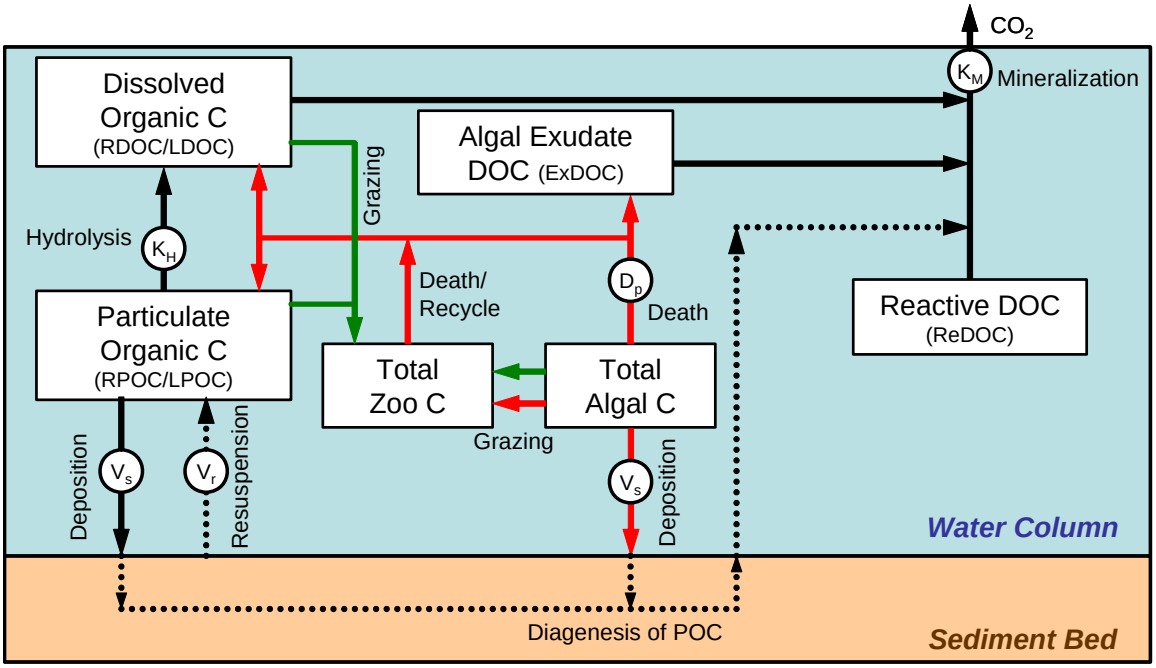

Figure 2-8. RCA Carbon Kinetics & Cycling

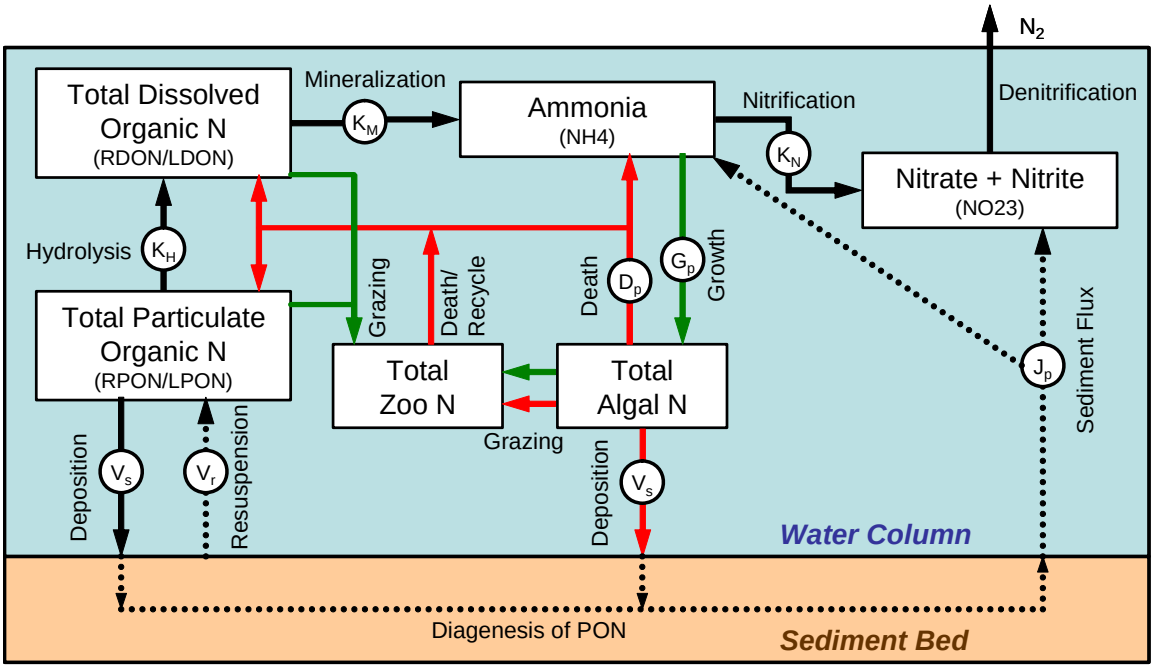

Figure 2-9. RCA Nitrogen Kinetics & Cycling

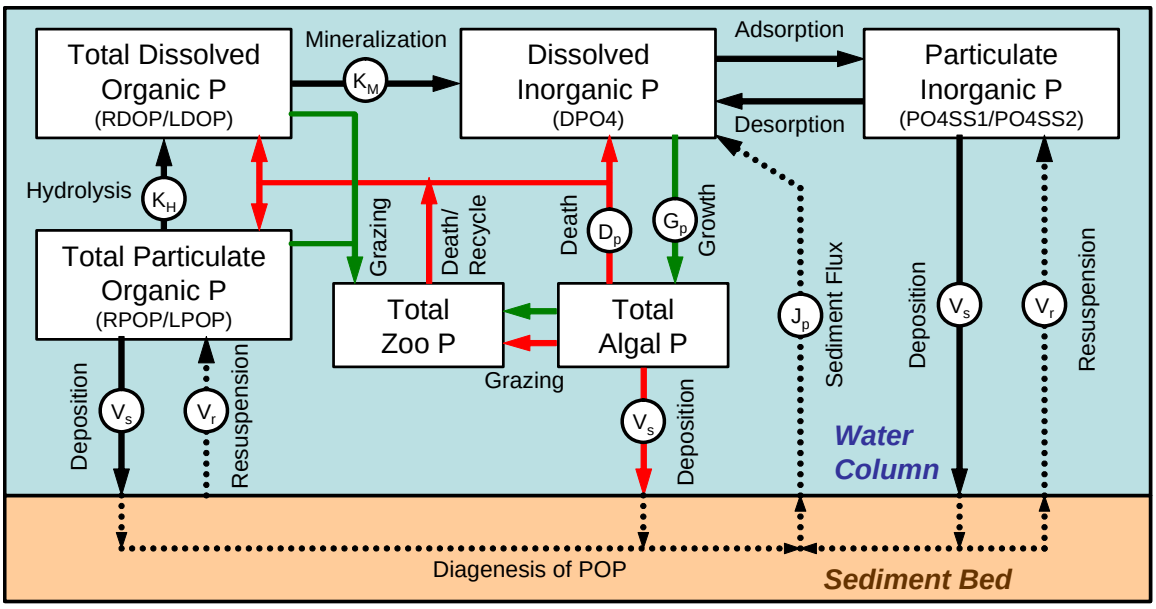

Figure 2-10. RCA Phosphorus Kinetics & Cycling

2.5 POST-PROCESSOR DEVELOPMENT

The "WinModel" software application was developed to handle the considerable pre- and post-processing and visualization tasks required to run and evaluate RCA model simulations. WinModel interfaces with a companion Microsoft Access database to accomplish these tasks. The companion database ("RCA_v4.mdb") contains all of the RCA model inputs in a carefully designed table structure. Field data used for model calibration are also contained in the database and are accessed by the WinModel visualization interface. The WinModel main menu interface provides the user with the option of "building" a RCA scenario ("Scenario Builder" button) or visualizing existing RCA scenario(s) ("Visualizing Scenarios") (Figure 2-11). These options are discussed below.

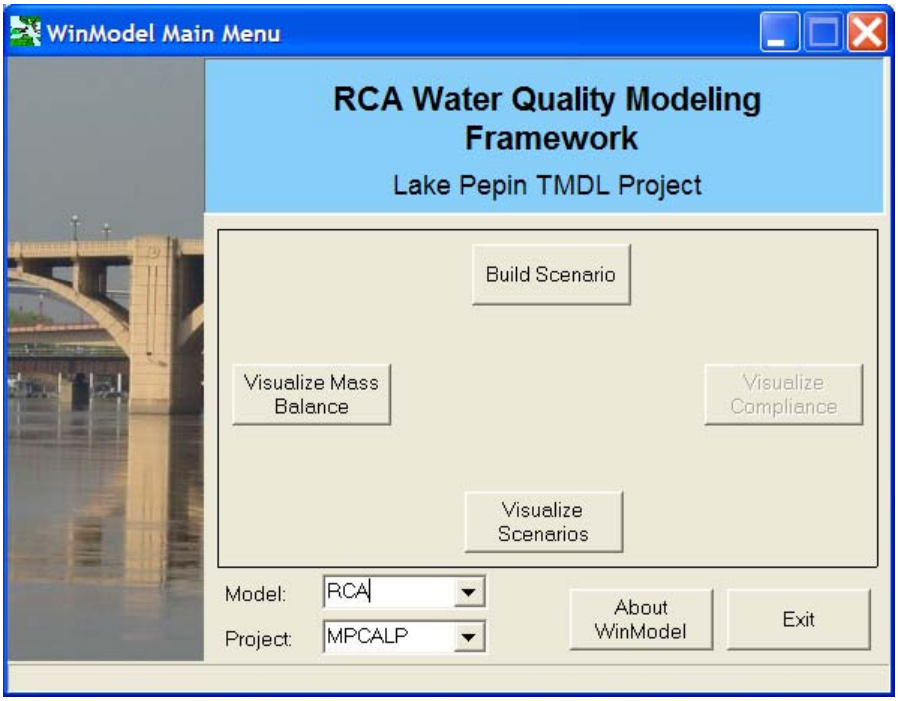

Figure 2-11. WinModel Main Menu

Building RCA Scenarios

With sufficient knowledge of the database structure and the RCA input structure, the user can quickly modify model coefficients and forcing functions via the database tables. Clicking on the "Scenario Builder" button on the main menu will launch the interface shown in Figure 2-12. Prior to launching a RCA model simulation, the user must specify the scenario ID and description and select the pools and years to simulate.

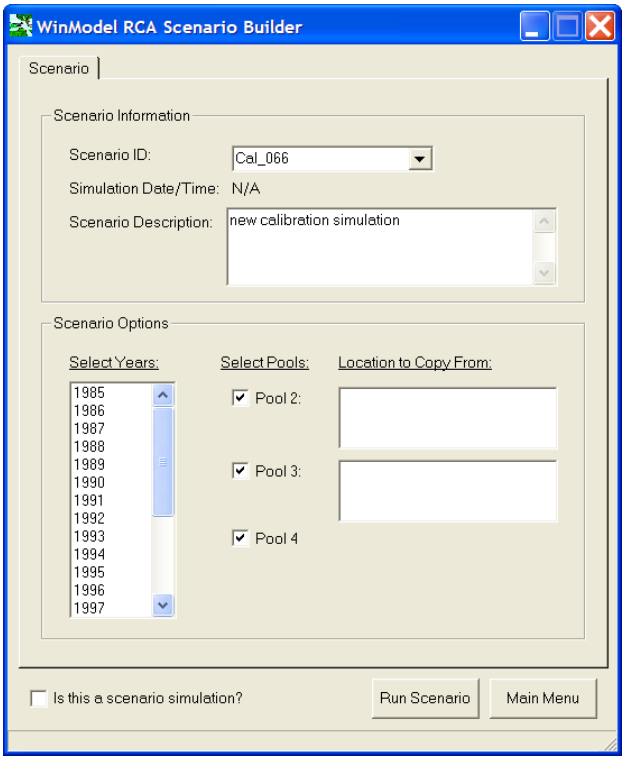

Figure 2-12. WinModel RCA Scenario Builder Interface

Visualizing RCA Scenarios

The WinModel RCA visualization interface can be accessed by clicking the "Visualize Scenarios" button on the main menu. This interface, shown in Figure 2-13, includes a variety of options for viewing static or animated plots of model results and available field data. Key options provided include:

- Option to view three different types of RCA results: water quality, sediment diagenesis, or phytoplankton diagnostic results ("Model" frame);
- Toggle between spatial and temporal profile plot types ("Plot Type" frame);
- Options to view multiple RCA scenarios or variables on a single plot ("Display Options" frame);
- Selection of scenarios and output variables ("Select Scenarios" and "Select Variables" frames);
- Selection of pre-defined system longitudinal (i.e., "downriver") profiles ("Select Options" frame);
- Options to animate any spatial or temporal profile plot ("Toolbar" frame);
- Toggling of data plotting feature and monthly vs. 5-day model-data comparisons ("Toolbar" frame);

- Map-based spatial animations of results for any output variable ("Show Map" button);
- Export of RCA model output to a Microsoft Excel workbook ("Excel Export" button); and
- Zooming capabilities for any plots.

The example WinModel visualization shown in Figure 2-13 is displaying a spatial plot of non-volatile suspended solids (NVSS) model results and field data for the "UMR mid-channel" profile for scenario "Cal_021". Because the "Plot Monthly" option is selected, the monthly average (solid line) and minimum and maximum (dotted lines) concentrations are displayed. Similarly, NVSS data are displayed as the mean monthly observed concentration by monitoring program (e.g., MCES, LTRMP, etc.) with error bars indicating the standard deviation for all observations within the month.

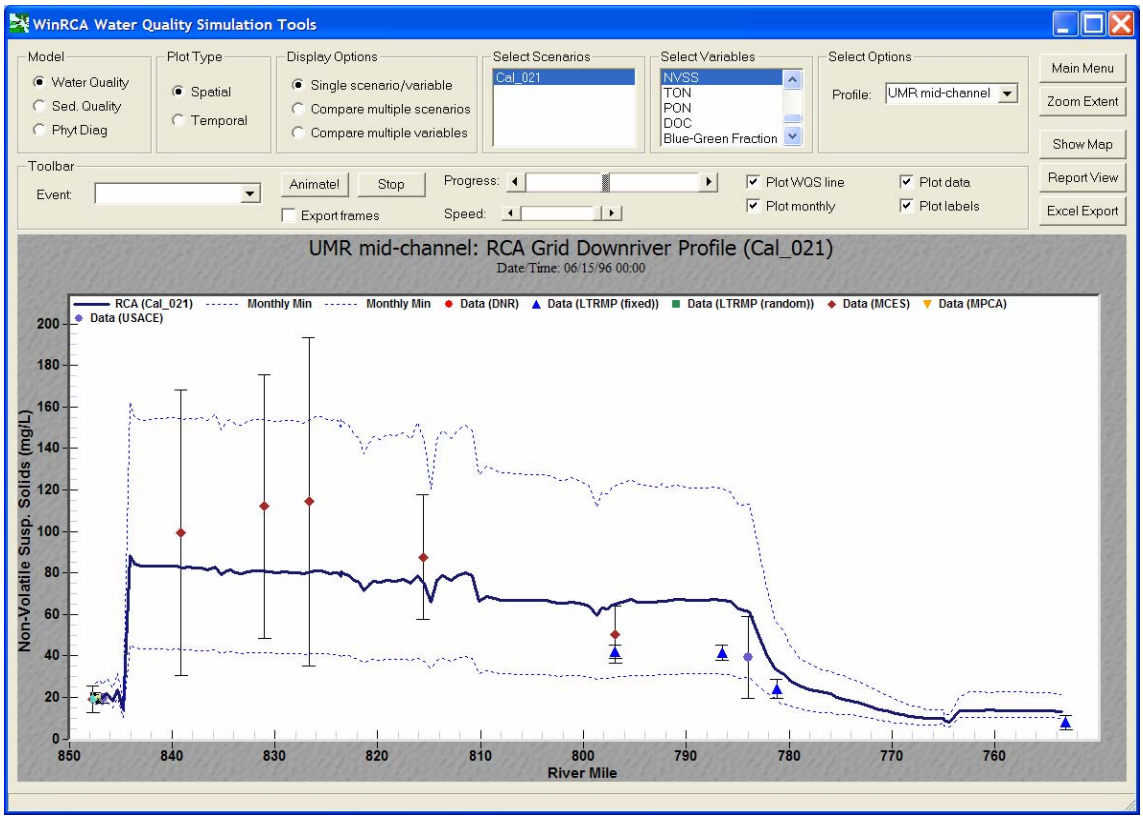

Figure 2-13. WinModel Visualization Interface

2.6 COMPUTATIONAL REQUIREMENTS / MODEL IMPLEMENTATION

This section provides an overview of information relevant to implementing ECOMSED and RCA model simulations, including computational requirements, model benchmarking information, and protocols for running model simulations

2.6.1 Computational Requirements

The ECOMSED and RCA models are configured and compiled to run on a personal computing (PC) system running a recent version of Microsoft Windows. Recommended PC machine specifications are as follows:

- Operating System: Windows 2000, XP, or Vista;
- Processor: Intel or AMD – 1.5 GHz minimum (2.4 GHz or higher recommended);
- Physical Memory (RAM): 500 MB minimum (1,000 MB or higher recommended).
- Virtual Memory: 1,000 MB minimum (2,000 MB recommended);
- Required Disk Space:
    - *ECOMSED:* 1.0 GB per simulation year (21.8 GB for the entire 1985-2006 period).
    - *RCA*: 0.3 GB per simulation year (6.1 GB for the entire 1985-2006 period) in addition the ECOMSED space requirement. If a common machine is used to run both model simulations, it is economical to move the ECOMSED "gcm_tran.bin" and "gcm_sedtran.bin" linkage files into the appropriate RCA "runfiles" folder.

Runtime benchmarking statistics for a machine with the recommended processing and memory specifications are provided in Section 2.6.2.

2.6.2 Runtime Benchmarking

The computational time required to complete a year-long simulation with ECOMSED or RCA depends on 1) the machine specifications, and 2) the timestep used in the model. Timesteps employed in ECOMSED vary depending on the year simulated (e.g., high-flow years require a shorter timestep than low-flow years), while RCA timesteps are specific to each pool simulation.

The following runtime statistics are based simulations conducted on a machine with a 2.4 GHz AMD Athlon 64 processor, 1 GB (1,000 MB) of physical memory (RAM), and 2 GB of virtual RAM:

- *ECOMSED*: The complete1985-2006 simulation for all three pools requires approximately 196 hours (8.2 days) of continuous runtime. The average runtime for a single year is approximately 9 hours.

- *RCA*: The complete1985-2006 simulation for all three pools requires approximately 132 hours (5.5 days) of continuous runtime. The average runtime for a single year is approximately 6 hours.

Although ECOMSED and/or RCA simulations could be attempted on a PC with less than the machine specifications described above, the runtimes described above section would likely increase dramatically. The models should always be run on a local hard drive, as running simulations on a network drive or an external hard drive could significantly increase model simulation runtime.

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