LLRM – Lake Loading Response Model
Users Guide and Quality Assurance Project Plan

Model Overview

The Lake Loading Response Model, or LLRM, originated as a teaching tool in a college course on watershed management, where it was called SHEDMOD. The intent was to provide a spreadsheet program that students could use to evaluate potential consequences of watershed management for a target lake, with the goal of achieving desirable levels of phosphorus (P), nitrogen (N), chlorophyll a (Chl) and Secchi disk transparency (SDT). As all cells in the spreadsheet are visible, the effect of actions could be traced throughout the calculations and an understanding of the processes and relationships could be developed.

LLRM remains spreadsheet based, but has been enhanced over the years for use in watershed management projects aimed at improving lake conditions. It is still a highly transparent model, but various functions have been added and some variables have been refined as new literature has been published and experience has been gained. It is adaptable to specific circumstances as data and expertise permit, but requires far less of each than more complex models such as SWAT or BASINS. Like any model, it is a tool, but like any tool, it can be properly or improperly used. This manual provides a basis for proper use of LLRM.

Model Platform

LLRM runs within Excel, a Microsoft product. It consists of three numerically focused worksheets within a spreadsheet:

1. Reference Variables – provides values for hydrologic, export and concentration variables that must be entered for the model to function. Those shown are applicable to the northeastern USA, and some would need to be changed to apply to other regions.
2. Calculations – Uses input data to generate estimates of water, N and P loads to the lake. All cells shaded in blue must have entries if the corresponding input or process applies to the watershed and lake. If site-specific values are unavailable, one typically uses the median value from the Reference Variables sheet.
3. Predictions – Uses the lake area and inputs calculated in the Calculations sheet to predict the long-term, steady state concentration of N, P and Chl in the lake, plus the corresponding SDT. This sheet applies multiple empirical models and provides averages final results from them, but with knowledge of the system or empirical models, one can eliminate models used in generating those averages to get the best fit for the targeted system.

Watershed Schematic

Generation of a schematic representation of the watershed is essential to the model. It is not a visible part of the model, but is embodied in the routing of water and nutrients performed in the model and is a critical step. For the example provided here, the lake and watershed shown in Figure 1 is modeled. It consists of a land area of 496.5 hectares (ha) and a lake with an area of 40 ha. There are two defined areas of direct drainage (F and G), from which water reaches the lake by overland sheetflow, piped or ditched stormwater drainage, or groundwater seepage (there are no tributaries in these two drainage basins).

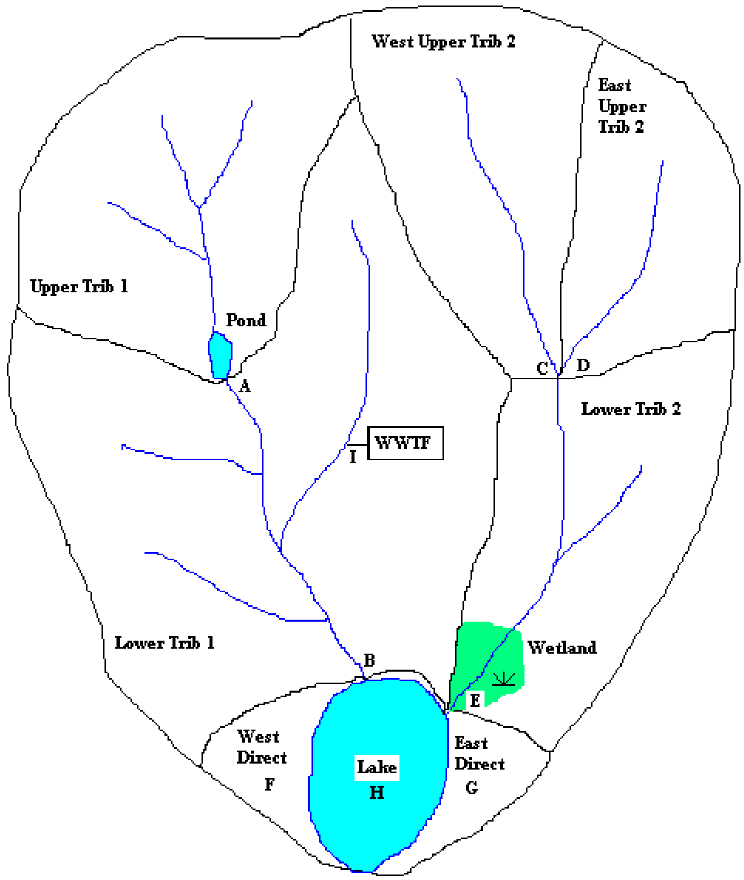

Figure 1. Watershed Map for Example System

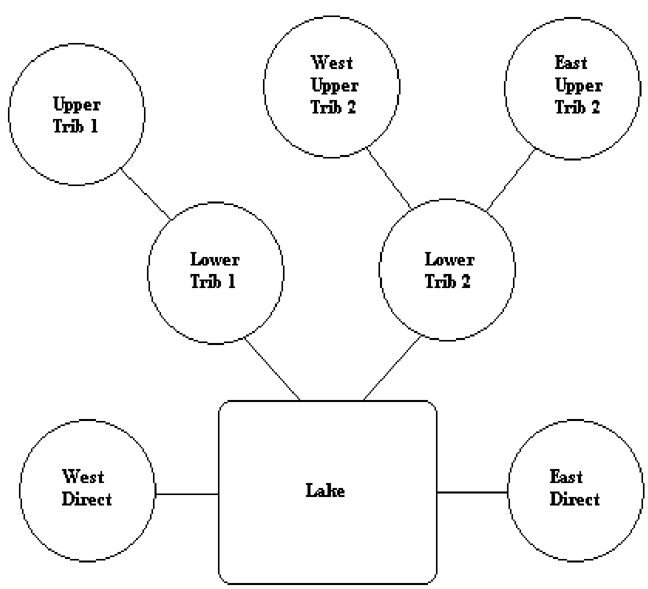

Figure 2. Watershed Schematic for Example System

There is also a tributary (Trib 1) that is interrupted by a small pond, such that the corresponding watershed might best be represented as two parts, upstream and downstream of that pond, which will provide some detention and nutrient removal functions. Sampling to assess outputs from each drainage area would be at A and B. There is another tributary (Trib 2) that consists of two streams that combine to form one that then enters the lake, the classic "Y' drainage pattern. With differing land uses associated with each of the upper parts of the Y and available data for each near the confluence, this part of the watershed is best subdivided into three drainage areas (C, D and E).

As shown in Figure 2, the watershed of Figure 1 is represented as the lake with two direct drainage units, a tributary with an upper and lower drainage unit, and a tributary with two upper drainage areas and one lower drainage unit. The ordering is important on several levels, most notably as whatever nutrient loading attenuation occurs in the two lower tributary basins will apply to loads generated in the corresponding upper basins. Loads are generated and may be managed in any of the drainage basins, but how they affect the lake will be determined by how those loads are processed on the way to the lake. LLRM is designed to provide flexibility when testing management scenarios, based on watershed configuration and the representation of associated processes.

Model Elements

There are three main types of inputs necessary to run LLRM:

1. Hydrology inputs – these factors govern how much water lands on the watershed and what portion is converted to runoff or baseflow. The determination of how much precipitation becomes runoff vs. baseflow vs. deep groundwater not involved in the hydrology of the target system vs. loss to evapotranspiration is very important, and requires some knowledge of the system. All precipitation must be accounted for, but all precipitation will not end up in the lake. In the northeast, runoff and baseflow may typically account for one to two thirds of precipitation, the remainder lost to evapotranspiration or deep groundwater that may feed surface waters elsewhere, but not in the system being modeled. As impervious surface increases as a percent of all watershed area, more precipitation will be directed to runoff and less to baseflow. There are two routines in the model to allow "reality checks" on resultant flow derivations, one using a standard areal water yield based on decades of data for the region or calculated from nearby stream gauge data, and the other applying actual measures of flow to check derived estimates.
2. Nutrient yields – export coefficients for N and P determine how much of each is generated by each designated land use in the watershed. These export values apply to all like land use designations; one cannot assign a higher export coefficient to a land use in one basin than to the same land use in another basin. Differences are addressed through attenuation. This is a model constraint, and is imposed partly for simplicity and partly to prevent varied export assignment without justification. Where differing export really does exist for the same land uses in different basins of the watershed, attenuation can be applied to adjust what actually reaches the lake. Nutrient export coefficients abound in the literature, and ranges, means and medians are supplied in the Reference Variables sheet. These are best applied with some local knowledge of export coefficients, which can be calculated from land area, flow and nutrient concentration data. However, values calculated from actual data will include attenuation on the way to the point of measurement. As attenuation is treated separately in

this model, one must determine the pre-attenuation export coefficients for entry to initiate the model. The model provides a calculation of the export coefficient for the “delivered” load that allows more direct comparison with any exports directly calculated from data later in the process.

3. Other nutrient inputs – five other sources of N and P are recognized in the model:
    a. Atmospheric deposition – both wet and dry deposition occur and have been well documented in the literature. The area of deposition should be the entire lake area. Choice of an export coefficient can be adjusted if real data for precipitation and nutrient concentrations is available.
    b. Internal loading – loads can be generated within the lake from direct release from the sediment (dissolved P, ammonium N), resuspension of sediment (particulate P or N) with possible dissociation from particles, or from macrophytes (“leakage” or scenescence). All of these modes have been studied and can be estimated with a range, but site specific data for surface vs. hypolimnetic concentrations, changes over time during dry periods (limited inflow), or direct sediment measures can be very helpful when selecting export coefficients.
    c. Waterfowl and other wildlife – inputs from various bird species and other water dependent wildlife (e.g., beavers, muskrats, mink or otter) have been evaluated in the literature. Site specific data on how many animals use the lake for how long is necessary to generate a reliable estimate.
    d. Point sources – LLRM allows for up to three point sources, specific input points for discharges with known quantity and quality. The annual volume, average concentration, and basin where the input occurs must be specified.
    e. On-site wastewater disposal (septic) systems – septic system inputs in non-direct drainage basins is accounted for in baseflow export coefficients, but a separate process is provided for direct drainage areas where dense housing may contribute disproportionately. The number of houses in two zones (closer and farther away, represented here as <100 ft and 100-300 ft from the lake) can be specified, with occupancy set at either seasonal (90 days) or year round (365 days). The number of people per household, water use per person per day, and N and P concentrations and attenuation factors must be specified. Alternatively, these inputs can be accounted for in the baseflow export coefficient for direct drainage areas if appropriate data are available, but this module allows estimation from what is often perceived as a potentially large source of nutrients.

LLRM then uses the input information to make calculations that can be examined in each corresponding cell, yielding wet and dry weather inputs from each defined basin, a combined total for the watershed, a summary of other direct inputs, and total loads of P and N to the lake, with an overall average concentration for each as an input level. Several constraining factors are input to govern processes, such as attenuation, and places to compare actual data to derived estimates are provided. Ultimately, the lake area and loading values are transferred to the Prediction sheet where, with the addition of an outflow P concentration and lake volume, estimation of average in-lake P, N, Chl and SDT is performed. The model is best illustrated through an example, which is represented by the watershed in Figures 1 and 2. Associated tables are directly cut and pasted from the example model runs.

Hydrology

Water is processed separately from P and N in LLRM. While loading of water and nutrients are certainly linked in real situations, the model addresses them separately, then recombines water and nutrient loads later in the calculations. This allows processes that affect water and nutrient loads differently (e.g., many BMPs) to be handled effectively in the model.

Water Yield

Where a cell is shaded, an entry must be made if the corresponding portion of the model is to work. For the example watershed, the standard yield from years of data for a nearby river, to which the example lake eventually drains, is 1.6 cubic feet per second per square mile of watershed (cfsm) as shown below. That is, one can expect that in the long term, each square mile of watershed will generate 1.6 cfs. This provides a valuable check on flow values derived from water export from various land uses later in the model.

COEFFICIENTS	
STD. WATER YIELD (CFSM)	1.6
PRECIPITATION (METERS)	1.21

Precipitation

The precipitation landing on the lake and watershed, based on years of data collected at a nearby airport, is 1.21 m (4 ft, or 48 inches) per year, as shown above. Certainly there will be drier and wetter years, but this model addresses the steady state condition of the lake over the longer term.

Runoff and Baseflow Coefficients

Partitioning coefficients for water for each land use type have been selected from literature values and experience working in this area. Studies in several of the drainage basins to the example lake and for nearby tributaries outside this example system support the applied values with real data. It is expected that the sum of export coefficients for runoff and baseflow will be <1.0; some portion of the precipitation will be lost to deep groundwater or evapotranspiration.

	RUNOFF EXPORT COEFF.			BASEFLOW EXPORT COEFF.		
LAND USE	Precip Coefficient (Fraction)	P Export Coefficient (kg/ha/yr)	N Export Coefficient (kg/ha/yr)	Precip Coefficient (Fraction)	P Export Coefficient (kg/ha/yr)	N Export Coefficient (kg/ha/yr)
Urban 1 (LDR)	0.30	0.65	5.50	0.15	0.010	5.00
Urban 2 (MDR/Hwy)	0.40	0.75	5.50	0.10	0.010	5.00
Urban 3 (HDR/Com)	0.60	0.80	5.50	0.05	0.010	5.00
Urban 4 (Ind)	0.50	0.70	5.50	0.05	0.010	5.00
Urban 5 (P/I/R/C)	0.10	0.80	5.50	0.05	0.010	5.00
Agric 1 (Cvr Crop)	0.15	0.80	6.08	0.30	0.010	2.50
Agric 2 (Row Crop)	0.30	1.00	9.00	0.30	0.010	2.50
Agric 3 (Grazing)	0.30	0.40	5.19	0.30	0.010	5.00
Agric 4 (Feedlot)	0.45	224.00	2923.20	0.30	0.010	25.00
Forest 1 (Upland)	0.10	0.20	2.86	0.40	0.005	1.00
Forest 2 (Wetland)	0.05	0.10	2.86	0.40	0.005	1.00
Open 1 (Wetland/Lake)	0.05	0.10	2.46	0.40	0.005	0.50
Open 2 (Meadow)	0.05	0.10	2.46	0.30	0.005	0.50
Open 3 (Excavation)	0.40	0.80	5.19	0.20	0.005	0.50
Other 1	0.10	0.20	2.46	0.40	0.050	0.50
Other 2	0.35	1.10	5.50	0.25	0.050	5.00
Other 3	0.60	2.20	9.00	0.05	0.050	20.00

Setting export coefficients for the division of precipitation between baseflow, runoff and other components (deep groundwater, evapotranspiration) that do not figure into this model is probably the hardest part of model set-up. Site specific data are very helpful, but a working knowledge of area hydrology and texts on the subject is often sufficient. This is an area where sensitivity testing is strongly urged, as some uncertainly around these values is to be expected. There is more often dry weather data available for tributary streams than wet weather data, and some empirical derivation of baseflow coefficients is recommended. Still, values are being assigned per land use category, and most basins will have mixed land use, so clear empirical validation is elusive. As noted, sensitivity testing by varying these coefficients is advised to determine the effect on the model of the uncertainty associated with this difficult component of the model.

Nutrient Yields for Land Uses

Phosphorus and Nitrogen in Runoff

The values applied in the table above are not necessarily the medians from the Reference Variables sheet, since there are data to support different values being used here. There may be variation across basins that is not captured in the table below, as the same values are applied to each land use in each basin; that is a model constraint. Values for “Other” land uses are inconsequential in this case, as all land uses are accounted for in this example watershed without creating any special land use categories. Yet if a land use was known to have strong variation among basins within the watershed, the use of an “Other” land use class for the strongly differing land use in one or another basin could incorporate this variability.

Phosphorus and Nitrogen in Baseflow

Baseflow coefficients are handled the same way as for runoff coefficients above. While much of the water is likely to be delivered with baseflow, a smaller portion of the P and N loads will be delivered during dry weather, as the associated water first passes through soil. In particular, P is removed effectively by many soils, and transformation of nitrogen among common forms is to be expected.

The table above is commonly adjusted to calibrate the model, but it is important to justify all changes. Initial use of the median P export value for a land use may be based on a lack of data or familiarity with the system, and when the results strongly over- or underpredict actual in-lake concentrations, it may be necessary to adjust the export value for one or more land use categories to achieve acceptable agreement. However, this should not be done without a clear understanding of why the value is probably higher or lower than represented by the median; the model should not be blindly calibrated, and field examination of conditions that affect export values is strongly recommended.

Other Nutrient Inputs

Atmospheric Deposition

Both wet and dry deposition are covered by the chosen values, and are often simple literature value selections. Where empirical data for wet or dry fall are available, coefficients should be adjusted accordingly. Regional data are often available and can be used as a reality check on chosen values. Choices of atmospheric export coefficients are often based on dominant land use in the contributory area (see Reference Variables sheet), but as the airshed for a lake is usually much larger than the watershed, it is not appropriate to use land use from the watershed as the sole criterion for selecting atmospheric export coefficients. Fortunately, except where the lake is large and the watershed is small, atmospheric inputs tend not to have much influence on the final concentrations of P or N in the lake, so this is not a portion of the model on which extreme investigation is usually necessary.

For the example system, a 40 ha lake is assumed to receive 0.2 kg P/ha/yr and 6.5 kg N/ha/yr, the median values from the Reference Variables sheet. The model then calculates the loads in kg/yr to the lake and uses them later in the summary.

AREAL SOURCES	Affected Lake Area (ha)	P Export Coefficient (kg/ha/yr)	N Export Coefficient (kg/ha/yr)	P Load (from coeff) (kg/yr)	N Load (from coeff) (kg/yr)	Period of Release (days)	P Rate of Release (mg/m2/day)	N Rate of Release (mg/m2/day)	P Load (from rate) (kg/yr)	N Load (from rate) (kg/yr)
Direct Atmospheric Deposition	40	0.20	6.50	8	260					
Internal Loading	20	2.00	5.00	40	100	100	2.00	5.00	40	100

Internal Loading

Internal release of P or N is generally described as a release rate per square meter per day. It can be a function of direct dissolution release, sediment resuspension with some dissociation of available nutrients, or release from rooted plants. The release rate is entered as shown in the table above, along with the affected portion of the lake, in this case half of the 40 ha area, or 20 ha. The period of release must also be specified, usually corresponding to the period of deepwater anoxia or the plant growing season. The model then calculates a release rate as kg/ha/yr and a total annual load as shown in the table above.

Waterfowl or Other Wildlife

Waterfowl or other wildlife inputs are calculated as a direct product of the number of animal-years on the lake (e.g., 100 geese spending half a year = 50 bird-years) and a chosen input rate in kg/animal/yr, as shown in the table below. Input rates are from the literature as shown in the Reference Variables sheet, while animal-years must be estimated for the lake.

NON-AREAL SOURCES	Number of Source Units	Volume (cu.m/yr)	P Load/Unit (kg/unit/yr)	N Load/Unit (kg/unit/yr)	P Conc. (ppm)	N Conc. (ppm)	P Load (kg/yr)	N Load (kg/yr)		
Waterfowl	50		0.20	0.95			10	47.5		
Point Sources										
PS-1		45000			3.00	12.00	135	540		
PS-2		0			3.00	12.00	0	0		
PS-3		0			3.00	12.00	0	0		
Basin in which Point Source occurs (0=NO 1=YES)										
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10
PS-1	0	0	0	1	0	0	0	0	0	0
PS-2	0	0	0	0	0	0	0	0	0	0
PS-3	0	0	0	0	0	0	0	0	0	0

Point Source Discharges

LLRM allows for three point source discharges. While some storm water discharges are legally considered point sources, the point sources in LLRM are intended to be daily discharge sources, such as wastewater treatment facility or cooling water discharges. The annual volume of the discharge must be entered as well as the average concentration for P and N, as shown in the table above. The model then calculates the input of P and N. It is also essential to note which basin receives the discharge, denoted by a 1 in the appropriate column. As shown in the table above, the example system has a discharge in Basin 4, and no discharges in any other basin (denoted by 0).

On-Site Wastewater Disposal Systems

While the input from septic systems in the direct drainage areas around the lake can be addressed through the baseflow export coefficient, separation of that influence is desirable where it may be large enough to warrant management consideration. In such cases, the existing systems are divided into those within 100 ft of the lake and those between 100 and 300 ft of the lake, each zone receiving potentially different attenuation factors. A further subdivision between dwelling occupied all year vs. those used only seasonally is made. The number of people per dwelling and the water use per person per day are specified, along with the expected concentrations of P and N in septic system effluent, as shown in the table below. The model then calculates the input of water, P and N from each septic system grouping. If data are insufficient to subdivide systems along distance or use gradients, a single line of this module can be used with average values entered.

DIRECT SEPTIC SYSTEM LOAD												
Septic System Grouping (by occupancy or location)	Days of Occupancy/Yr	Distance from Lake (ft)	Number of Dwellings	Number of People per Dwelling	Water per Person per Day (cu.m)	P Conc. (ppm)	N Conc. (ppm)	P Attenuation Factor	N Attenuation Factor	Water Load (cu.m/yr)	P Load (kg/yr)	N Load (kg/yr)
Group 1 Septic Systems	365	<100	25	2.5	0.25	8	20	0.2	0.9	5703	9.1	102.7
Group 2 Septic Systems	365	100 - 300	75	2.5	0.25	8	20	0.1	0.8	17109	13.7	273.8
Group 3 Septic Systems	90	<100	50	2.5	0.25	8	20	0.2	0.9	2813	4.5	50.6
Group 4 Septic Systems	90	100 - 300	100	2.5	0.25	8	20	0.1	0.8	5625	4.5	90.0
Total Septic System Loading										31250	31.8	517.0

Subwatershed Functions

The next set of calculations addresses inputs from each defined basin within the system. Basins can be left as labeled, 1, 2, 3, etc., or the blank line between Basin # and Area (Ha) can be used to enter an identifying name. In this case, basins have been identified as the East Direct drainage, the West Direct drainage, Upper Tributary #1, Lower Tributary #1, East Upper Tributary #2, West Upper Tributary #2, and Lower Tributary #2, matching the watershed and schematic maps in Figures 1 and 2.

Land Uses

The area of each defined basin associated with each defined land use category is entered, creating the table below. The model is set up to address up to 10 basins; in this case there are only seven defined basins, so the other three columns are left blank and do not figure in to the calculations. The total area per land use and per basin is summed along the right and bottom of the table. Three “Other” land use lines are provided, in the event that the standard land uses provided are inadequate to address all land uses identified in a watershed. It is also possible to split a standard land use category using one of the

“Other” lines, where there is variation in export coefficients within a land use that can be documented and warrants separation.

Land use data is often readily available in GIS formats. It is always advisable to ground truth land use designation, especially in rapidly developing watersheds. The date on the land use maps used as sources should be as recent as possible.

BASIN AREAS											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	TOTAL
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
LAND USE	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)
Urban 1 (LDR)	12.0	8.5	8.4	47.4	6.7	4.5	18.1				105.5
Urban 2 (MDR/Hwy)	3.7	5.5	0.0	5.9	0.8	0.6	2.3				18.8
Urban 3 (HDR/Com)	3.6	5.8	0.0	5.9	0.8	0.6	2.3				19.0
Urban 4 (Ind)	0.0	0.0	0.0	23.5	0.0	0.0	0.0				23.5
Urban 5 (P/I/R/C)	0.0	3.2	0.0	0.0	0.0	0.0	0.0				3.2
Agric 1 (Cvr Crop)	0.0	0.0	0.0	0.8	12.3	0.0	0.0				13.1
Agric 2 (Row Crop)	0.0	0.0	0.0	0.0	16.2	0.0	0.0				16.2
Agric 3 (Grazing)	0.0	0.0	0.0	0.0	4.0	0.0	0.0				4.0
Agric 4 (Feedlot)	0.0	0.0	0.0	0.0	0.5	0.0	0.0				0.5
Forest 1 (Upland)	7.7	17.5	50.3	90.3	9.2	32.0	33.6				240.6
Forest 2 (Wetland)	0.0	0.2	0.0	14.5	0.0	0.0	1.9				16.6
Open 1 (Wetland/Lake)	2.5	0.6	2.0	0.1	0.0	0.1	14.2				19.4
Open 2 (Meadow)	2.0	1.3	0.0	10.2	0.1	0.0	0.2				13.8
Open 3 (Excavation)	0.1	0.1	0.0	2.3	0.0	0.0	0.0				2.5
Other 1											0.0
Other 2											0.0
Other 3											0.0
TOTAL	31.6	42.6	60.7	200.9	50.6	37.7	72.4	0	0		496.5

Load Generation

At this point, the model will perform a number of calculations before any further input is needed. These are represented by a series of tables with no shaded cells, and include calculation of water, P and N loads from runoff and baseflow as shown below. These loads are intermediate products, not subject to attenuation or routing, and have little utility as individual values. They are the precursors of the actual loads delivered to the lake, which require some additional input information.

WATER LOAD GENERATION: RUNOFF											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	TOTAL
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
LAND USE	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)
Urban 1 (LDR)	43560	30855	30492	172056	24182	16277	65563	0	0	0	382985
Urban 2 (MDR/Hwy)	18005	26457	0	28676	4030	2713	10927	0	0	0	90808
Urban 3 (HDR/Com)	26136	42108	0	43014	6045	4069	16391	0	0	0	137763
Urban 4 (Ind)	0	0	0	142175	0	0	0	0	0	0	142175
Urban 5 (P/I/R/C)	0	3872	0	0	0	0	0	0	0	0	3872
Agric 1 (Cvr Crop)	0	0	0	1387	22325	0	0	0	0	0	23712
Agric 2 (Row Crop)	0	0	0	0	58806	0	0	0	0	0	58806
Agric 3 (Grazing)	0	0	0	0	14520	0	0	0	0	0	14520
Agric 4 (Feedlot)	0	0	0	0	2723	0	0	0	0	0	2723
Forest 1 (Upland)	9325	21175	63283	109263	11126	38720	40600	0	0	0	293493
Forest 2 (Wetland)	0	150	0	8746	0	0	1153	0	0	0	10049
Open 1 (Wetland/Lake)	1494	334	0	56	0	37	8591	0	0	0	10512
Open 2 (Meadow)	1210	768	0	6199	38	0	122	0	0	0	8336
Open 3 (Excavation)	593	454	0	10991	0	0	0	0	0	0	12038
Other 1	0	0	0	0	0	0	0	0	0	0	0
Other 2	0	0	0	0	0	0	0	0	0	0	0
Other 3	0	0	0	0	0	0	0	0	0	0	0
TOTAL (CU.M/YR)	100323	126173	93775	522564	143794	61816	143347	0	0	0	1191792
TOTAL (CFS)	0.11	0.14	0.11	0.59	0.16	0.07	0.16	0.00	0.00	0.00	1.33

WATER LOAD GENERATION: BASEFLOW											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	TOTAL
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)
Urban 1 (LDR)	21780	15428	15246	86028	12091	8139	32781	0	0	0	191492
Urban 2 (MDR/Hwy)	4501	6614	0	7169	1008	678	2732	0	0	0	22702
Urban 3 (HDR/Com)	2178	3509	0	3585	504	339	1366	0	0	0	11480
Urban 4 (Ind)	0	0	0	14218	0	0	0	0	0	0	14218
Urban 5 (P/I/R/C)	0	1936	0	0	0	0	0	0	0	0	1936
Agric 1 (Cvr Crop)	0	0	0	2775	44649	0	0	0	0	0	47424
Agric 2 (Row Crop)	0	0	0	0	58806	0	0	0	0	0	58806
Agric 3 (Grazing)	0	0	0	0	14520	0	0	0	0	0	14520
Agric 4 (Feedlot)	0	0	0	0	1815	0	0	0	0	0	1815
Forest 1 (Upland)	37301	84700	253132	437052	44504	154880	162402	0	0	0	1173971
Forest 2 (Wetland)	0	1203	0	69969	0	0	9220	0	0	0	80393
Open 1 (Wetland)	11953	2672	0	450	0	294	68728	0	0	0	84097
Open 2 (Meadow)	7260	4605	0	37192	226	0	732	0	0	0	50016
Open 3 (Excavation)	297	227	0	5496	0	0	0	0	0	0	6019
Other 1	0	0	0	0	0	0	0	0	0	0	0
Other 2	0	0	0	0	0	0	0	0	0	0	0
Other 3	0	0	0	0	0	0	0	0	0	0	0
Point Source #1	0	0	0	45000	0	0	0	0	0	0	45000
Point Source #2	0	0	0	0	0	0	0	0	0	0	0
Point Source #3	0	0	0	0	0	0	0	0	0	0	0
TOTAL (CU.M/YR)	85270	120894	268378	708932	178122	164330	277961	0	0	0	1803888
TOTAL (CFS)	0.10	0.14	0.30	0.79	0.20	0.18	0.31	0.00	0.00	0.000	2.02

LOAD GENERATION: RUNOFF P											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	TOTAL
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
LAND USE	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)
Urban 1 (LDR)	7.8	5.5	5.5	30.8	4.3	2.9	11.7	0.0	0.0	0.0	68.6
Urban 2 (MDR/Hwy)	2.8	4.1	0.0	4.4	0.6	0.4	1.7	0.0	0.0	0.0	14.1
Urban 3 (HDR/Com)	2.9	4.6	0.0	4.7	0.7	0.4	1.8	0.0	0.0	0.0	15.2
Urban 4 (Ind)	0.0	0.0	0.0	16.5	0.0	0.0	0.0	0.0	0.0	0.0	16.5
Urban 5 (P/I/R/C)	0.0	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6
Agric 1 (Cvr Crop)	0.0	0.0	0.0	0.6	9.8	0.0	0.0	0.0	0.0	0.0	10.5
Agric 2 (Row Crop)	0.0	0.0	0.0	0.0	16.2	0.0	0.0	0.0	0.0	0.0	16.2
Agric 3 (Grazing)	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	1.6
Agric 4 (Feedlot)	0.0	0.0	0.0	0.0	112.0	0.0	0.0	0.0	0.0	0.0	112.0
Forest 1 (Upland)	1.5	3.5	10.5	18.1	1.8	6.4	6.7	0.0	0.0	0.0	48.5
Forest 2 (Wetland)	0.0	0.0	0.0	1.4	0.0	0.0	0.2	0.0	0.0	0.0	1.7
Open 1 (Wetland/Lake)	0.2	0.1	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	1.7
Open 2 (Meadow)	0.2	0.1	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4
Open 3 (Excavation)	0.1	0.1	0.0	1.8	0.0	0.0	0.0	0.0	0.0	0.0	2.0
Other 1:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other 2:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other 3:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	15.6	20.6	15.9	79.4	147.1	10.2	23.6	0.0	0.0	0.0	312.4

LOAD GENERATION: RUNOFF N											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	TOTAL
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
LAND USE	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)
Urban 1 (LDR)	66.0	46.8	46.2	260.7	36.6	24.7	99.3	0.0	0.0	0.0	580.3
Urban 2 (MDR/Hwy)	20.5	30.1	0.0	32.6	4.6	3.1	12.4	0.0	0.0	0.0	103.2
Urban 3 (HDR/Com)	19.8	31.9	0.0	32.6	4.6	3.1	12.4	0.0	0.0	0.0	104.4
Urban 4 (Ind)	0.0	0.0	0.0	129.3	0.0	0.0	0.0	0.0	0.0	0.0	129.3
Urban 5 (P/I/R/C)	0.0	17.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.6
Agric 1 (Cvr Crop)	0.0	0.0	0.0	4.6	74.8	0.0	0.0	0.0	0.0	0.0	79.4
Agric 2 (Row Crop)	0.0	0.0	0.0	0.0	145.8	0.0	0.0	0.0	0.0	0.0	145.8
Agric 3 (Grazing)	0.0	0.0	0.0	0.0	20.8	0.0	0.0	0.0	0.0	0.0	20.8
Agric 4 (Feedlot)	0.0	0.0	0.0	0.0	1461.6	0.0	0.0	0.0	0.0	0.0	1461.6
Forest 1 (Upland)	22.0	50.1	149.6	258.3	26.3	91.5	96.0	0.0	0.0	0.0	693.7
Forest 2 (Wetland)	0.0	0.7	0.0	41.3	0.0	0.0	5.4	0.0	0.0	0.0	47.5
Open 1 (Wetland/Lake)	6.1	1.4	0.0	0.2	0.0	0.1	34.9	0.0	0.0	0.0	42.7
Open 2 (Meadow)	4.9	3.1	0.0	25.2	0.2	0.0	0.5	0.0	0.0	0.0	33.9
Open 3 (Excavation)	0.6	0.5	0.0	11.8	0.0	0.0	0.0	0.0	0.0	0.0	12.9
Other 1:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other 2:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other 3:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	139.9	182.0	195.8	796.6	1775.2	122.5	261.0	0.0	0.0	0.0	3473.0

LOAD GENERATION: BASEFLOW P											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	TOTAL
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
LAND USE	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)
Urban 1 (LDR)	0.12	0.09	0.08	0.47	0.07	0.04	0.18	0.00	0.00	0.00	1.06
Urban 2 (MDR/Hwy)	0.04	0.05	0.00	0.06	0.01	0.01	0.02	0.00	0.00	0.00	0.19
Urban 3 (HDR/Com)	0.04	0.06	0.00	0.06	0.01	0.01	0.02	0.00	0.00	0.00	0.19
Urban 4 (Ind)	0.00	0.00	0.00	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.24
Urban 5 (P/I/R/C)	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Agric 1 (Cvr Crop)	0.00	0.00	0.00	0.01	0.12	0.00	0.00	0.00	0.00	0.00	0.13
Agric 2 (Row Crop)	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.16
Agric 3 (Grazing)	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.04
Agric 4 (Feedlot)	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
Forest 1 (Upland)	0.04	0.09	0.26	0.45	0.05	0.16	0.17	0.00	0.00	0.00	1.21
Forest 2 (Wetland)	0.00	0.00	0.00	0.07	0.00	0.00	0.01	0.00	0.00	0.00	0.08
Open 1 (Wetland/Lake)	0.01	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.09
Open 2 (Meadow)	0.01	0.01	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.07
Open 3 (Excavation)	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Other 1:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other 2:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other 3:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Point Source #1	0.00	0.00	0.00	135.00	0.00	0.00	0.00	0.00	0.00	0.00	135.00
Point Source #2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Point Source #3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	0.25	0.33	0.35	136.42	0.46	0.22	0.48	0.00	0.00	0.00	138.50

LOAD GENERATION: BASEFLOW N											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	TOTAL
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
LAND USE	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)
Urban 1 (LDR)	60.00	42.50	42.00	236.99	33.31	22.42	90.31	0.00	0.00	0.00	527.53
Urban 2 (MDR/Hwy)	18.60	27.33	0.00	29.62	4.16	2.80	11.29	0.00	0.00	0.00	93.81
Urban 3 (HDR/Com)	18.00	29.00	0.00	29.62	4.16	2.80	11.29	0.00	0.00	0.00	94.88
Urban 4 (Ind)	0.00	0.00	0.00	117.50	0.00	0.00	0.00	0.00	0.00	0.00	117.50
Urban 5 (P/I/R/C)	0.00	16.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.00
Agric 1 (Cvr Crop)	0.00	0.00	0.00	1.91	30.75	0.00	0.00	0.00	0.00	0.00	32.66
Agric 2 (Row Crop)	0.00	0.00	0.00	0.00	40.50	0.00	0.00	0.00	0.00	0.00	40.50
Agric 3 (Grazing)	0.00	0.00	0.00	0.00	20.00	0.00	0.00	0.00	0.00	0.00	20.00
Agric 4 (Feedlot)	0.00	0.00	0.00	0.00	12.50	0.00	0.00	0.00	0.00	0.00	12.50
Forest 1 (Upland)	7.71	17.50	52.30	90.30	9.20	32.00	33.55	0.00	0.00	0.00	242.56
Forest 2 (Wetland)	0.00	0.25	0.00	14.46	0.00	0.00	1.91	0.00	0.00	0.00	16.61
Open 1 (Wetland/Lake)	1.23	0.28	0.00	0.05	0.00	0.03	7.10	0.00	0.00	0.00	8.69
Open 2 (Meadow)	1.00	0.63	0.00	5.12	0.03	0.00	0.10	0.00	0.00	0.00	6.89
Open 3 (Excavation)	0.06	0.05	0.00	1.14	0.00	0.00	0.00	0.00	0.00	0.00	1.24
Other 1:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other 2:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other 3:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Point Source #1	0.00	0.00	0.00	540.00	0.00	0.00	0.00	0.00	0.00	0.00	540.00
Point Source #2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Point Source #3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	106.60	133.54	94.30	1066.71	154.61	60.06	155.54	0.00	0.00	0.00	1771.36

Load Routing Pattern

The model must be told how to route all inputs of water, P and N before they reach the lake. Since attenuation in a downstream basin can affect inputs in an upstream basin that passes through the downstream basin, the model must be directed as to where to apply attenuation factors and additive effects. In the table below, each basin listed on the lines labeled on the left that passes through another basin labeled by column is denoted with a 1 in the column of the basin through which it passes. Otherwise, a 0 appears in each shaded cell. All basins pass through themselves, so the first line has a 1 in each cell. Basins 1 and 2 go direct to the lake, and so all other cells on the corresponding lines have 0 entries. Basin 3 passes through Basin 4 (see Figure 2), and so the line for Basin 3 has a 1 in the column for Basin 4. Likewise, Basins 5 and 6 pass through Basin 7, so the corresponding lines have a 1 entered in the column for Basin 7.

The model then combines the appropriate watershed areas as shown above, generating larger sub-watersheds that are used later to calculate overall export coefficients, comparative water yields, and related checks for model accuracy.

ROUTING PATTERN										
	(Basin in left hand column passes through basin in column below if indicated by a 1)									
1=YES 0=NO XXX=BLANK	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2			
	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)
INDIVIDUAL BASIN	1	1	1	1	1	1	1	1	1	1
BASIN 1 OUTPUT	XXX	0	0	0	0	0	0	0	0	0
BASIN 2 OUTPUT	0	XXX	0	0	0	0	0	0	0	0
BASIN 3 OUTPUT	0	0	XXX	1	0	0	0	0	0	0
BASIN 4 OUTPUT	0	0	0	XXX	0	0	0	0	0	0
BASIN 5 OUTPUT	0	0	0	0	XXX	0	1	0	0	0
BASIN 6 OUTPUT	0	0	0	0	0	XXX	1	0	0	0
BASIN 7 OUTPUT	0	0	0	0	0	0	XXX	0	0	0
BASIN 8 OUTPUT	0	0	0	0	0	0	0	XXX	0	0
BASIN 9 OUTPUT	0	0	0	0	0	0	0	0	XXX	0
BASIN 10 OUTPUT	0	0	0	0	0	0	0	0	0	XXX

CUMULATIVE DRAINAGE AREAS										
	(Total land area associated with routed water and nutrients)									
1=YES 0=NO XXX=BLANK	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2			
	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)
INDIVIDUAL BASIN	31.6	42.6	60.7	200.9	50.6	37.7	72.4	0.0	0.0	0.0
BASIN 1 OUTPUT	XXX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 2 OUTPUT	0.0	XXX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 3 OUTPUT	0.0	0.0	XXX	60.7	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 4 OUTPUT	0.0	0.0	0.0	XXX	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 5 OUTPUT	0.0	0.0	0.0	0.0	XXX	0.0	50.6	0.0	0.0	0.0
BASIN 6 OUTPUT	0.0	0.0	0.0	0.0	0.0	XXX	37.7	0.0	0.0	0.0
BASIN 7 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	XXX	0.0	0.0	0.0
BASIN 8 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	XXX	0.0	0.0
BASIN 9 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	XXX	0.0
BASIN 10 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	XXX
TOTALS	31.6	42.6	60.7	261.6	50.6	37.7	160.7	0.0	0.0	0.0

Load Routing and Attenuation

With the loads calculated previously for each basin under wet and dry conditions and the routing of those loads specified, the model can then combine those loads and apply attenuation values chosen to reflect expected losses of water, P or N while the generated loads are on their way to the lake.

Water

Water is attenuated mostly by evapotranspiration losses. Some depression storage is expected, seepage into the ground is possible, and wetlands can remove considerable water on the way to the lake. In general, a 5% loss is to be expected in nearly all cases, and greater losses are plausible with lower gradient or wetland dominated landscapes. In the example system, only the lower portion of Tributary 2 is expected to have more than a 5% loss, with a 15% loss linked to the wetland associated with this drainage area and tributary (see Figure 1).

WATER ROUTING AND ATTENUATION										
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2			
SOURCE	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)	(CU.M/YR)
INDIVIDUAL BASIN	185594	247067	362153	1231497	321916	226145	421308	0	0	0
BASIN 1 OUTPUT	XXX	0	0	0	0	0	0	0	0	0
BASIN 2 OUTPUT	0	XXX	0	0	0	0	0	0	0	0
BASIN 3 OUTPUT	0	0	XXX	344045	0	0	0	0	0	0
BASIN 4 OUTPUT	0	0	0	XXX	0	0	0	0	0	0
BASIN 5 OUTPUT	0	0	0	0	XXX	0	305820	0	0	0
BASIN 6 OUTPUT	0	0	0	0	0	XXX	214838	0	0	0
BASIN 7 OUTPUT	0	0	0	0	0	0	XXX	0	0	0
BASIN 8 OUTPUT	0	0	0	0	0	0	0	XXX	0	0
BASIN 9 OUTPUT	0	0	0	0	0	0	0	0	XXX	0
BASIN 10 OUTPUT	0	0	0	0	0	0	0	0	0	XXX
CUMULATIVE TOTAL	185594	247067	362153	1575542	321916	226145	941966	0	0	0
BASIN ATTENUATION	0.95	0.95	0.95	0.95	0.95	0.95	0.85	1.00	1.00	1.00
OUTPUT VOLUME	176314	234714	344045	1496765	305820	214838	800671	0.0	0.0	0.0
Reality Check from Flow Data				1500000.0			800000.0			
Calculated Flow/Measured Flow	#DIV/0!	#DIV/0!	#DIV/0!	0.998	#DIV/0!	#DIV/0!	1.001	#DIV/0!	#DIV/0!	#DIV/0!
Reality Check from Areal Yield X Basin Area	174638.7	235450.8	335258.2	1444750.2	279386.8	208035.3	887509.1	0.0	0.0	0.0
Calculated Flow/Flow from Areal Yield	1.010	0.997	1.026	1.036	1.095	1.033	0.902	#DIV/0!	#DIV/0!	#DIV/0!

The resulting output volume for each basin is calculated in the table below, and two reality check opportunities are provided. First any actual data can be added for direct comparison; average flows are available for only two points, the inlets of the two tributaries, but these are useful. In many cases no flow data may be available. The model therefore generates an estimate of the expected average flow as a function of all contributing upstream watershed area and the water yield provided near the top of the Calculations sheet (covered previously). While this flow estimate is approximate, it should not vary from the modeled flow by more than about 20% unless there are unusual circumstances.

In the example, the ratio of the calculated flow from the complete model generation and routing to the estimated yield from the contributing drainage area ranges from 0.902 to 1.095, suggesting fairly close agreement. As some ratios are lower than 1 and others are higher than 1, no model-wide adjustment is likely to bring the values into closer agreement. Slight changes in attenuation for each basin could be applied, but are not necessary when the values agree this closely.

Phosphorus

The same approach applied to attenuation of water is applied to the phosphorus load, as shown in the table below. Here attenuation can range from 0 to 1.0, with the value shown representing the portion of the load that reaches the terminus of the basin. With natural or human enhanced removal processes, it is unusual for all of the load to pass through a basin, but it is also unusual for more than 60 to 70% of it to be removed. What value to pick depends on professional judgment regarding the nature of removal processes in each basin. Infiltration, filtration, detention and uptake will lower the attenuation value entered below, and knowledge of the literature on Best Management Practices is needed to make reliable judgments on attenuation values.

LOAD ROUTING AND ATTENUATION: PHOSPHORUS										
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2			
	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)
BASIN 1 INDIVIDUAL	15.8	20.9	16.3	215.8	147.6	10.4	24.1	0.0	0.0	0.0
BASIN 1 OUTPUT	XXX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 2 OUTPUT	0.0	XXX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 3 OUTPUT	0.0	0.0	XXX	12.2	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 4 OUTPUT	0.0	0.0	0.0	XXX	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 5 OUTPUT	0.0	0.0	0.0	0.0	XXX	0.0	118.1	0.0	0.0	0.0
BASIN 6 OUTPUT	0.0	0.0	0.0	0.0	0.0	XXX	7.8	0.0	0.0	0.0
BASIN 7 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	XXX	0.0	0.0	0.0
BASIN 8 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	XXX	0.0	0.0
BASIN 9 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	XXX	0.0
BASIN 10 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	XXX
CUMULATIVE TOTAL	15.8	20.9	16.3	228.0	147.6	10.4	149.9	0.0	0.0	0.0
BASIN ATTENUATION	0.90	0.90	0.75	0.85	0.80	0.75	0.70	1.00	1.00	1.00
OUTPUT LOAD	14.2	18.8	12.2	193.8	118.1	7.8	104.9	0.0	0.0	0.0

In the example system, the direct drainage basins were assigned values of 0.90, representing a small amount of removal mainly by infiltration processes. Upper Tributary #1 has a small pond and was accorded a value of 0.75 (25% removal); a larger pond might have suggested a value closer to 0.5. Lower Tributary #1 has an assigned value of 0.85 based on channel processes that favor uptake and adsorption. West and East Upper Tributary #2 have value based on drainage basin features as evaluated in the field, while the wetland associated with Lower Tributary #2 garners it the lowest load pass-through at 0.7. A more extensive wetland with greater sheet flow might have earned a value near 0.5. Resulting output loads are then calculated.

Nitrogen

The same process used with water and P attenuation applies to N, but attenuation of N is rarely identical to that for P. Nitrogen moves more readily through soil, and while transformations occur in the stream, losses due to denitrification require slower flows and low oxygen levels not commonly encountered in steeper, rockier channels. However, losses from uptake and possibly denitrification are possible in wetland areas, such as that associated with Lower Tributary #2. Accordingly, attenuation values are assigned as shown in the table below, with generally lower losses for N than for P. As with P attenuation, choosing appropriate values does require some professional judgment.

LOAD ROUTING AND ATTENUATION: NITROGEN										
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2			
	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)	(KG/YR)
BASIN 1 INDIVIDUAL	246.5	315.6	290.1	1863.3	1929.8	182.6	416.6	0.0	0.0	0.0
BASIN 1 OUTPUT	XXX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 2 OUTPUT	0.0	XXX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 3 OUTPUT	0.0	0.0	XXX	232.1	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 4 OUTPUT	0.0	0.0	0.0	XXX	0.0	0.0	0.0	0.0	0.0	0.0
BASIN 5 OUTPUT	0.0	0.0	0.0	0.0	XXX	0.0	1543.8	0.0	0.0	0.0
BASIN 6 OUTPUT	0.0	0.0	0.0	0.0	0.0	XXX	146.0	0.0	0.0	0.0
BASIN 7 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	XXX	0.0	0.0	0.0
BASIN 8 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	XXX	0.0	0.0
BASIN 9 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	XXX	0.0
BASIN 10 OUTPUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	XXX
CUMULATIVE TOTAL	246.5	315.6	290.1	2095.4	1929.8	182.6	2106.4	0.0	0.0	0.0
BASIN ATTENUATION	0.95	0.95	0.80	0.90	0.80	0.80	0.75	1.00	1.00	1.00
OUTPUT LOAD	234.2	299.8	232.1	1885.8	1543.8	146.0	1579.8	0.0	0.0	0.0

Load and Concentration Summary

Water

Water loads were handled to the extent necessary in the previous loading calculations, and are used in this section only to allow calculation of expected P and N concentrations, facilitating reality checks with actual data.

Phosphorus

Using the calculated load of P for each basin and the corresponding water volume, an average expected concentration can be derived, as shown in the table below. Where sampling provides actual data, values can be compared to determine how well the model represents known reality. Sufficient sampling is needed to make the reality check values reliable; it is not appropriate to assume that either the data or the model is necessarily accurate when the values disagree. However, with enough data to adequately characterize the concentrations observed in the stream, the model can be adjusted to produce a better match. Estimated and actual concentrations are used to generate a ratio for easy comparison.

The P loads previously calculated represent the load passing through each basin, but do not represent what reaches the lake, as not all basins are terminal input sources. The model must be told which basins actually drain directly to the lake, and for which the exiting load is part of the total load to the lake.

LOAD AND CONCENTRATION SUMMARY: PHOSPHORUS											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
OUTPUT (CU.M/YR)	176314	234714	344045	1496765	305820	214838	800671	0	0	0	
OUTPUT (KG/YR)	14.2	18.8	12.2	193.8	118.1	7.8	104.9	0.0	0.0	0.0	
OUTPUT (MG/L)	0.081	0.080	0.035	0.129	0.386	0.036	0.131	#DIV/0!	#DIV/0!	#DIV/0!	
REALITY CHECK CONC. (FROM DATA)	0.078	0.076	0.040	0.150	0.325	0.035	0.125				
CALCULATED CONC./MEASURED CONC.	1.035	1.056	0.886	0.863	1.188	1.038	1.049	#DIV/0!	#DIV/0!	#DIV/0!	
BASIN EXPORT COEFFICIENT	0.45	0.44	0.20	0.74	2.33	0.21	0.65	#DIV/0!	#DIV/0!	#DIV/0!	
TERMINAL DISCHARGE?	1	1	0	1	0	0	1	1	1	1	
(1=YES 2=NO)											
LOAD TO RESOURCE											TOTAL
WATER (CU.M/YR)	176314	234714	0	1496765	0	0	800671	0	0	0	2708464
PHOSPHORUS (KG/YR)	14.2	18.8	0.0	193.8	0.0	0.0	104.9	0.0	0.0	0.0	331.8
PHOSPHORUS (MG/L)	0.081	0.080	0.000	0.129	0.000	0.000	0.131	#DIV/0!	#DIV/0!	#DIV/0!	0.123

For the example system, the ratio of the calculated concentration to average actual values derived from substantial sampling (typically on the order of 10 or more samples representing the range of dry to wet conditions) ranges from 0.886 to 1.188, or from 11% low to 19% high, within a generally acceptable range of $\pm$20%. This is not a strict threshold, especially with lower P concentrations where detection limits and intervals of expression for methods can produce higher percent deviation with very small absolute differences. Yet in general, <20% difference between observed and expected watershed basin output values is considered reasonable for a model at this level of sophistication.

That some values are higher than expected and others lower suggests that now model-wide adjustment will improve agreement (such as an export coefficient change), but attenuation values for individual basins could be adjusted if there is justification.

For the example system, Basins 1, 2, 4 and 7 contribute directly to the lake, and are so denoted by a 1 in their respective columns on the line for terminal discharge. These loads will be summed to derive a watershed load of P to the lake.

Nitrogen

The process followed for N is identical to that applied to P loads from basins. For N in the example system, comparison of expected vs. observed values yields a range of ratios from 0.929 to 1.188, representing 7% low to 19% high. Only one out of seven values is lower than 1, so perhaps some adjustment of the N export coefficients is in order, but most individual basin values are within 8% of each other, so without clear justification, the judgment exercised in the original choices for export coefficients and attenuation is not generally overridden. The same basins denoted as terminal discharges for P are so noted for N, allowing calculation of the total watershed load of N to the lake.

LOAD AND CONCENTRATION SUMMARY: NITROGEN											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
OUTPUT (CU.M/YR)	176314	234714	344045	1496765	305820	214838	800671	0	0	0	
OUTPUT (KG/YR)	234.2	299.8	232.1	1885.8	1543.8	146.0	1579.8	0.0	0.0	0.0	
OUTPUT MG/L	1.328	1.277	0.675	1.260	5.048	0.680	1.973	#DIV/0!	#DIV/0!	#DIV/0!	
REALITY CHECK CONC. (FROM DATA)	1.430	1.240	0.650	1.180	4.250	0.650	1.830				
CALCULATED CONC./MEASURED CONC.	0.929	1.030	1.038	1.068	1.188	1.046	1.078	#DIV/0!	#DIV/0!	#DIV/0!	
BASIN EXPORT COEFFICIENT	7.41	7.03	3.82	7.21	30.52	3.88	9.83	#DIV/0!	#DIV/0!	#DIV/0!	
TERMINAL DISCHARGE?	1	1	0	1	0	0	1	1	1	1	
(1=YES 2=NO)											
LOAD TO RESOURCE											TOTAL
WATER (CU.M/YR)	176314	234714	0	1496765	0	0	800671	0	0	0	2708464
NITROGEN (KG/YR)	234.2	299.8	0.0	1885.8	0.0	0.0	1579.8	0.0	0.0	0.0	3999.7
NITROGEN (MG/L)	1.328	1.277	0.000	1.260	0.000	0.000	1.973	#DIV/0!	#DIV/0!	#DIV/0!	1.477

Grand Totals

The final portion of the Calculation sheet is a summary of all loads to the lake and a grand total load with associated concentrations for P and N, as shown below. The breakdown of sources is provided for later consideration in both overall target setting and in consideration of BMPs. For the example system, the watershed load is clearly dominant, and would need to be addressed if substantial reductions in loading were considered necessary. The loads of water, P and N are then transferred automatically to the Prediction sheet to facilitate estimation of in-lake concentrations of P, N and Chl and a value for SDT. The derived overall input concentration for P is also transferred; the in-lake predictive models for N do not require that overall input concentration, but the comparison of P and N input levels can be insightful when considering what types of algae are likely to dominate the lake phytoplankton.

LOAD SUMMARY			
DIRECT LOADS TO LAKE	P (KG/YR)	N (KG/YR)	WATER (CU.M/YR)
ATMOSPHERIC	8.0	260.0	484000
INTERNAL	40.0	100.0	0
WATERFOWL	10.0	47.5	0
SEPTIC SYSTEM	31.8	517.0	31250
WATERSHED LOAD	331.7	3998.4	2707372
TOTAL LOAD TO LAKE	421.5	4922.9	3222622
(Watershed + direct loads)			
TOTAL INPUT CONC. (MG/L)	0.131	1.528	

Water Quality Predictions

Prediction of P, N, Chl and SDT is based on empirical equations from the literature, nearly all pertaining to North American systems. Only a few additional pieces of information are needed to run the model; most needed input data are automatically transferred from the Calculations sheet. As shown below, only the concentration of P leaving the lake and the lake volume must be entered on the Prediction sheet. If the outflow P level is not known, the in-lake surface concentration is normally used. If the volume is not specifically known, an average depth can be multiplied by the lake area to derive an input volume, which will then recalculate the average depth one cell below. The nature of the N prediction models does not require any N concentration input.

IN-LAKE MODELS FOR PREDICTING CONCENTRATIONS: Current Conditions					
THE TERMS					
	PHOSPHORUS				
SYMBOL	**PARAMETER**	**UNITS**	**DERIVATION**	**VALUE**	
TP	Lake Total Phosphorus Conc.	ppb	From in-lake models	To Be Predicted	
KG	Phosphorus Load to Lake	kg/yr	From export model	422	
L	Phosphorus Load to Lake	g P/m2/yr	KG*1000/A	1.054	
TPin	Influent (Inflow) Total Phosphorus	ppb	From export model	131	
TPout	Effluent (Outlet) Total Phosphorus	ppb	From data, if available	75	Enter Value (TP out)
I	Inflow	m3/yr	From export model	3222622	
A	Lake Area	m2	From data	400000	
V	Lake Volume	m3	From data	1625300	Enter Value (V)
Z	Mean Depth	m	Volume/area	4.063	
F	Flushing Rate	flushings/yr	Inflow/volume	1.983	
S	Suspended Fraction	no units	Effluent TP/Influent TP	0.573	
Qs	Areal Water Load	m/yr	Z(F)	8.057	
Vs	Settling Velocity	m	Z(S)	2.330	
Rp	Retention Coefficient (settling rate)	no units	((Vs+13.2)/2)/(((Vs+13.2)/2)+Qs)	0.491	
Rlm	Retention Coefficient (flushing rate)	no units	1/(1+F^0.5)	0.415	
	NITROGEN				
SYMBOL	**PARAMETER**	**UNITS**	**DERIVATION**	**VALUE**	
TN	Lake Total Nitrogen Conc.	ppb	From in-lake models	To Be Predicted	
KG	Nitrogen Load to Lake	kg/yr	From export model	4923	
L1	Nitrogen Load to Lake	g N/m2/yr	KG*1000/A	12.31	
L2	Nitrogen Load to Lake	mg N/m2/yr	KG*1000000/A	12307	
C1	Coefficient of Attenuation, from F	fraction/yr	2.7183^(0.5541(ln(F))-0.367)	1.01	
C2	Coefficient of Attenuation, from L	fraction/yr	2.7183^(0.71(ln(L2))-6.426)	1.30	
C3	Coefficient of Attenuation, from L/Z	fraction/yr	2.7183^(0.594(ln(L2/Z))-4.144)	1.85	

Phosphorus Concentration

P concentration is predicted from the equations shown below. The mass balance calculation is simply the P load divided by the water load, and assumes no losses to settling within the lake. Virtually all lakes have settling losses, but the other equations derive that settling coefficient in different ways, providing a range of possible P concentration values. Where there is knowledge of the components of the settling calculations, a model might be selected as most representative or models might be eliminated as inapplicable, but otherwise the average of the five empirical models (excluding the mass balance calculation) is accepted as the predicted P value for the lake.

The predicted in-lake P concentration can be compared to actual data (an average value is entered in the shaded cell as a reality check) and to calculation of the permissible and critical concentrations as derived from Vollenweider’s 1968 work. For the example lake, the predicted P level of 75 ug/L is an exact match for the measured value of 75 ug/L, but both are well above the critical concentration.

The permissible concentration is the value above which algal blooms are to be expected on a potentially unacceptable frequency, while the critical concentration is the level above which unacceptable algal growths are to be expected, barring extreme flushing, toxic events, or light limitation from suspended sediment.

THE MODELS				
	PHOSPHORUS	**PRED.**	**PERMIS.**	**CRITICAL**
		CONC.	**CONC.**	**CONC.**
NAME	**FORMULA**	**(ppb)**	**(ppb)**	**(ppb)**
Mass Balance	TP=L/(Z(F))*1000	131		
(Maximum Conc.)				
Kirchner-Dillon 1975	TP=L(1-Rp)/(Z(F))*1000	67	18	36
(K-D)				
Vollenweider 1975	TP=L/(Z(S+F))*1000	101	27	55
(V)				
Larsen-Mercier 1976	TP=L(1-Rlm)/(Z(F))*1000	76	21	41
(L-M)				
Jones-Bachmann 1976	TP=0.84(L)/(Z(0.65+F))*1000	83	22	45
(J-B)				
Reckhow General (1977)	TP=L/(11.6+1.2(Z(F)))*1000	50	13	27
(Rg)				
Average of Model Values		75	20	41
(without mass balance)				
Measured Value		75		
(mean, median, other)				
From Vollenweider 1968				
Permissible Load (g/m2/yr)	Lp=10^(0.501503(log(Z(F)))-1.0018)	0.28		
Critical Load (g/m2/yr)	Lc=2(Cp)	0.57		

Use of the range of values derived from these empirical equations provides some sense for the uncertainty in the analysis. Changing input loads, lake volume, or other key variables allows for sensitivity analysis.

Nitrogen Concentration

Prediction of N is based on three separate empirical equations from the same work, each calculating settling losses differently. A mass balance equation is applied as well, as with the prediction of P. An actual mean value is normally entered in the shaded cell as a reality check. For the example system, the actual mean N value is within the range of predicted values, but is about 5.6% lower than the average of predicted values. One might consider adjusting export coefficients or attenuation rates in the Calculations sheet, to bring these values closer together, but the discrepancy is relatively minor.

	NITROGEN	
Mass Balance	TN=L/(Z(F))*1000	1528
(Maximum Conc.)		
Bachmann 1980	TN=L/(Z(C1+F))*1000	1011
Bachmann 1980	TN=L/(Z(C2+F))*1000	923
Bachmann 1980	TN=L/(Z(C3+F))*1000	789
Average of Model Values		908
(without mass balance)		
Measured Value		860
(mean, median, other)		

Chlorophyll Concentration, Water Clarity and Bloom Probability

Once an average in-lake P concentration has been established, the Predictions sheet derives corresponding Chl and SDT values, as shown below. Five different equations are used to derive a predicted Chl value, and an average is derived. Peak Chl is estimated with three equations, with and average generated. Average and maximum expected SDT are estimated as well. Bloom frequency is based on the relationship of mean Chl to other threshold levels from other studies, and the portion of time that Chl is expected to exceed 10, 15, 20, 30 and 40 ug/L is derived.

A set of shaded cells are provided for entry of known measured values for comparison. For the example lake, the average and peak Chl levels predicted from the model are slightly higher than actual measured values, while the average and maximum SDT from the model are slightly lower than observed values, consistent with the Chl results. Agreement is generally high, however, with differences between 10 and 20%. There were not enough data to construct a dependable actual distribution of Chl over the range of thresholds provided for the example lake.

There are other factors besides nutrients that can strongly affect the standing crop of algae and resulting Chl levels, including low light from suspended sediment, grazing by zooplankton, and flushing effects from high flows. Consequently, close agreement between predicted and actual Chl will be harder to achieve than for predicted and actual P. Knowledge of those other potentially important influences can help determine if model calibration is off, or if closer agreement is not rationally achievable.

PREDICTED CHL AND WATER CLARITY			
MODEL	**Value**	**Mean**	**Measured**
Mean Chlorophyll (ug/L)			
Carlson 1977	45.9		
Dillon and Rigler 1974	38.4		
Jones and Bachmann 1976	44.7		
Oglesby and Schaffner 1978	40.4		
Modified Vollenweider 1982	35.5	41.0	37.5
Peak Chlorophyll (ug/L)			
Modified Vollenweider (TP) 1982	119.7		
Vollenweider (CHL) 1982	133.1		
Modified Jones, Rast and Lee 1979	139.5	130.8	118.1
Secchi Transparency (M)			
Oglesby and Schaffner 1978 **(Avg)**	0.8		1.0
Modified Vollenweider 1982 **(Max)**	2.9		3.1
Bloom Probability			
Probability of Chl >10 ug/L **(% of time)**	99.5%		
Probability of Chl >15 ug/L **(% of time)**	96.1%		
Probability of Chl >20 ug/L **(% of time)**	88.2%		
Probability of Chl >30 ug/L **(% of time)**	64.6%		
Probability of Chl >40 ug/L **(% of time)**	42.0%		

Evaluating Initial Results

LLRM is not meant to be a “black box” model. One can look at any cell and discern which steps are most important to final results in any give case. Several quality control processes are recommended in each application.

Checking Values

Many numerical entries must be made to run LLRM. Be sure to double check the values entered. Simple entry errors can cause major discrepancies between predictions and reality. Where an export coefficient is large, most notably with Agric4, feedlot area, it is essential that the land use actually associated with that activity be accurately assessed and entered.

Following Loads

For any individually identified load that represents a substantial portion of the total load (certainly >25%, perhaps as small a portion as 10%), it is appropriate to follow that load from generation through delivery to the lake, observing the losses and transformations along the way. Sometimes the path will be very short, and sometimes there may be multiple points where attenuation is applied. Consider dry vs. wet weather inputs and if the ratio is reasonable in light of actual data or field observations. Are calculated concentrations at points of measurement consistent with the actual measurements? Are watershed processes being adequately represented? One limitation of the model involves application of attenuation for all loads within a defined basin; loads may enter at the distal or proximal ends of the basin, and attenuation may not apply equally to all sources. Where loading and attenuation are not being properly represented, consider subdividing the basin to work with drainages of the most meaningful sizes.

Reality Checks

LLRM can be run with minimal actual water quality data, but to gain confidence in the predictions it is necessary to compare results with sufficient amounts of actual data for key points in the modeled system. Ideally, water quality will be tested at all identified nodes, including the output points for all basins, any point source discharges, any direct discharge pipes to the lake, and in the lake itself. Wet and dry weather sampling should be conducted. Flow values are highly desirable, but without a longer term record, considerable uncertainty will remain; variability in flow is often extreme, necessitating large data sets to get representative statistical representation. Where there are multiple measurement points, compare not just how close predicted values are to observed values, but the pattern. Are observed values consistently over- or underpredicted? A rough threshold of ±20% is recommended as a starting point, with a mix of values in the + or – categories.

Sensitivity Testing

The sensitivity of LLRM can be evaluated by altering individual features and observing the effect on results. For any variable for which the value is rather uncertain, enter the maximum value conceivable, and record model results. Then repeat the process with the minimum plausible value, and compare to ascertain how much variation can be induced by error in that variable. Which variables seem to have the greatest impact on results? Those variables should receive the most attention in reality checking, ground truthing, and future monitoring, and would also be the most likely candidates for adjustment in model calibration, unless the initially entered values are very certain.

For example, the runoff coefficients for P from the various land uses were set below the median literature values, based on knowledge of loads for some drainage areas from actual data for flow and concentration. However, it is possible that the actual load generated from various land uses is higher than initially assumed, and it is the attenuation that should be adjusted to achieve a predicted in-lake concentration that matches actual data. If the median P export for runoff is entered into the Calculations sheet, substituting the unshaded values for the shaded values in the table below, the resulting in-lake P prediction is 89 ug/L, much higher than the 75 ug/L from real data.

LAND USE	Original P Export Coefficient (kg/ha/yr)	New P Export Coefficient (kg/ha/yr)
Urban 1 (LDR)	0.65	1.10
Urban 2 (MDR/Hwy)	0.75	1.10
Urban 3 (HDR/Com)	0.80	1.10
Urban 4 (Ind)	0.70	1.10
Urban 5 (P/I/R/C)	0.80	1.10
Agric 1 (Cvr Crop)	0.80	0.80
Agric 2 (Row Crop)	1.00	2.20
Agric 3 (Grazing)	0.40	0.80
Agric 4 (Feedlot)	224.00	224.00
Forest 1 (Upland)	0.20	0.20
Forest 2 (Wetland)	0.10	0.20
Open 1 (Wetland/Lake)	0.10	0.20
Open 2 (Meadow)	0.10	0.20
Open 3 (Excavation)	0.80	0.80
Other 1	0.20	0.20
Other 2	1.10	1.10
Other 3	2.20	2.20

To get a closer match for the known in-lake value, attenuation would have to be adjusted (reduction in the portion of the generated load that reaches the lake) by about 0.1 units (10%), as shown below. This would result in a predicted in-lake P concentration of 77 ug/L, not far above the measured 75 ug/L. It is apparent that choice of export coefficients is fairly important, but that error in those choices can be compensated by adjustments in attenuation that are not too extreme to be believed. Yet those choices will affect the results of management scenario testing, and should be made carefully. The intent is to properly represent watershed processes, both loading and attenuation, not just the product of the two.

	BASIN 1 E. Direct	BASIN 2 W. Direct	BASIN 3 Upper T1	BASIN 4 Lower T1	BASIN 5 W. Upper T2	BASIN 6 E. Upper T2	BASIN 7 Lower T2
ORIGINAL BASIN ATTENUATION	0.90	0.90	0.75	0.85	0.80	0.75	0.70
NEW BASIN ATTENUATION	0.80	0.80	0.65	0.75	0.70	0.65	0.60

Aside from changes in all export coefficients, one might consider the impact is of changing a single value. As that value applies to all area given for the corresponding land use, its impact will be proportional to the magnitude of that area relative to other land uses. A change in forested land use exports may be very influential if most of the watershed is forested. A much larger change would be necessary to cause similar impact for a land use that represents a small portion of the watershed.

Model Calibration

Actual adjustment of LLRM to get predicted results in reasonable agreement with actual data can be achieved by altering any of the input data. The key to proper calibration is to change values that have some uncertainty, and to change them in a way that makes sense in light of knowledge of the target watershed and lake. One would not change entered land use areas believed to be correct just to get the predictions to match actual data. Rather, one would adjust the export coefficients for land uses within the plausible range (see Reference Variables sheet), and in accordance with values that could be derived for selected drainage areas (within the target system or nearby) from actual data. Or one could adjust attenuation, determining that a detention area, wetland, or other landscape feature had somewhat greater or lesser attenuation capacity that initially estimated. Justification for all changes should be provided; model adjustment should be transparent and amenable to scrutiny.

For the example system, it may be appropriate to adjust either N export coefficients or attenuation to get the average of the three empirical equation results for N (see Predictions sheet) to match the observed average more closely. In the example, a predicted N concentration of 908 ug/L was derived, while the average of quite a few in-lake samples was 860 ug/L. With a difference of <6%, this is not a major issue, but since all but one of the individual basin predictions for N concentration were also overpredictions, adjustment can be justified.

If all the N export coefficients in the Calculations sheet are reduced by 10%, an entirely plausible situation, the new N prediction for the lake becomes 861 ug/L, a very close match for the observed 860 ug/L. Export coefficients were not changed selectively by land use; all were simply adjusted down a small amount, well within the range of possible variation in this system. Alternatively, if the N attenuation coefficient for each basin is reduced in the Calculations sheet by 0.05 (representing 5% more loss of N on the way to the lake), the new predicted in-lake N concentration becomes 842 ug/L, not far below the observed 860 ug/L. Attenuation in each basin was adjusted the same way, showing no bias. Either of these adjustments (export coefficients or attenuation values) would be reasonable within the constraints of the model and knowledge of the system.

The only way to change the export coefficient for land use in a single basin is to split off that land use into one of the “Other” categories and have it appear in only the basins where a different export coefficient is justified. This is hardly ever done, and justification should involve supporting data. Likewise, if one basin had a particularly large load and a feature that might affect that load, one might justify changing the attenuation for just that one basin, but justification should be strong to interject this level of individual basin bias.

Model Verification

Proper verification of models involves calibration with one set of data, followed by running the model with different input data leading to different results, with data to verify that those results are appropriate. Where data exist for conditions in a different time period that led to different in-lake conditions, such verification is possible with LLRM, but such opportunities tend to be rare. If the lake level was raised by dam modification, and in-lake data are available for before and after the pool rise, a simple change in the lake volume (entered in the Predictions sheet) can simulate this and allow verification. If in-lake data exist from a time before there was much development in the watershed, this could also allow verification by changing the land use and comparing results to historic P and N levels in the lake. However, small changes in watershed land use are not likely to yield sufficiently large changes in in-lake conditions to be detectable with this model. Additionally, as LLRM is a steady state model, testing conditions in one year with wetter conditions against another year with drier conditions, with no change in land use, is really not a valid approach.

Model verification is a function of data availability for at least two periods of multiple years in duration with different conditions that can be represented by the model. Where available, use of these data to verify model performance is strongly advised. If predictions under the second set of conditions do not reasonably match the available data, adjustments in export coefficients, attenuation, or other features of the model may be needed. Understanding why conditions are not being properly represented is an important aspect of modeling, even when it is not possible to bring the model into complete agreement with available data.

Scenario Testing

LLRM is meant to be useful for evaluating possible consequences of land use conversions, changes in discharges, various management options, and related alterations of the watershed or lake. The primary purpose of this model is to allow the user to project possible consequences of actions and aid management and policy decision processes. Testing a conceived scenario involves changing appropriate input data and observing the results. Common scenario testing includes determining the likely “original” or “pre-settlement” condition of the lake, termed “Background Condition” here, and forecasting the benefit from possible Best Management Practices (BMPs).

Background Conditions

Simulation of Background Conditions is most often accomplished by changing all developed land uses to forest, wetland or water, whichever is most appropriate based on old land use maps or other sources of knowledge about watershed features prior to development of roads, towns, industry, and related human features. Default export coefficients for undeveloped land use types are virtually the same, so the distinction is not critical if records are sparse.

For the example system, all developed land uses were converted to forested upland, although it is entirely possible that some wetlands were filled for development before regulations to protect wetlands were promulgated, and some may even have been filled more recently. The resulting land use table, shown below, replaces that in the original model representing current conditions. The watershed area is the same, although in some cases diversions may change this aspect as well. Many lakes have been created by human action, such that setting all land uses to an undeveloped state would correspond to not having a lake present, but the assumption applied here is that the user is interested in the condition of the lake as it currently exists, but in the absence of human influences.

BASIN AREAS											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	TOTAL
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
LAND USE	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)
Urban 1 (LDR)											0.0
Urban 2 (MDR/Hwy)											0.0
Urban 3 (HDR/Com)											0.0
Urban 4 (Ind)											0.0
Urban 5 (P/I/R/C)											0.0
Agric 1 (Cvr Crop)											0.0
Agric 2 (Row Crop)											0.0
Agric 3 (Grazing)											0.0
Agric 4 (Feedlot)											0.0
Forest 1 (Upland)	27.1	40.6	60.7	176.0	50.5	37.6	56.2				448.7
Forest 2 (Wetland)	0.0	0.2	0.0	14.5	0.0	0.0	1.9				16.6
Open 1 (Wetland/Lake)	2.5	0.6	0.0	0.1	0.0	0.1	14.2				17.4
Open 2 (Meadow)	2.0	1.3	0.0	10.2	0.1	0.0	0.2				13.8
Open 3 (Excavation)											0.0
Other 1											0.0
Other 2											0.0
Other 3											0.0
TOTAL	31.6	42.7	60.7	200.8	50.6	37.7	72.5	0	0		496.5

Also altered in this example, but not shown explicitly here, are the internal load (reduced to typical background levels of 0.5 mg P/m2/d and 2.0 mg N/m2/d), point source (removed), septic system inputs (removed), and attenuation of P and N (values in cells lowered by10%, representing lesser transport to the lake through the natural landscape).

Resulting in-lake conditions, as indicated in the column of the table below labeled “Background Conditions,” include a P concentration of 16 ug/L and a N level of 366 ug/L. Average Chl is predicted at 5.7 ug/L, leading to a mean SDT of 2.7 m. Bloom frequency is expected to be 8.6% for Chl >10 ug/L and 1.5% for Chl >15 ug/L, with values >20 ug/L very rare. While the example lake appears to have never had extremely high water clarity, it was probably much more attractive and useable than it is now, based on comparison with current conditions in the table. If this lake was in an ecoregion with a target P level of <16 ug/L, it is expected that meeting that limit would be very difficult, given apparent natural influences.

SUMMARY TABLE FOR SCENARIO TESTING	Existing Conditions		Background Conditions	Complete Build-out	WWTF Enhanced	Feasible BMPs
	Calibrated Model Value	Actual Data	Model Value	Model Value	Model Value	Model Value
Phosphorus (ppb)	75	75	16	83	49	24
Nitrogen (ppb)	861	860	366	965	745	540
Mean Chlorophyll (ug/L)	40.7	37.5	5.7	46.7	23.3	9.3
Peak Chlorophyll (ug/L)	130.0	118.1	20.1	148.5	76.1	31.6
Mean Secchi (m)	0.8	1.0	2.7	0.8	1.2	2.0
Peak Secchi (m)	2.9	3.1	4.5	2.8	3.3	4.0
Bloom Probability						
Probability of Chl >10 ug/L	99.5%		8.6%	99.8%	92.6%	34.4%
Probability of Chl >15 ug/L	96.0%		1.5%	97.8%	73.6%	11.3%
Probability of Chl >20 ug/L	87.9%		0.3%	92.6%	52.3%	3.7%
Probability of Chl >30 ug/L	64.1%		0.0%	73.8%	22.5%	0.5%
Probability of Chl >40 ug/L	41.5%		0.0%	52.5%	9.2%	0.1%

Changes in Land Use

Another common scenario to be tested involves changes in land use. How much worse might conditions become if all buildable land became developed? For the example system, with current zoning and protection of some undeveloped areas, a substantial fraction of currently forested areas could still become low density residential housing. Adjusting the land uses in the corresponding input table to reflect a conversion of forest to low density urban development, as shown below, and adding 28 septic systems to that portion of the loading analysis (not shown here) an increase in P, N and Chl is derived, and a decrease in SDT are observed (see summary table above). P rises to 83 ug/L and N to 965 ug/L, but the change in Chl and SDT are not large, as the lake would already be hypereutrophic.

BASIN AREAS											
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10	TOTAL
	E. Direct	W. Direct	Upper T1	Lower T1	W. Upper T2	E. Upper T2	Lower T2				
LAND USE	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)	AREA (HA)
Urban 1 (LDR)	16.0	18.5	23.4	87.4	6.7	12.5	38.6				203.1
Original Urban 1 (LDR)	12.0	8.5	8.4	47.4	6.7	4.5	18.1				105.5
Urban 2 (MDR/Hwy)	3.7	5.5	0.0	5.9	0.8	0.6	2.3				18.8
Urban 3 (HDR/Com)	3.6	5.8	0.0	5.9	0.8	0.6	2.3				19.0
Urban 4 (Ind)	0.0	0.0	0.0	23.5	0.0	0.0	0.0				23.5
Urban 5 (P/I/R/C)	0.0	3.2	0.0	0.0	0.0	0.0	0.0				3.2
Agric 1 (Cvr Crop)	0.0	0.0	0.0	0.8	12.3	0.0	0.0				13.1
Agric 2 (Row Crop)	0.0	0.0	0.0	0.0	16.2	0.0	0.0				16.2
Agric 3 (Grazing)	0.0	0.0	0.0	0.0	4.0	0.0	0.0				4.0
Agric 4 (Feedlot)	0.0	0.0	0.0	0.0	0.5	0.0	0.0				0.5
Forest 1 (Upland)	3.7	7.5	35.3	50.3	9.2	24.0	13.0				143.0
Original Forest (Upland)	7.7	17.5	50.3	90.3	9.2	32.0	33.6				240.6
Forest 2 (Wetland)	0.0	0.2	0.0	14.5	0.0	0.0	1.9				16.6
Open 1 (Wetland/Lake)	2.5	0.6	2.0	0.1	0.0	0.1	14.2				19.4
Open 2 (Meadow)	2.0	1.3	0.0	10.2	0.1	0.0	0.2				13.8
Open 3 (Excavation)	0.1	0.1	0.0	2.3	0.0	0.0	0.0				2.5
Other 1											0.0
Other 2											0.0
Other 3											0.0
TOTAL	31.6	42.6	60.7	200.9	50.6	37.7	72.4	0	0		496.5

Changes in Wastewater Management

Managing wastewater is often a need in lake communities. In LLRM, wastewater treatment facilities (WWTF) are represented as point sources, with flow and concentration provided. On-site wastewater disposal (septic) systems are part of the baseflow of drainage areas with tributaries, and can be represented that way for direct drainage areas as well, but the option exists to account separately for septic systems in the direct drainage area. Changes to point sources or septic systems can be made in LLRM to simulate possible management actions.

In the example system, there is one small WWTF that discharges into Lower Tributary #1 and 250 residential units that contribute to septic system inputs in the two defined direct drainage areas (see Figure 1). If the units now served by septic systems were tied into the WWTF via a pumping station, the flow through the WWTF would increase from 45,000 cu.m/yr under current conditions to 71,953 cu.m/yr, the amount of wastewater calculated to be generated by those 250 residential units. If WWTF effluent limits for P and N were established at 0.1 and 3.0 mg/L, respectively, the concentration in the discharge would be reduced from 3.0 and 12.0 mg/L (current values from monitoring) to the new effluent limits. The result would be a higher flow from the WWTF with lower P and N levels, and an elimination of septic system inputs in the model, both simple changes to make, as shown in the table below.

NON-AREAL SOURCES												
	Number of Source Units	Volume (cu.m/yr)	P Load/Unit (kg/unit/yr)	N Load/Unit (kg/unit/yr)	P Conc. (ppm)	N Conc. (ppm)	P Load (kg/yr)	N Load (kg/yr)				
Waterfowl	50		0.20	0.95			10	47.5				
Point Sources												
PS-1		71953			0.10	3.00	7.2	215.9				
PS-2		0			3.00	12.00	0	0				
PS-3		0			3.00	12.00	0	0				
Basin in which Point Source occurs (0=NO 1=YES)												
	BASIN 1	BASIN 2	BASIN 3	BASIN 4	BASIN 5	BASIN 6	BASIN 7	BASIN 8	BASIN 9	BASIN 10		
PS-1	0	0	0	1	0	0	0	0	0	0		
PS-2	0	0	0	0	0	0	0	0	0	0		
PS-3	0	0	0	0	0	0	0	0	0	0		
DIRECT SEPTIC SYSTEM LOAD												
Septic System Grouping (by occupancy or location)	Days of Occupancy/Yr	Distance from Lake (ft)	Number of Dwellings	Number of People per Dwelling	Water per Person per Day (cu.m)	P Conc. (ppm)	N Conc. (ppm)	P Attenuation Factor	N Attenuation Factor	Water Load (cu.m/yr)	P Load (kg/yr)	N Load (kg/yr)
Group 1 Septic Systems	365	<100	0	2.5	0.25	8	20	0.2	0.9	0	0.0	0.0
Group 2 Septic Systems	365	100 - 300	0	2.5	0.25	8	20	0.1	0.8	0	0.0	0.0
Group 3 Septic Systems	90	<100	0	2.5	0.25	8	20	0.2	0.9	0	0.0	0.0
Group 4 Septic Systems	90	100 - 300	0	2.5	0.25	8	20	0.1	0.8	0	0.0	0.0
Total Septic System Loading										0	0.0	0.0

The result, shown in the summary table for scenario testing above, is an in-lake P concentration of 49 ug/L and a new N level of 745 ug/L. These are both substantial reductions from the current levels, but continued elevated Chl (mean = 23.3 ug/L, peak = 76.1 ug/L) and a high probability of algal blooms is expected. Water clarity improves slightly (from 0.8 to 1.2 m on average), but at the cost of the sewerage and treatment, this is unlikely to produce a success story.

Best Management Practices

The application of BMPs is generally regarded as the backbone of non-point source pollution management in watershed programs. Considerable effort has been devoted to assessing the percent removal for various pollutants that can be attained and sustained by various BMPs. BMPs tend to fall into one of two categories: source controls and pollutant trapping. Source controls limit the generation of P and N, include actions like bans on lawn fertilizers containing P or requirements for post-development infiltration to equal pre-development conditions, and would be most likely addressed in LLRM by a change in export coefficient. Pollutant trapping limits the delivery of generated loads to the lake, includes such methods as detention, infiltration, and buffer strips, and is most often addressed in LLRM by changes in attenuation values.

There are limits on what individual BMPs can accomplish. While some site specific knowledge and sizing considerations help modify general guidelines, the following table provides a sense for the level of removal achievable with common BMPs.

While BMPs in series can improve removal, the result is rarely multiplicative; that is, application of two BMPs expected to remove 50% of TP are unlikely to result in 0.5 X 0.5 = 0.25 of the load remaining (75% removal) unless each BMP operates on a different fraction of TP (particulates vs. soluble, for example). This is where judgment and experience become critical to the modeling process. In general, BMPs rarely remove more than 2/3 of the load of P or N, and on average can be expected to remove around 50% of the P and 40% of the N unless very carefully designed, built and maintained. The luxury of space is not often affordable, forcing creativity or greater expense to achieve higher removal rates.

Range and Median ( ) for Expected Removal (%) for Key Pollutants by Selected Management Methods, Compiled from Literature Sources for Actual Projects and Best Professional Judgment Upon Data Review.

	TSS	Total P	Soluble P	Total N	Soluble N	Metals
Street sweeping	5-20	5-20	<5	5-20	<5	5-20
Catch basin cleaning	5-10	<10	<1	<10	<1	5-10
Buffer strips	40-95 (50)	20-90 (30)	10-80 (20)	20-60 (30)	0-20 (5)	20-60 (30)
Conventional catch basins (Some sump capacity)	1-20 (5)	0-10 (2)	0-1 (0)	0-10 (2)	0-1 (0)	1-20 (5)
Modified catch basins (deep sumps and hoods)	25 (25)	0-20 (5)	0-1 (0)	0-20 (5)	0-1 (0)	20 (20)
Advanced catch basins (sediment/floatables traps)	25-90 (50)	0-19 (10)	0-21 (0)	0-20 (10)	0-6 (0)	10-30 (20)
Porous Pavement	40-80 (60)	28-85 (52)	0-25 (10)	40-95 (62)	-10-5 (0)	40-90 (60)
Vegetated swale	60-90 (70)	0-63 (30)	5-71 (35)	0-40 (25)	-25-31 (0)	50-90 (70)
Infiltration trench/chamber	75-90 (80)	40-70 (60)	20-60 (50)	40-80 (60)	0-40 (10)	50-90 (80)
Infiltration basin	75-80 (80)	40-100 (65)	25-100 (55)	35-80 (51)	0-82 (15)	50-90 (80)
Sand filtration system	80-85 (80)	38-85 (62)	35-90 (60)	22-73 (52)	-20-45 (13)	50-70 (60)
Organic filtration system	80-90 (80)	21-95 (58)	-17-40 (22)	19-55 (35)	-87-0 (-50)	60-90 (70)
Dry detention basin	14-87 (70)	23-99 (65)	5-76 (40)	29-65 (46)	-20-10 (0)	0-66 (36)
Wet detention basin	32-99 (70)	13-56 (27)	-20-5 (-5)	10-60 (31)	0-52 (10)	13-96 (63)
Constructed wetland	14-98 (70)	12-91 (49)	8-90 (63)	6-85 (34)	0-97 (43)	0-82 (54)
Pond/Wetland Combination	20-96 (76)	0-97 (55)	0-65 (30)	23-60 (39)	1-95 (49)	6-90 (58)
Chemical treatment	30-90 (70)	24-92 (63)	1-80 (42)	0-83 (38)	9-70 (34)	30-90 (65)

In the example system, setting attenuation for all basins to 0.5 for P and 0.6 for N is viewed as a practical level of BMP application for a first cut at what BMPs might be able to do for the lake. Careful consideration of which BMPs will be applied where in which basins is in order in the final analysis, but to set a reasonable approximation of what can be achieved, these are supportable attenuation values. Note that values are not set at 0.5 or 0.6 of the value in place in the calibrated model, but rather a low end of 0.5 or 0.6. If, as with Basin 7 (Lower Tributary #2) in the example system, the attenuation values for P and N under current conditions are 0.70 and 0.75, the practical BMP values of 0.5 and 0.6, respectively, represent less of a decline through BMPs than for the direct drainage areas, which have current condition attenuation values of 0.9 for P and 0.95 for N.

In addition to setting P attenuation at 0.5 for P in all basins and 0.6 for N in all basins in the example system, the WWTF has been routed to a regional WWTF out of the watershed, and the all areas within 300 ft of the lake have been sewered, with that waste also going to the regional WWTF. Consequently, the WWTF and direct drainage septic system inputs have been eliminated. Finally, internal loading has been reduced to 0.5 mg P/m/day and 2.0 mg N/m^2/day, achievable with nutrient inactivation and lowered inputs over time.

The results, as indicated in the summary table for scenario testing above, include an in-lake P concentration of 24 ug/L and an N level of 540 ug/L. The predicted mean Chl is 9.3 ug/L, with a peak of 31.6 ug/L. SDT would be expected to average 2.0 m and have a maximum of 4.0 m. While much improved over current conditions, these are marginal values for supporting the range of lake uses, particularly contact recreation and potable water supply. As a first cut assessment of what BMPs might do for the system, it suggests that more extreme measures will be needed, or that in-lake maintenance should be planned as well, since algal blooms would still be expected. Further scenario testing with the model, combined with cost estimation for potential BMPs, may shed light on the cost effectiveness of rehabilitating the example lake.

Quality Assurance Project Plan

PROBLEM DEFINITION/BACKGROUND

Project Background

LLRM is used to evaluate nutrient loading to a lake and the consequences of that loading in terms of algal blooms and water clarity. ***Describe the project and how the model applies to it. Potentially suitable language includes:*** *Example lake*, in *location* is impacted by elevated levels of nutrients. The watershed (Figure *xxx*) covers approximately *xxx* ha and includes *land uses*. Local interest is focused on *lake uses*. Identified in *year* as a waterbody not meeting state water quality standards, it is subject to TMDL preparation and LLRM supports that effort. Monitoring conducted by *groups* has demonstrated the magnitude of loading and resultant concentrations and conditions. Now what is needed is a partitioning of loading among sources and a plan for reducing loading to the point were water quality goals are achievable.

Project Objectives

- To develop a model application that may be utilized to better understand lake response to nutrient loading.
- To determine the location of sources of phosphorus and nitrogen responsible for eutrophication.
- To determine the relative contributions from sources in order to select and prioritize BMPs.
- To predict the results of BMP application and determine the level of effort necessary to achieve water quality compliance.

This process will facilitate implementation of corrective actions where the greatest positive impact will be realized.

Field Data Collection

A field program to collect data necessary to develop and run the model in accordance with the QAPP has been conducted. The field program is organized as follows:

- In-lake measurement of forms of nitrogen (N), phosphorus (P), Secchi disk transparency (SDT) and Chlorophyll-a (CHLA) at the deepest part of the lake, sometimes with additional sampling in other areas to assess variability over space. Sampling includes near surface and near bottom sample collection in areas that may stratify. A target of 10 in-lake measurements over at least two spring-summer periods is set. Ideally, the range of dry to wet years is covered.
- Watershed sampling for forms of N and P at as many inlets as possible, with dry weather, pre-storm sampling, active or passive collection of first flush inflows from the drainage basin, and post-storm sampling where flows persist, within 24 hours of the storm. Sampling is repeated for multiple wet weather events, with a target of at least three events sampled and five to ten storms preferred.
- Watershed sampling at any key node in the system, where drainage basins are subdivided. Sampling is conducted as for inlet sampling above, but at points upstream of the inlets where the stream may fork, where key BMPs may exist or be contemplated, or where major land use changes occur.

- Samples are collected in appropriate containers, kept on ice in the dark until delivered to a certified laboratory within the prescribed holding time for analysis of targeted water quality variables by standard methods.
- Duplicate or replicate samples are collected to facilitate assessment of error due to natural variability, sample collection, or lab procedures. In general a target of 5-10% sample duplication/replication is applied. In general, an upper limit of 20% relative percent difference is desired, but at low values this may be difficult to achieve due to the reporting increment for results.
- Data are recorded in a spreadsheet and checked for accuracy after entry.

A responsible party will coordinate with the field program to make sure there are sufficient data to support model application.

In order to carry out the sampling plan, a map of targeted sampling locations is needed. Maps may be set up in any form that provides sufficient information, with watershed and lake aerial mapping often producing the most useful results. Sometimes a street map, or hybrid map with an aerial view with key streets labeled, is appropriate, particularly if participants are not extremely familiar with the area.

Figure A1: Example aerial photograph of watershed showing sampling stations

Model Application - Review of other Data Sources and Historical Data

Besides data generated from field collection, other necessary data and information will include lake morphometric data, information on precipitation and flows, watershed and subwatershed areas and land uses from GIS databases and other available sources, and other water quality data where available from ongoing or past studies. GIS data are typically used to set up the model, as are morphometric and hydrologic data. Recent water quality data for point sources, as required by NPDES or similar permits, may also be used for model set up and calibration. Additional water quality data may be used to verify the model once calibrated, or for simple historic perspective on lake problems and causes, but are not typically involved in model set up.

Key data inputs for model application that are typically obtained from existing sources or obtained by field work other than water quality sampling include:

- Lake bathymetry and hypsographs – allows calculation of volume at any depth or water level.
- Areal water yield – normally obtained from USGS or similar hydrologic database for target or nearby systems, this is used as a check on flow values derived from land use and precipitation.
- Precipitation - normally obtained from NOAA or similar precipitation database for target or nearby systems, this is used to calculate flows from land use and precipitation data.
- Flow data or calculations of detention time – sets flushing rate, used as a check on calculations from other data.

- Watershed and subwatershed delineation – defines areas to which loading functions and water quality comparisons will be applied in the model.
- Subwatershed land uses and corresponding areas – determines range of possible loading to be used in the model.
- Point source monitoring data – normally a reliable source, required by permit, and may be the only way to gather such data (permission to sample point sources may be necessary otherewise).
- On-site wastewater disposal (septic) system locations within direct drainage to the lake – allows estimation of septic inputs by calculation using data for distance from lake, population served, and frequency of use.
- Wildlife inputs – usually focused on waterfowl, estimates of the type and number of bird units are obtained by observation or previous studies. Inputs of N and P per bird-year are typically drawn from the literature.
- Atmospheric loading – unless data are collected for precipitation and dryfall from the target area, loading per unit area per year is normally estimated from literature values and lake area.
- Internal loading – a complicated area of study, releases from bottom sediments can be measured directly or indirectly or estimated from literature values keyed to measured in-lake conditions, most notably area and duration of anoxia.

Quality assessment of literature, historical or other data not collected directly in an approved sampling program but to be used as model inputs is to be performed. Documentation of past QA/QC efforts may be sufficient, or values may need to be evaluated from Best Professional Judgment (BPJ). Where possible, confidence intervals or plausible ranges should be established to allow the range of possible results to be determined from the model. Land use data will be ground truthed to a level commensurate with the recentness of the available data, with some ground truthing in all cases.

The model report should address the following four issues regarding information on how non-direct measurements (historical data and data from other sources) are acquired and used in the project:

- The need and intended use of each type of data or information to be acquired
- How the data will be identified or acquired, and expected sources of these data
- The method of determining the underlying quality of the data
- The criteria established for determining whether the level of quality for a given set of data is acceptable for use on the project.

Model Application

Lake Loading Response Model, LLRM, is described in detail in the accompanying user’s guide. This model integrates water quantity and nutrient inputs to the lake from the watershed, then predicts the in-lake conditions based on mass balance and empirical models that incorporate losses from settling (yielding lower N and P concentrations than mass balance approaches). Provisions for model set up, calibration, verification, and use in scenario testing are all described in the user’s guide.

QUALITY OBJECTIVES & CRITERIA

Data Quality Objectives (DQOs) are qualitative and quantitative statements that clarify the intended use of data, define the types of data needed to support a decision, identify the conditions under which the data should be collected, and specify tolerable limits on the probability of making a decision error because of uncertainty in the data.

Data Quality Objectives for Data Collection

Table A1 summarizes the DQO for needed measurements. These criteria are minimum levels necessary for subsequent use in the modeling and analysis component of the project for the most reliable results. There may be cases where lesser DQO can be accepted, but the uncertainty in model results that will result may limit utility in management planning. All instruments to be used must be capable of meeting these requirements.

Table A4: Example Data Quality Objectives

Water Quality Variable	Instrument	Data Quality Objective

Data Quality Objectives for Model Application

All model applications typically include three primary phases or steps: database development, system characterization, and calibration and validation. QA issues are involved in all aspects of model application, but they are especially critical for the calibration and validation phase since the outcome establishes how well the model represents the watershed. An accurate numerical representation of the study area is the primary goal of the model application effort because it determines whether the model results can be relied upon and used effectively for decision-making.

Calibration and validation/verification can be defined as follows:

(a) Calibration—A test of the model with known input and output information that is used to adjust or estimate factors for which data are not available.

(b) Validation/verification—Comparison of model results with numerical data independently derived from experiments or observations of the environment.

Model Calibration

The draft USEPA Modeling Guidance (January 2004) specifically emphasizes model performance criteria, which are the basis by which judgments will be made on whether the model results are adequate to support the decisions required to address the study objectives. Therefore, the quality assurance on calibration for includes expected accomplishments of the calibration and how the predictive quality of the model might be improved as a result of implementing the calibration procedures. The specific limits, standards, goodness-of-fit, or other criteria on which a model will be judged as being properly calibrated will be assessed (e.g. the percentage difference between reference data values from the field or laboratory and predicted results from the model).

Time series plots are generally evaluated visually as to the agreement, or lack thereof, between the simulated and observed values. Scatter plots usually include calculation of a correlation coefficient, along with the slope and intercept of the linear regression line; thus the graphical and statistical assessments are combined. When observed data are adequate and/or uncertainty estimates are available, confidence intervals for the observed data will be calculated so they can be considered in the model performance evaluation.

There are a variety of ways to compare simulated and observed mean values. For example, the sporadic observed data can be aggregated over annual, seasonal, or monthly timeframes and compared to the full range of simulated values. The hydrodynamic and water quality components of models will include following types of graphical and statistical procedures:

(1) Graphical Comparisons:

(a). Time series plots of observed and simulated values for fluxes (e.g., flow) or state variables (e.g., stage, chemical and ______________ concentrations).

(b). Observed versus simulated scatter plots, with a best-fit linear regression line displayed, for fluxes or state variables.

(c). Cumulative frequency distributions of observed and simulated fluxes or state variables.

(2) Statistical Tests:

(a). Error statistics (e.g., mean error, absolute mean error, relative error, relative bias, and standard error of estimate).

(b). Correlation tests (e.g., linear correlation coefficient, coefficient for goodness-of-fit).

(c). Cumulative distribution tests.

Table A6 lists example model calibration and validation targets. Because of the uncertain state-of-the-art in model performance criteria, the inherent error in input and observed data, and the approximate nature of model formulations, absolute criteria for model acceptance or rejection are not appropriate for this effort. Consequently, example tolerance ranges shown in Table A6 are examples of general targets or goals for model calibration and validation for the corresponding modeled quantities.

Table A6: Example Model Calibration and Validation Targets

Table A6: Proposed Model Calibration and Validation Targets for Southport Modeling Project

Error Measure	Property	Target Value
Relative Mean Error, *rme*	Hydrodynamic (tide range)	+/-1%
	Hydrodynamic (maximum velocity)	+/- 30%
	Water Quality (dye)	+/- 45%
Error Coefficient of Variation, *ecv*	Hydrodynamic (tide range)	4%
	Hydrodynamic (maximum velocity)	10%
	Water Quality (dye)	90%
Correlation Coefficient, *r*	Hydrodynamic (tide range)	0.94
	Hydrodynamic (maximum velocity)	0.65
	Water Quality (dye)	0.60

The values shown in Table A6 are derived from extensive past experience with the individual model performance criteria. If preliminary model results do not satisfy the target tolerances listed in Table A6, additional efforts will be required to investigate all possible errors in, and the accuracy of, input data, model formulations, and field observations. If adjustments in these tolerances are needed, they will be fully investigated and documented, and revisions to this QAPP will be issued through the formal QA process. Detailed description of key model calibration parameters is covered Section E of this QAPP.

It is important that the different calibrations, the approaches taken (e.g., qualitative versus quantitative), and their acceptance criteria are properly justified. This justification can refer to the overall quality of the standards being used as a reference or of the quality of the input data (e.g., whether data are sufficient for statistical tests to achieve desired levels of accuracy). Both graphical comparison and statistical test will be performed during calibration process. Please also refer to Section E for detailed description on model calibration.

INSERT- Calibration Stop Criteria

Model Validation

Model validation is defined as all quantitative and qualitative methods for evaluating the degree to which a model corresponds to reality. Thus model validation is in reality an extension of the calibration process. Its purpose is to assure that the calibrated model properly assesses all the variables and conditions that can affect model results.

- Qualitative validation: Qualitative model validation involves expert judgment and tests of intuitive behavior. This type of validation uses “knowledge” of the behavior of the system in question, but does not treat model validation in a formalized statistical manner.

- Quantitative validation: When data are available, model validation may involve comparing model predictions to independent empirical observations to investigate how well the model’s description of the world fits the observational data.

One of the most effective procedures for model validation is to use only a portion of the available record of observed values for calibration. Once the final parameter values are developed through calibration, simulation is performed for the remaining period of observed values and goodness-of-fit between recorded and simulated values is reassessed. Both qualitative and quantitative validation approaches will be used.

Furthermore, sensitivity analysis will be performed on key __________ model parameters for ___________ ______ study. Sensitivity analysis measures the effect of changes in input values or assumptions (including boundaries and model function form) on the outputs.

It is the study of how uncertainty in a model output can by systematically apportioned to different sources of uncertainty in the model input. By investigating the “relative sensitivity” of model parameters, a user can become knowledgeable of the relative importance of parameters in the model. The results of sensitivity analysis will be documented following the draft USEPA Modeling Guidance (January 2004).

A8 SPECIAL TRAINING REQUIREMENTS/CERTIFICATIONS

The staff involved in the compilation and assessment of data to support modeling efforts will have, at a minimum, a bachelor’s degree in environmental science as well as a minimum of two years experience with data management.

The application of models to be used will be guided by individuals with highly specialized expertise in their respective model. The staff responsible for modeling will have, at a minimum, a master’s degree in environmental engineering and 6 years of experience in watershed and water quality modeling. The lead staff who is directly involved in the development of model input data sets and model application for this project have gained experience in water quality modeling through their work on numerous model application projects. Any staff training, if needed, and oversight will be provided by one or more of the senior modelers. There are no other special training or certification requirements.

A9 DOCUMENTATION AND RECORDS

Table A7 lists the documentation and records retention from both field sampling (including field and laboratory analysis) and subsequent modeling study. Detailed description of modeling data and report is given as follows.

The draft USEPA Modeling Guidance (January 2004) requires a modeling projects to include the following elements of model documentations:

- Management Objectives (Scope of problem; Technical objectives that result from management objectives; Level of analysis needed; Level of confidence needed)
- Conceptual Model
- Choice of Technical Approach
- Parameter Estimation
- Uncertainty/Error
- Results

The modeling team will develop a central file as a repository for information and data used in the preparation of any reports and documents during the project and will supervise the use of materials in the file. The model application will include complete record keeping of each step of the modeling process. The documentation (all data files, source codes, and executable versions of the computer software used in the modeling study) will consist of reports and files addressing the following items:

- Initial and final assumptions.
- Parameter values and sources.
- Nature of grid and grid design justification.
- Actual input used.
- Calibration and validation procedures and results from the model.
- Output of model scenario runs and interpretation.

The project reporting will also include descriptions of calibration targets, measures of calibration, calibrated variables, calibration assessment, and model validation results. The main objective of the model application is a management scenario analysis and screening of the proposed alternative scenarios. The scenario analysis steps will be carefully executed and extensively documented. Important elements of this documentation include code execution options used, a complete set of input data, output model result files, and an overview of the results of the simulations. If any change(s) in this QAPP are required during the study, a memo will be sent to each person on the distribution list describing the change(s), following approval by the appropriate persons.

In summary, all data and assumptions used in the modeling will be documented in the final report (in hard copies and whenever possible, electronic copies as well). Model run input and output data, QA documentation, assumptions, and other permanent information will be maintained in the project files for a retention time of 5 years (Table A7). USEPA and CTDEP may elect to take possession of the records prior to the end or at the conclusion of the 5-year retention period.

Table A7: Example Documentation and Records Retention

Table A7: Documentation and Records Retention

Document/Record	Location	Retention Period‡	Format
Original QAPP and Amendments	Parsons	5 years	Paper/Electronic
QAPP Distribution Documentation	Parsons	5 years	Paper/Electronic
Field Instrument Calibration Records	ASA /CTDEP /USEPA	5 years	Paper/Electronic
Field Instrument Inspection and Maintenance Records	ASA /CTDEP /USEPA	5 years	Paper/Electronic
Laboratory Instrument Calibration Records	DA/BA	5 years	Paper/Electronic
Laboratory Instrument Inspection and Maintenance Records	DA/BA	5 years	Paper/Electronic
Media Log Books	DA/BA	5 years	Paper
Field Logs and Field Data Collection Forms	ASA /CTDEP /USEPA	5 years	Paper
Sample Chain of Custody Records	CTDEP /DA/BA	5 years	Paper
Maps, photographs, and drawings	Parsons/ASA	5 years	Paper/Electronic
Monthly Reports, Memo and All Written Correspondence	Parsons	5 years	Paper/Electronic
Draft Report, Response to Comments, Final Report*	Parsons/ASA	5 years	Paper/Electronic

‡ USEPA or CTDEP may elect to take possession of the records prior to the end of the retention period.

*Note: Upon Further Funding Approval

SECTION B - DATA GENERATION AND ACQUISITION

B1 QUALITY CONTROL

Section A7 lists the required DQOs for the measured parameters. Specific requirements are outlined below.

Quality Control for Physical Field Instruments - specifications for quality control not part of the scope of this QAPP but may be found in the approved QAPP for ___________ dated ________.

B2 NON-DIRECT MEASUREMENTS

Historical data have been collected for a number of sample sites. The data is available in electronic format starting in 1989 and it is proposed to use this data qualitatively to observe for patterns and trends. All sampling and analytical methods for the collection of this data will be in accordance with the NSSP. Therefore, data collection of the historical data proposed for use in this project was accomplished using the most current information and methods available at that time and the laboratory's quality control procedures. Based on the intended use (observation) of historical data for this project, the laboratory's quality control procedures are acceptable for this study.

Additional environmental measurement data required for model development that will be obtained from other sources and not measured during this project are described in Section E of this QAPP.

B3 DATA MANAGEMENT

Laboratory data generated by the ________ laboratory is reviewed by the laboratory technician and submitted to the supervisor to assure compliance with the laboratory's quality control guidelines. The original collection form and analytical forms are retained at the laboratory for 5 years. Once the data is released by the laboratory, copies will be transmitted via fax and mail to the CTDEP for entry into an excel spreadsheet. The CTDEP will correlate the results with the number of samples on the chain of custody documentation and review the data for any inconsistencies. Hard copies of the data will also be maintained at the CTDEP in the project folder. Data will reside on a Novell Computer local area network, which is maintained by the CTDEP's Information Technology Department. The network is backed up nightly, weekly, monthly, and annually on computer tapes. In addition, the CTDEP will specifically back up the data spreadsheet for ___________ ______ when it is updated. With these back up systems in place, the database can be retrieved following loss or destruction.

The CTDEP will email the data spreadsheet and send hard copies of the results to the _____________ project managers who are responsible for assuring that the data complies with the data quality objectives of the model prior to data input. Figure B2 is an example data management flow chart.

Table B1: Summary of Station Information

Icon	Station Description	Frequency	Use in Modeling
Pink Triangles	Current meter sites	2 sites, deployment for 1 month (July – August)	Use in hydrodynamic model calibration
Purple Plus Signs	Dye release sites	2 dye release sites, one for each study (Late July)	Use in pollutant transport model calibration
Green Circles	Dye and water quality profile stations	11 sites, 6 samples each site per sampling period (tidal cycle), 2 dye studies (Late July)	Use in pollutant transport model calibration
Yellow Triangles	Continuous dye monitoring sites	2 sites, deployment for 1 week (Late July)	Use in pollutant transport model calibration
Black Squares	Intensive bacterial monitoring stations	14 sites, 6 samples each site per sampling period (tidal cycle), 3 sampling periods during July – August	Use in pollutant transport model calibration
Red Squares with x.x Numbers	Present DA/BA bacterial monitoring stations	Not applicable	Not applicable

Sample Collection
CTDEP

Sample Analysis
___________Laboratory

Laboratory review and transfer of data
CTDEP

CTDEP Acceptance and review of data

CTDEP Enter data into excel spreadsheet. Transfer of data to _____________ for review with model DQOs.

__ input of data into model.

Figure B2: Example Data Management Flow Chart

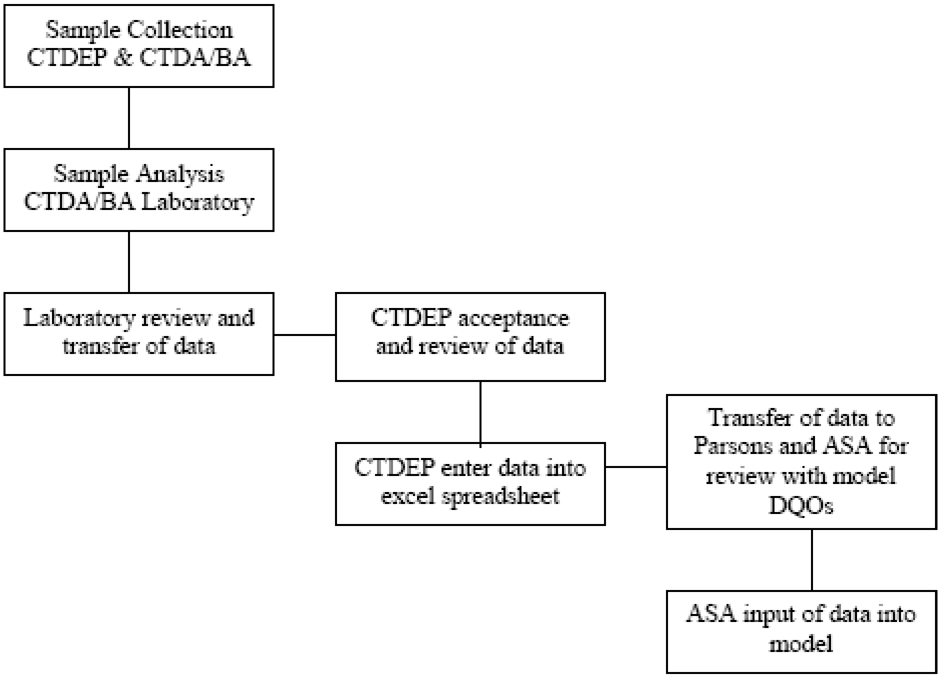

Figure B2: Data Management Flow Chart for Bacterial Monitoring

SECTION C - ASSESSMENTS AND OVERSIGHT (SAMPLING)

C1 ASSESSMENTS AND RESPONSE ACTIONS

The data must be representative of actual field conditions in order to be entered into the model application and accurately locate pollutant sources. As such, the _____________ monitoring quality assurance plan will be reviewed in preparation of field sampling activities. The CTDEP will evaluate the field sampling plan after each sampling event and determine if changes or modifications to the plan are necessary in order to ensure the production of quality data. The CTDEP will review quality assurance samples in conjunction with data review and prior to the release of the data. Once released, the CTDEP will review the data to assure that analytical and quality control procedures were adhered to. If inconsistencies are detected, the CTDEP will notify the laboratory and advise the appropriate corrective actions. The laboratory will continue to conduct routine audits as required by the QAPP.

The following table presents types of assessments and response action for data collection activities applicable to the QAPP.

Table C1: Example Assessment and Response Actions

Table C1: Assessment and Response Actions

Assessment Activity	Approximate Schedule	Responsible Party	Scope	Response Requirements
Status monitoring, oversight, etc.	Continuous	Parsons/ ASA Project Managers	Monitoring of the project status and records to ensure requirements are being fulfilled. Monitoring and review of laboratory performance and data quality	Report to USEPA and CTDEP in Monthly Progress Report. Ensure project requirements are being fulfilled.

Corrective Action

The Project Manager is responsible for implementing and tracking corrective action procedures as a result of audit findings. Records of audit findings and corrective actions are maintained by ___________QAO, CTDEP and USEPA.

If audit findings and corrective actions cannot be resolved, then the authority and responsibility for terminating work is specified in the USEPA QMP and in agreements or contracts between participating organizations.

C2 REPORTS TO MANAGEMENT

Laboratory Collection Form

Laboratory collection form contains the results of all specified QC measures listed in section ____, including but not limited to method blanks and laboratory duplicates. This information is reviewed and compared to the pre-specified acceptance criteria to determine acceptability of data before forwarding to the Project Manager. This information is available for inspection by the USEPA.

Reports to USEPA Project Management

A Monthly Progress Report summarizes the activities for each task (including costs and level of efforts expended to date); reports problems, delays, and corrective actions; and outlines the status of each task's deliverables.

A final report detailing the project design, model application, and model output, etc. will be prepared by_______ at completion of the project.

SECTION D - DATA VALIDATION AND USABILITY

D1 DATA REVIEW, VALIDATION, AND VERIFICATION

For the purposes of this document, verification means the processes taken to determine compliance of data with project requirements, including documentation and technical criteria. Validation means those processes taken independently of the data-generation processes to determine the usability of data for its intended use(s). Integrity means the processes taken to assure that no falsified data will be reported.

All data obtained from field and laboratory measurements will be reviewed and verified for conformance to project requirements, and then validated against the data quality objectives which are listed in Section A7. Only those data which are supported by appropriate quality control data and meet the data quality objectives will be considered acceptable for use in models. All other
data will be rejected.

The procedures for verification and validation of data are described in Section D2, below. The CTDEP managers are responsible for ensuring that field data collected by their respective agency are properly reviewed and verified for integrity. The Laboratory Manager is responsible for ensuring that laboratory data are scientifically valid, defensible, of acceptable precision and accuracy, and reviewed for integrity. The CTDEP Project Manager will be responsible for ensuring that all data are properly reviewed and verified, and submitted in the required format to the project database. The _______QAO is responsible for validating the data. Finally, the CTDEP Project Manager, with the concurrence of the _____QAO, is responsible for validating that all data to be reported meet the objectives of the project and are suitable for use in model development.

D2 VERIFICATION AND VALIDATION METHODS

One objective of this project is to use the collected data to calibrate models in order to quantify the origin, fate and transport of the indicator __________. All acquired data will be reviewed and verified for integrity and continuity, reasonableness, and conformance to project requirements (sampling procedures, analytical methods, representativeness, and accuracy) and then validated against the DQOs. The validation process shall include verification of the sampling design and execution (location, dates, time, procedures, etc), sample handling procedures (preservation, holding times, chain-of-custody, etc), laboratory procedures (sample identification, analytical methods, equipment maintenance, etc.), and analytical results (project and quality control samples). The results of the validation process shall be compared with the applicable requirements in the QAPP to determine if the data can be used. The validation, comparison, and final determination must be documented and the documentation must be maintained with other project record and available for audit or inspection. Only those data which are supported by appropriate QC data and meet the DQOs will be considered acceptable.

All data will be verified to ensure they are representative of the samples analyzed and locations where measurements were made, and that the data and associated quality control data conform to project specifications. The staff and management of the respective field, laboratory, and data management tasks are responsible for the integrity, validation and verification of the data each task generates or handles throughout each process. The field and laboratory tasks ensure the verification of raw data, electronically generated data, and data on chain-of-custody forms and hard copy output from instruments.

Verification, validation and integrity review of data will be performed using self-assessments and peer review, as appropriate to the project task, followed by technical review by the manager of the task. The laboratory analysis data to be verified (listed by task in Table D1) are evaluated against project specifications and are checked for errors, especially errors in transcription, calculations, and data input. Potential outliers are identified by examination for unreasonable data, or identified using computer-based statistical software. If a question arises or an error or potential outlier is identified, the manager of the task responsible for generating the data is contacted to resolve the issue. Issues which can be corrected are corrected and documented electronically or by initialing and dating the associated paperwork. If an issue cannot be corrected, the task manager consults with higher level project management to establish the appropriate course of action, or the data associated with the issue are rejected.

The laboratory will review and verify the results from each sampling event for consistency with its Quality Assurance Plan. The CTDEP will review and validate the results from each sampling event to assure that the data meets QAPP objectives. The data will be verified with the collection forms. Any deviations detected will be further investigated and documented for communication to ______________. ______________ will review and validate the data to determine if it meets the project's quality specifications outlined in Section A7 in order to assure that the data is suitable for use in the model application.

Table D1: Example Data Verification Procedures

D3 RECONCILIATION WITH USER REQUIREMENTS

Data quality objectives described in Section A7 of this document are deemed to be consistent with and support the intended use of data set forth in the same section. Data will be evaluated continuously by the Project Team representatives during the life-term of the project to ensure that they are of sufficient quality and quantity to meet the project goals. These data and data collected by other organizations may be subsequently analyzed and used by CTDEP for TMDL development, permit decisions, and water quality assessments. If the data do not meet the goals specified in Section A7 of this document, they will not be used in decision-making. The evaluation of this data for decision-making is not part of this QAPP????

SECTION E - MODELING

E1 MODEL APPLICATION

A modeling system that predicts the circulation and pollutant transport is required. A unique requirement is the ability of the model system to estimate source locations and strengths as well as the more typical pollutant distributions from those sources. Toward this end we will use __'s __________ modeling system to build the ______ modeling system with components added from _________modeling system:

INSERT SPECIFIC MODELS HERE

__________, which includes a boundary-fitted, two-dimensional hydrodynamic model to generate water elevation and velocity and a pollutant transport model to estimate the resulting concentrations from known sources, and __________, which is a particle-based model system that directly uses the __________ hydrodynamic model output to estimate either resulting concentrations from known sources (forward tracking) or probabilities of source locations from known impacted resources (backward tracking). This model was originally developed for use in oil spill tracking but can be similarly used to track other pollutants.

The __________ model systems have been widely tested in a variety of applications, have been peer reviewed, and have been accepted for use by public environmental agencies. Details of the applications, reviews and acceptance follow in the subsequent subsections and in appendices D and E to this document.

This model system will be applicable to any number of other locations for use in looking at ____ contamination problems. The model systems have similar software architectures and use identical interfaces and data handling routines. An overview of the model system will be presented below with additional information provided in attachments to this document. In addition, model description, data management and model output will be discussed in this section.

E1.1 Model Overview and Description

Model Overview

Models used include systems that integrates geographic information (coastlines, land use, watersheds, etc.) and models (analytical and numerical, hydrodynamic, pollutant transport, etc.) to provide the user with tools to analyze (with a graphical user interface) many alternatives to determine the optimum solution to a particular problem. Models used will have been applied to Total Maximum Daily Load (TMDL) analyses. The particle tracking model has also been applied, with different models, to many problems including spill modeling, spill response decision support, spill response training, impact and risk assessment, spill drill exercises, and spill response and contingency planning studies. A general description of the modeling system using the receptor mode calculation is found in French et al. (1994).

The geographic information component of models used hold user-specified layers of data appropriate for the task. Such layers might include shorelines, land use, pollutant point source locations, sampling locations, habitat maps, etc. Each data layer can be easily input, either directly into models with a mouse and screen forms or through import from existing geographic information systems such as ArcInfo. Data can be exported as well. Each layer can be displayed separately or in any combination. Graphics can be generated and sent directly to a printer (color or black and white) or stored for later use in a computer-driven slide show.

The modeling systems are uniquely versatile with an ability to link one or more of a suite of models of varying complexity into the system. These range from simple calculations of flushing time in a small basin to full three-dimensional, time-dependent, boundary-fitted numerical models of hydrodynamics and water quality. For example, projects may use a boundary-fitted, two-dimensional hydrodynamic model to generate water elevation and velocity and a companion pollutant transport model to generate ________concentration distributions from single or multiple sources. The unique ability of the particle tracking model component to both forward and backward track pollutants make this modeling system unique and particularly useful in the application to the
source tracking problem. The integration of geographic information and models provides a powerful tool with which to analyze pollutant transport and fate.

The models used will have been successfully applied to many areas in both the United States and internationally. Table E1 lists some example applications. During model development the models will have been extensively tested against analytic solutions.

Table E1: Example Applications

Table E1: WQMAP applications

Location	Location
California	**Rhode Island**
San Diego Harbor	Narragansett Bay
L.A./Long Beach Harbor	Mt. Hope Bay/Taunton River
San Francisco Bay	Greenwich Bay
Connecticut	Providence River
Long Island Sound	Warren, Barrington and Palmer Rivers
Thames River	Block Island Sound
Housatonic River	Narrow River
Jordan Cove	Rhode Island Sound
Alewife Cove	Seekonk River
Norwalk Harbor	Sakonnet River
West Haven River	**South Carolina**
New Haven Harbor	Charleston Harbor
Delaware	**Vermont**
Delaware Bay and River	Mississquoi Bay, Lake Champlain
Florida	Lake Champlain
St. Lucie Bay	**Virginia**
Rehobeth Bay/Indian River	Norfolk Harbor
Tampa Bay	Chesapeake Bay
Biscayne Bay	**Washington**
Naples Bay	Columbia River
Ft. Lauderdale	**St. John, U.S. Virgin Islands**
Georgia	Enighed Pond
Savannah River	**Canada**
Hawaii	McKenzie River
Oahu	St. Johns River
Maryland	**Chile**
Baltimore Harbor	San Vicente Bay
Massachusetts	**India**
Cohasset Harbor	Saldia Bay
Boston Harbor	**Indonesia**

Model Descriptions

There are two principal models used: a hydrodynamic model and a pollutant transport model. The pollutant transport models may consist of sub models: a concentration-based model and a particle-based model. A modeling framework example is shown in Figure E1. The data from the project field program is used for calibration of these models. Details of the models follow.

Figure E1: Example Modeling Framework Showing Relationship of Models and Field Data Use

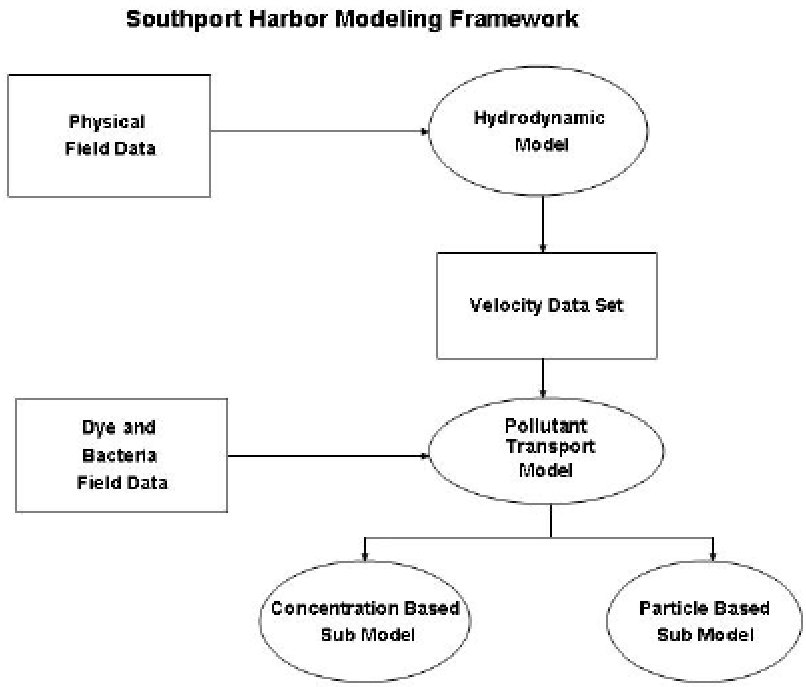

Figure E1: Southport Harbor Modeling Framework Showing Relationship of Models and Field Data Use

(1) Hydrodynamic Model
The hydrodynamic models may be used to solve the three-dimensional conservation of water mass, momentum, salt and energy equations on a spherical, boundary-conforming grid system. Boundary-fitted models match the model coordinates with the shoreline boundaries of the water body, accurately representing the study areas. This system also allows the user to adjust the model grid resolution as desired. The boundary fitted method uses a set of coupled quasi-linear elliptic transformation equations to map an arbitrary horizontal multi-connected region from physical space to a rectangular mesh structure in the transformed horizontal plane. The model can also be run using a simplified grid of square or rectangular cells for quick model application.

The models used will have been successfully peer reviewed by both reviewers in the refereed literature as well as by agency reviews for specific application. A bibliography of peer-reviewed articles appears as Appendix D. The models will have undergone review by a number of state and federal agencies such as USEPA Region 1, MA DEP, RI DEM and VT ANR.

(2) Pollutant Transport Model
Pollutant transport is based on the solution of the advective-diffusive equation with appropriate kinetics for the pollutant of interest (i.e., decay rate). Modeling approaches will include:

ADD LIST HERE

The particle-based model can be run in both forward in time and backward in time to track particle movement. Typically many particles are used in these calculations to provide statistically-based results. Forward tracking (also known as stochastic mode) is useful for identifying where pollutants will travel from a known source. Backward tracking (receptor mode) is useful for identifying source locations that impact a known resource.

The multi-particle, forward tracking stochastic model runs a number of individual particle trajectory simulations from a single source. The wind forcing for each individual trajectory simulation is varied to approximate the variation in environmental forcing one might expect for a release at this location. Stochastic simulations are started randomly from a time windows to sample wind and current variations. The current fields used for this type of simulation are typically tidally forced flows for the study area. The resulting multiple trajectories are then superimposed to produce contours showing the probability of pollutant location. If resource information is stored in the GIS database, a resource hit calculation may be performed to predict the probability of pollutant impacting specific important resources.

The multi-particle, backward tracking receptor model is similar to the stochastic model, except that the model is run in reverse. The source of the pollutant is, in fact, the final position of the particles and the model calculates locations from which the pollutant most likely came. The receptor model performs a large number of simulations for a given receptor site, varying the wind conditions for each scenario, and creating a probability distribution of particle trajectories and the minimum time of travel from posited source locations to the resource site. This model is useful in estimating where sources are located that impact the resource areas.

E1.2 Data Acquisition and Management

Model Inputs

The major hydrodynamic model inputs include run control, model parameters and physical parameters such as time step, output time step, as well as boundary condition information for those processes that are important in driving the hydrodynamics. Details of all required model inputs for the hydrodynamic model are given in Chapter __ of Appendix __. Details of the input file structure and formats are included in Appendices ___and ___.

The major inputs for both pollutant sub models are the binary data file generated by the hydrodynamic model. Model control parameters include source strength, dispersion coefficient and decay rate. Details of all required model inputs for the concentration-based model are given in Chapter ___of Appendix ___. Details of all required model inputs for the particle based model are given in Chapter __of Appendix ___.

The historical and non-directly measured data are summarized in Example Table E2. The sources of the data, how the data were or will be quality assured are also summarized in the table. The time variable data sets are typically available on a one-hour reporting frequency basis.

Table E2: Historical and Non-Directly Measured Data

Table E2: Historical and Non-Directly Measured Data

Data	Type	Source	QA Process
Bathymetry	Historical	NOAA CD (NGDC 1998)	Previously published and quality assured by the agency
		NOAA Chart 12369	Previously published and quality assured by the agency
		USACE predredge condition survey	Previously published and quality assured by the agency
Shoreline	Historical	NOAA Digital Coastline	Previously published and quality assured by the agency
Tides	Historical	NOAA via Tides & Currents	Previously published and quality assured by the agency
	Non-Directly	NOAA/NOS CO-OPS Real time Station 8467150 (Bridgeport)	NOAA/NOS performs preliminary QA, data will be compared to predictions
Winds	Historical	NOAA NCDC Station (Bridgeport MSikorsky Memorial)	Previously published and quality assured by the agency
	Non-Directly	NWS Station COOP ID 060806 (Bridgeport Sikorsky Memorial)	NWS performs preliminary QA, data will be reviewed for outliers
River Flow	Historical	USGS Station 01208950 (Sasco Brook)	Previously published and quality assured by the agency
	Non-Directly	USGS Real time Station 01208950 (Sasco Brook)	USGS performs preliminary QA, data will be reviewed for outliers

Model Calibration and Confirmation

The calibration of numerical models is a complex process. Much literature has been published over the past few decades describing various approaches (McCutcheon et al., 1990; Hess and Bosley, 1992; Lynch and Davies, 1995). In general the calibration process is an organized procedure to select model coefficients to best match experimental data. The calibration should be based on two principles (McCutcheon et al., 1990):

. The simplest model formulation should be used to solve the problem at hand, and
. The model coefficients and parameters should be uniform in space and time unless there is strong evidence in the experimental data that they should change.

The validation or confirmation process is a verification that the chosen model coefficients are applicable to one or more independent sets of data. This process defines the range over which the model can be considered valid. Therefore the experimental data should ideally be collected at the extremes of the conditions of interest when possible. The model is not necessarily valid outside this range.

Confirmation or validation of the model is performed with an independent set of data to determine how well the model can predict the distribution of the model variables. It is expected that the verification results will be similar to the calibration results. If not, then a review is warranted to determine what model parameters were responsible. If necessary, the model is recalibrated to the original verification data set and then verified against the original calibration data set.

A series of comparisons are used to provide measures for the success of the calibration and confirmation steps. These measures are both qualitative and quantitative. The comparison of model results and observations depends on data dimensionality. For example, a time series of data collected at a particular site can be plotted together with model output to provide a visual comparison. This comparison can provide information on the suitability of the model to simulate the range of variability evident in the observations. Each process that affects the observations has a characteristic frequency or set of frequencies. Examples are ____________. The data can be filtered to remove low, mid or high frequencies, as an aid in understanding the important physical processes and their time scales. No model can simulate the entire range of frequencies since neither the forcing functions are known with sufficient precision nor is the model grid fine enough to resolve the small scales. It is often necessary to filter the observations (i.e., remove the high frequencies) when comparing to model results. Care must be taken to avoid removing any important frequencies, however.

The most direct way to provide a qualitative comparison is to plot the model predictions and the observed data for each variable over the time of the simulation. This can be done with time series plots of the variables of interest or contour plots when looking at spatially varying patterns.

Another analysis viewpoint is the frequency domain, which, in fact, is a surrogate for time. This approach allows one to examine the frequency content of the data directly. Time series data are transformed mathematically so that the frequencies in the data are determined. Power spectra indicate the relative energy in the data at different frequencies. Spectra of field data and model predictions when plotted together can help to determine what natural processes are important and whether the model is adequately simulating their effects.

Quantitative comparisons are statistical measures that can be applied to the model predictions and field data sets that provide a numerical assessment of the comparison. These statistical measures can be grouped into two major components: those measures that describe an individual set of data (e.g., a time series of one variable) and those that relate the degree of difference (error) between two data sets (e.g. time series of model predictions and field observations). Individual statistical measures include the mean, standard deviation, percentiles, minimum, and maximum. The independent variable can be time, depth or distance in these data. The quantitative comparisons between data sets include relative error, root mean square error, linear regression (correlation coefficient), and comparison of means. McCutcheon et al (1990) describes these quantitative comparisons in detail and provide guidance on acceptable values.

There is some guidance available on the target levels of model calibration (McCutcheon, et al., 1990). Example Table E3 shows a summary of this guidance for different error measures and properties. The error measures have been defined above and the properties include tide range (the difference between high and low water), maximum current velocity (at flood and ebb) and dye. There is a unique value suggested for each property and error measure based on mean estimates of a series of calibration studies that were examined. McCutcheon, et al. (1990) stated that these target guidance values are representative of a mean level of calibration among multiple comparisons and are not to be considered an upper limit for individual comparisons.

Table E3: Example Model Calibration Guidance (McCutcheon, et al., 1990)

Table E3: Model Calibration Guidance (McCutcheon, et al., 1990)

Error Measure	Property	Target Value
Relative Mean Error, rme	Hydrodynamic (tide range)	+/-1%
	Hydrodynamic (maximum velocity)	+/- 30%
	Water Quality (dye)	+/- 45%
Error Coefficient of Variation, *ecv*	Hydrodynamic (tide range)	4%
	Hydrodynamic (maximum velocity)	10%
	Water Quality (dye)	+/-90%
Correlation Coefficient, *r*	Hydrodynamic (tide range)	0.94
	Hydrodynamic (maximum velocity)	0.65
	Water Quality (dye)	0.60

In addition to the calibration and confirmation process that compares model predictions to field observations a series of sensitivity tests will be performed on model control parameters. Parameters include the pollutant transport diffusivity coefficient and the _______decay rate. The tests will consist of running the models using values within typical literature ranges. A specific set of tests will be run at 0.5 and 2 times the parameter value chosen from the calibration and confirmation process.

The major source of uncertainty is whether there are processes with time and space scales that the models cannot simulate. For insistence, there may be ________ that would not be reflected in the one-hour stepped time series used to force the model, yet the circulation and pollutant transport measurements may pick up responses to that forcing. Because such short term variability may not be significant to the continuous closure of the _________ area, its importance is not great. A discussion of uncertainty will be included in project reports.

E1.3 Model Output

Hydrodynamic model output is discussed in Chapter ___of Appendix ____. The primary output is a binary file of surface elevation and velocities at each cell at a selected time step. This binary file is read by __________ and displayed in snapshot or animation format. The file is also used by the subsequent pollutant transport model to advect Lagrangian particles. Time series of model predictions at user-selected sites is another output that is displayable and exportable. In addition the input environmental forcing (boundary condition data) is also displayable. Details of the output file structure are included in Appendices __ and ___ contained in Appendix ____ of this document.

Concentration-based model output is discussed in Chapter __of Appendix __ with details of the output file structure discussed in Appendix __. The primary output is a displayable file of pollutant concentrations over the modeled area for a series of time steps. Time series at individual sites are also available. Particle-based model output is discussed in Chapter ___of Appendix __. The primary output is a displayable file of particle locations for a series of time steps displayed as an animation sequence. Other output options include viewing contoured images of the probability of water surface area being affected and the time of travel of the pollutant. The receptor mode output shows these contours as the spatial distribution of the probability of pollutant affecting a specific resource area and the travel time to that resource from throughout the modeled area.

One primary output of the modeling system is the statistical identification of pollutant source locations that can affect a specified location. This information provides the user (CTDEP) with a probability map of source locations. From this map the user can get a sense of the location of probable sources.

A second primary output of the modeling system is the pattern of pollutant concentrations generated from specified source locations (identified from the probability maps). By adjusting the source strength the user can determine the relative contribution of various sources that impact a particular resource. This will aid the user in identifying which sources are most critical to the resource.

To help ensure that the modeling system will provide optimum information to CTDEP the system will be tested. Input and output data is accessible for review through the ___________ interface or via ASCII input and ASCII and binary output files.

E2 ASSESSMENT AND OVERSIGHT (MODELING)

E2.1 ASSESSMENT AND RESPONSE ACTIONS

Data of known quality will be used to the extent possible, which means that QC data accompanying the measurement data must be available. If such QC data are unavailable, this will be noted. Data obtained from government databases and peer-reviewed publications will be assumed to be accurate. However, all data will be reviewed for usability, general quality, and consistency with other data sources, prior to use in the modeling activities. Limitations in the data sets will be acknowledged and included in discussions of their use. All data entered manually or electronically will be confirmed by checking the source data. Computer-generated metric calculations will be confirmed by manually calculating a subset of the values to the extent possible.

Performance audits will consist of comparison of model results with observed historical and newly collected data, and general evaluation to ensure reasonable model behavior for state variables and other output lacking historical data. Table A6 will be used as proposed performance measure for model calibration and validation targets. Parameter estimates will be compared to literature values to determine if the model is providing reasonable estimates. If the results are not reasonable, the
hydrodynamic and water quality variables/coefficients required by the model will be modified and the model will be rerun. The output data will be checked to make sure it covers the appropriate boundaries and is complete.

E2.2 REPORTS TO MANAGEMENT

A formal modeling status report will be provided to management. Anomalies will be summarized
by memorandum from the modeling team to the Project Manager, Quality Assurance Officer, and USEPA, as appropriate.

All of the reports that are contract deliverables will be transferred to the USEPA Task Order Manager via hardcopy or e-mail in accordance with contract requirements. Other memos or correspondence to USEPA will be submitted through the USEPA Task Order Manager. Modeling results will be incorporated into the final report.

Monthly Progress Reports – Provide a summary of activities that outlines the status of each task; reports any problems, delays, or corrective actions; identifies anticipated future activities; and highlights the budget status.

Project Reports – A preliminary draft report will be submitted to USEPA for review. The draft report will be revised to incorporate any comments by USEPA and CTDEP. A final report, which will incorporate a response to any technical comments, will be submitted to USEPA for approval and eventual incorporation into the CTDEP's future planning.

E3 DATA VALIDATION AND USABILITY (MODELING)

E3.1 DEPARTURES FROM VALIDATION CRITERIA

Validation criteria are those that are used to determine whether the data satisfy user requirements, whereas verification criteria determine whether the data are sufficient for drawing conclusions related to the data quality objectives (DQOs).

Internal consistency checks will be completed on the integrity of the input data for __________. For example, ___________will make certain that the grid boundaries data coincide with the boundaries of each and contributing watershed. Any discrepancies will be corrected prior to running the ________model.

Raw data received in hard copy format will be entered into the standard database. All entries will be compared to the original hard copy data logs by the team personnel. Data manipulation will also be accomplished using specialized programs and/or commercial spreadsheet programs.

Prior to input the data into the model (either historical or newly-collected), all data will be reviewed and verified for conformance to project requirements, and then validated against the data quality objectives that are listed in Section A7. Only those data that are supported by appropriate quality control data and meet the data quality objectives will be considered acceptable for use.

Experienced professionals will perform the data review, compilation, and evaluation phases of the study. The modeling team members will be responsible for reviewing data entries, transmittals, and analyses for completeness and adherence to QA requirements. The data shall be organized into a standard database on a microcomputer. A screening process will be used that scans the database and flags data that are outside of typical ranges for a given parameter. The database will be scanned to ensure data for all parameters are within typical ranges. Values outside of typical ranges will not be used to develop model calibration data sets or model kinetic parameters.

E3.2 VALIDATION METHODS

Data validation is the process of determining whether the data satisfy user requirements, whereas data verification is the process of ensuring that the data are sufficient for drawing conclusions related to the DQOs.

The Modeling Manager will be responsible for setting up the model, calibrating the model and running the model scenarios. ________will be responsible for completing and documenting the internal model checks. ____________internal consistency checks for __ modeling work will consist of the following three elements:

. Check __________ grid boundaries for consistency with basin and contributing watershed boundaries.
. Double check the procedure of parameter estimation and references of coefficients selected for the model.
. Independently review the documents for model output and scenario runs by __ to make certain that results are reasonable.

________ Quality Assurance Officer (or Project Manager) will be responsible for making sure that the internal consistency checks are completed and documented. All discrepancies and the response action will be documented and maintained in the modeling files.

E3.3 RECONCILIATION WITH USER REQUIREMENTS

The intended purpose of this modeling project is to develop an integrated hydrodynamic and pollutant transport model system. The model would be used to identify the location and relative contribution of _____________ sources that result in elevated levels.

Evaluation of data representativeness will determine the degree to which data accurately and precisely represent characteristic conditions (e.g., pollutant concentrations) and, therefore, address the natural variability or the spatial and temporal heterogeneity of a site.

The final report will follow the draft USEPA Modeling Guidance (January 2004) and document all the assumptions and calculations utilized in estimating the ________ transport so that potential Users and reviewers can understand uncertainties and limitations of the data.

ADD MODELING REPORT RQUIREMENTS HERE

REFERENCES