CHAPTER II

LITERATURE REVIEW

This chapter covers reviews of Substance Flux Analysis used for database preparation, models used, the use of GIS for preparing model input and past studies on Songkhla Lake Basin.

2.1 SUBSTANCE FLUX ANALYSIS

Substance Flux Analysis (SFA) is an environmental accounting tool based on a physical input-output analysis, or the mass balance principle. It is a tool which can be used to evaluate how substances are introduced into, utilized within, and disposed from a system. The technique can be used to identify causes of pollution problems associated with the flows of specific substances in a given time frame and region, and subsequently for considering possibilities for preventing pollution. (Baccini and Brunner, 1991; Guinee *et al.*, 1998; Kleijn *et al.*, 2000; Bouman *et al.*, 2000 and Barr Engineering Company, 2001). Substances analyzed using the SFA method can be elements, chemical compounds or a group of chemical compounds (Lassen and Hansen, 2000). The SFA technique is useful for supporting environmental policy by enabling policy makers to trace the origins of pollution problems and to evaluate appropriate means for the management of potentially hazardous substances by society.

2.1.1 The Principle of the Substance Balance

According to the principle of conservation of mass, recognized since the 18th century, the total mass of a substance is always constant. This principle can be rephrased in terms of a simple mass balance: input equals output plus stock. In the case of chemical compounds that are composed of more than one element, chemical, biological or thermal processes may lead to their formation and degradation. The mass balance principle can therefore be further rearticulated as the basis for SFA.

These entities must be quantified in the context of a system which is precisely defined in time and space. Over a given period of time, for example, a substance entering the system may have not been fully used up, hence resulting in development of a stockpile of the substance - referred to as "accumulation" (Kleijn *et al.*, 2000). By incorporating a time boundary, the substance balance can be expressed as equation 2-1:

$$\text{INPUT} + \text{FORMATION} = \text{OUTPUT} + \text{DEGRADATION} + \text{ACCUMULATION} \quad (2\text{-}1)$$

If left side of equation > right side of equation the substance will accumulate and stocks will be formed within the system. If LHS < RHS, there will be a negative accumulation and the stocks in the system will become depleted. Equations (2-1) can be articulated in a number of ways depending on the system they aim to describe. Equation (2-1) describes substance balances in the simplest form. They can become more sophisticated depending on the level of detail desired in analysis. For example, substance can enter and leave the system via multiple pathways.

2.1.2 General Framework for the SFA Approach

A methodology for the SFA framework consists of four steps (Brunner and Rechberger, 2003): 1) goal and system definition; 2) system analysis; 3) inventory and evaluation of data; and 4) interpretation of the results:

1) Goal and System Definition: the overall goal of SFA is to provide a comprehensive picture of the flow of a substance through the system based on fundamental considerations relating to risk minimization. The SFA system is defined by boundaries in space and time which are established as the first step of the study. It is not uncommon for the definition and interpretation of goals to be modified following the system analysis step.

2) System Analysis: the whole system is considered thoroughly in this phase. All types of transports and processes with potential impacts on the flow of the substance through the system are identified. During

this phase the data requirements and degree of accuracy needed are determined. It should be noted that the flow system established in this phase is seldom perfect. Certain aspects will probably have been overlooked and other types of transport or process identified as essential may turn out to be unimportant. In practice system analysis is an iterative process through which the system is modified continuously as more knowledge is obtained. The outcome of this phase may affect both the goal and system definition and the inventory.

3) Inventory and Evaluation of Data: this phase begins with collection of accessible data consisting of statistical information about the production, import and export of relevant raw materials, semi-manufactured goods and finished products. Monitoring data concerning waste streams is also required. A strategy is then devised for continued collection of data. During the inventory the pieces of the puzzle (the individual data sets) are put together to give an overview. The figures will often not correspond precisely and there will be need for more detailed evaluation of the data to find out the reasons for this.

4) Interpretation of the Results: the basic interpretation should be reported with a discussion of the flow chart derived from the study and the cross-checks made. In reality much of the data collected for an SFA is so uncertain that it has little value until it has been cross-checked. The main sources of the substance to the environment and losses to waste are identified, together with their potential importance for more data.

Although the principles of the SFA approach are very simple, the practical procedures are seldom so straightforward. The reality is often complex and acquiring the necessary data can be very difficult. The data is seldom 100% accurate and is usually subject to varying degrees of uncertainty (Barr Engineering Company, 2001). The procedures used in a particular case will depend on the patterns of application and flow of the chemical substances to be analyzed, the purpose of the analysis, the level of detail required, and the level of reliability which is necessary.

2.1.3 Benefit of the SFA Approach

SFA can provide environmental policy-maker *a priori* information about the likely major sources of hazardous substances. It can be used for prioritizing management actions and for identifying areas which contributes pollutants to lakes. SFA helps in the development of alternative substance flow control strategies. These options include banning the use of some selected substances in some goods, limiting the concentration in goods (e.g., limiting the cadmium concentration in phosphate fertilizer), increasing the recycling rate of some goods (e.g., NiCd in batteries), and improving the level of treatment in waste treatment processes. Strategies will consist of different combinations of options for each element of concern. Before cost-effective control measures can be targeted, we must identify critical source areas vulnerable to phosphorus and cadmium loss from a catchment, account for variations in the catchment response to protection measures which are implemented, and ultimately aim to predict the response of affected waters.

2.2 NON POINT SOURCE POLLUTANT TRANSPORT MODELS

In recent years the numbers of available water quality models have increased. The capabilities and scope of these models range from the simple empirical (minimum data required, hydrology independent, export coefficient based) models to the complex mechanistic (large data required, hydrology dependent) models. When selecting a model, the user should utilize the simplest but yet reasonably accurate model that will satisfy the project objectives, use a good prediction model consistent with available data and minimum number of parameters, and of suitable time scale. A review of several models that have been recently developed follows:

2.2.1 ANSWERS Model

ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation; Beasley *et al.*, 1980) was developed at Purdue University. It is an event based single-storm distributed parameter model. The model divides a watershed into uniform cells and simulates the process of interception, infiltration, surface storage, surface flow, subsurface drainage, sediment detachment, and movement across the cell. Considerable amounts of spatial data are required for watershed simulations and predictions. Nutrients are simulated using correlation relationships between chemical concentrations, sediment yield and runoff volume (Novotny and Olem, 1993).

2.2.2 BASINS Model

BASINS (Better Assessment Science Integrating Point and Non-point Sources; Lahlou *et al.*, 1996 and 1998) is an EPA software package that integrates GIS, nationally supported watershed data and watershed and stream models. BASINS uses an AVENUE-scripted object-oriented interface, the SWAT, WinHSPF, and QUAL2E models and a compilation of generalized and site-specific data to perform three primary functions. The functions are to facilitate examination of environmental information, to provide an integrated watershed and modeling framework and to support analysis of point and non-point source management alternatives.

2.2.3 CREAMS Model

CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management)(Knisel, 1980 and 1993), is a USDA-ARS lumped parameter, deterministic, continuous simulation model. It is based on the steady-state mass balance of sediment transport, detachment and re-deposition of surface runoff, but does not address base-flow (Novotny, 1995). This field-scale model uses USDA SCS (Soil Conservation Service) curve numbers (USDA-SCS,1972) for hydrology and modified USLE (Universal Soil Loss Equation) to simulate sediment, N, P and pesticide load from agricultural sources (Novotny and Olem, 1993).

2.2.4 HSPF Model

HSPF (Hydrologic Simulation Program–Fortran) (Johanson *et al.*, 1980; Donigian *et al.*, 1984; Bicknell *et al.*, 1997; Bicknell *et al.*, 2001) has its origins in the Stanford Watershed Model (Crawford and Linsley, 1966) and can be classified as an advanced lumped parameter or semi-distributed model. Among its processes and state variables, HSPF simulates interception, infiltration, soil moisture, surface runoff, interflow, base flow, snowpack depth and water content, snowmelt, evapotranspiration, groundwater recharge, dissolved oxygen (DO) and biochemical oxygen demand (BOD), temperature, pesticides, fecal coliform bacteria, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, nitrogen and phosphorus compounds, and plankton. Hydrologic processes are represented as flows and storages. Routing is performed using a modified form of the kinematic wave equation. Generally, flow is a one-dimensional outflow from storage, expressed as a function of the present storage amount and the physical characteristics of the subsystem. Although the overall model is physically based, many of the flows and storages are represented in a simplified or conceptual manner. This requires use of calibrated parameters but has the advantage of avoiding the need to explicitly specify all physical dimensions and characteristics of the flow system.

2.2.5 KINEROS Model

KINEROS (Kinetic Runoff and Erosion) (Woolhiser *et al.,* 1990) is a semi-distributed, physically based, event-oriented model that simulates rainfall, interception, infiltration, surface runoff and erosion. A rainfall record is used to describe the spatial and temporal distribution of rainfall to simulate runoff for catchments. A watershed is represented by a (cascading) series of planes and channels (open channels or pipes). The kinematic wave approximation and the Manning equation are used for one-dimensional flow routing. Infiltration is determined using the Smith-Parlange (1978) equation. KINEROS does not include groundwater flow processes other than infiltration and overland flow is Hortonian. Erosion overland is represented by splash and hydraulic rate components and a transport capacity relation of the form summarized by Julien and Simons (1985), such as tractive force (Meyer and Wischmeier, 1969), unit stream power (Yang, 1973), Ackers and White (1973), and Engelund and Hansen (1967). Erosion in channels is similar with the exception that splash erosion is neglected and lateral inflow is not. Deposition is computed from particle fall velocity for the particle concentration in excess of the concentration computed from the transport capacity equation. Sediment transport is represented for a single effective grain size (d50) that can vary by element in the model domain.

2.2.6 SWAT Model

SWAT (Soil and Water Assessment Tool) (Neistch *et al.,* 2002) is an advanced lumped/semi-distributed, physically based, continuous simulation model that simulates rainfall, infiltration, flow routing through basin streams and reservoirs (including lateral flow, groundwater flow, and transmission losses), and sediment and chemical transport through ponds, reservoirs, and streams. Simulated watersheds can be divided into sub-basins or hydrologic response units. SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. Major components model include weather, hydrology, erosion, soil temperature, crop growth, nutrients, pesticides, subsurface flow, and agricultural management. Instream chemical transport in SWAT is based on algorithms adapted from the QUAL2E (Brown and Barnwell, 1987) stream water quality model and includes first order decay relationships for algae, dissolved oxygen (DO), carbonaceous biochemical oxygen demand (CBOD), as well as nitrogen and phosphorus compounds. However, it does not simulate metals. Bian *et al.* (1996) linked SWAT with the Arc/Info geographic information system (GIS).

Soil profiles can be divided into ten layers. Infiltration is computed as precipitation minus runoff (SCS curve number approach) or using the Green and Ampt (1911) relationship. Infiltration moves into the soil profile and is routed through the soil layers. A storage routing coefficient is used to compute flow through each layer, with flow occurring when a layer exceeds field capacity. When water percolates past the bottom layer of the soil profile, it enters the shallow aquifer zone (Arnold *et al.*, 1993). Channel transmission losses and pond/reservoir seepage replenish the shallow aquifer layer, which can interact directly with the stream. Flow to the deep aquifer system is lost and cannot return (Arnold *et al.*, 1993a). An irrigation algorithm allows water transfers from any reach or reservoir to any other in the watershed. Based on surface runoff calculated using the SCS runoff equation, excess surface runoff not lost to other pathways is delivered to the channel network and is routed downstream. Sediment erosion for stream transport is determined with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). For sediment routing, deposition is based on fall velocities for various sediment sizes. Channel degradation rates are determined using the Bagnold (1977) stream power equation. Sediment size is estimated from the primary particle size distribution (Foster *et al.*, 1981) for soils the described in the STATSGO database (USDA, 1991). Stream power is also used in the sediment routing routine to calculate re-entrainment of loose and deposited material in the system until all of the material has been removed. SWAT is a continuous time (long-term yield) model and is not designed to simulate detailed, single event flood routing (Neistch *et al.*, 2002).

2.2.7 CASC2D Model

CASC2D (CASC2D-SED) (Julien and Saghafian, 1991; Julien *et al.*, 1995; Johnson *et al.*, 2000; Ogden and Julien, 1994 and 2002; Rojas, 2002; Julien and Rojas, 2002) is a fully distributed, physically based, event-oriented model that simulates rainfall, interception, infiltration, overland flow, channel flow, as well as sediment erosion and deposition. For surface waters, flow routing is performed using the diffusive wave approximation and is two dimensional overland and one-dimensional in channels. CASC2D does not include groundwater flow processes other than infiltration and overland flow is Hortonian. However, it can be directly coupled with GIS-based site characterization data obtained from remote sensing sources.

CASC2D has been applied at a wide variety of spatial scales from large river basins (12,000 km^2) to moderate watersheds (560 km^2) (Molnár and Julien, 2000) to small watersheds (20-30 km^2) (Rojas, 2002). Overland erosion is computed using a modified form of the Kilinc-Richardson (1973) method (Johnson *et al.*, 2000). Channel erosion is computed using the Engelund and Hansen (1967) method. Up to three solids classes can be simulated (Rojas, 2002). Chemical transport and fate is not simulated. CASC2D source code is publicly available. It should be noted that variants of CASC2D exist (Ogden, 1997), including the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model (Downer and Ogden, 2004). These variants may offer some improvement relative to CASC2D in terms of representation of subsurface flows.

2.2.8 TREX Model

TREX, the Two-dimensional Runoff, Erosion, and Export model, is generalized watershed rainfall-runoff, sediment transport, and contaminant transport modeling framework. This framework is based on the CASC2D watershed model (Julien *et al.*, 1995; Johnson *et al.*, 2000; Julien and Rojas, 2002) with chemical transport and fate processes from the USEPA WASP and IPX series of stream water quality models (Ambrose *et al.*, 1993; Velleux *et al.*, 1996; Velleux *et al.*, 2001). TREX has three main components: 1) hydrology; 2) sediment transport; and 3) chemical transport and fate.

The model simulated the transport and toxicity of metals at the California Gulch, Colorado mine-impacted watershed with a spatially distributed watershed model. Using a database of observations for the period 1984-2004, hydrology, sediment transport, and metals transport were simulated for a June 2003 calibration event and a September 2003 validation event. Simulated flow volumes were within approximately 10% of observed conditions. Observed ranges of total suspended solids, cadmium, copper, and zinc concentrations were also successfully simulated. The model was then used to simulate the potential impacts of a 1-in-100-year rainfall event. Driven by large flows and corresponding soil and sediment erosion for the 1-in-100-year event, estimated solids and metals export from the watershed is 10,000 metric tons for solids, 215 kg for Cu, 520 kg for Cu, and 15,300 kg for Zn.

2.2.9 AnnAGNPS Model

The Annualized Agricultural Non-Point Source Pollution Model AnnAGNPS) is a continuous simulation watershed-scale program. It is an expansion of the capabilities in the single event model AGNPS.(Young *et al.*, 1987, Young *et al.* 1994). AnnAGNPS simulates quantities of surface water, sediment, nutrients, and pesticides leaving the land areas and their subsequent travel through the watershed. Runoff quantities are based on runoff curve numbers while sediment is determined by using the Revised Universal Soil Loss Equation (RUSLE). Special components are included to handle concentrated sources of nutrients (feedlots and point sources), concentrated sediment sources (gullies), and added water (irrigation). Output is expressed on an event basis for selected stream reaches and as source accounting (contribution to outlet) from land or reach components over the simulation period. The model can be used to evaluate best management practices (BMPs). Srivastava *et al.*, (2002) conducted a study using AnnAGNPS and genetic algorithm of optimization of best management practices. Baginska *et al.*, (2003) applied AnnAGNPS and PEST model to predict nutrient export from a small catchment in Australia and found that the accuracy of predictions was moderate. In a model evaluation study, Yuan *et al.*, (2001) found out that the model-predicted monthly sediment yield was in close agreement ($R^2 = 0.7$) with the actual observed sediment yield, but the short-term individual event predictions were not acceptable. In another study, Yuan *et al.*, (2003) found out that AnnAGNPS predictions of monthly loadings were poor though statistically not significantly different from observed values.

2.3 PROCESES INCLUDED IN NON POINT SOURCE POLLUTANT TRANSPORT MODELS

A review of descriptions of hydrological and sediment transport processes included in the models is informative to illustrate the physics behind individual model process representations. The processes reviewed are specific to the needs of formulating a fully distributed watershed chemical transport and fate model framework applicable to contaminants such as nutrients and metals. The major components of the framework are hydrology, sediment transport, and chemical transport and fate. Each of the major components can be viewed as sub models within the overall framework. The reviews are provided in Appendix A

2.4 MODEL SELECTION

There are a wide variety of models available and it is often difficult to choose an appropriate model for the study objective. In this research, the objective was to model the non-point source loading of phosphorus and cadmium to the Songkhla Lake from the surrounding drainage area. The lake covers approximately an area of 1,042 km^2 with a drainage area of 7,687 km^2. The land area of the Basin (excluding 102 km^2 on islets) is divided, by the Royal Irrigation Department, into 12 sub-basins. The majority of SLB land, 5,660 km^2 is used for agriculture. Most of the agricultural land is used for rubber plantation and paddy rice (60% and 30%, respectively). Second land use category is forest, which occupies 1,164 km^2, most of which is the rainforest covering upstream area on the hillsides, the remaining areas are mangrove and swamp forest. Other land use categories are natural water body (12.5% of the Basin area); residential area (2.6%).

Based on the needs of the study, the following criteria were used in selecting appropriated models.

1. Availability of the program (free)
2. Distributed – modeling capability
3. Compatibility with raster GIS to facilitate the use of GIS at all stages of modeling
4. Support for an overland routing approach

5. Ability to simulate event hydrology
6. Ability to simulate transport of nutrients and/or metals via surface runoff

The advantages and disadvantages of each model are summarized in Table 2-1 and 2-2 respectively (Borah and Bera, 2003 and 2004). Because the contributing area is predominantly in agricultural use AnnAGNPS was selected for phosphorus transport. The only model which accommodates metal transport via surface runoff is TREX. Therefore, TREX was selected for tracking cadmium. TREX and AnnAGNPS also satisfy most of the other criteria. These two models are described in detail in the following sections.

Table 2-1 Model Advantages

Model	**ANSWERS**	**BASIN**	**CREAMS**	**HSPF**	**KINEROS**	**SWAT**	**CASC2D**	**TREX**	**AnnAGNPS**
• Availability	X	X	X	X	X	X	X	X	X
• Distributed parameter/semi-distributed model	X	X			X	X	X	X	X
• GIS integrated		X				X	X		X
• Flows and storages are represented in a simplified or conceptual manner.				X			X		X
• Heavy metal transport and fate processes								X	
• Simulate event hydrology	X		X	X	X		X	X	X
• Two-dimensional overland routing approach							X	X	X

Table 2-2 Model Disadvantages

Model	**ANSWERS**	**BASIN**	**CREAMS**	**HSPF**	**KINEROS**	**SWAT**	**CASC2D**	**TREX**	**AnnAGNPS**
• Considerable amounts of spatial data are required.	X			X	X			X	
• Scripted object-oriented interface		X						X	
• Lumped parameter			X	X					

2.5 ANNAGNPS MODEL

AnnAGNPS is a continuous-simulation, watershed-scale model intended to be used as a tool to evaluate non-point source pollution from agricultural watersheds ranging in size up to 300,000 ha. It is an expansion of the capabilities of AGNPS (Figure 2-1) and as such shares many similarities to the original model. Details of AGNPS can be found in Appendix B. A tabular summary of model components is presented in Table 2-3. The watershed is subdivided into homogenous land areas (cells) with respect to soil type, land use, and land management. These areas can be of any shape from the original square grid cells of AGNPS to more appropriate hydrologic boundaries that can be generated by terrain-following Geographical Information System (GIS) software. AnnAGNPS simulates surface water, sediment, nutrients, and pesticides leaving the cells and their transport through the watershed. The model can be used to examine current conditions or to compare the effects of implementing various conservation alternatives over time within the watershed. Alternative cropping and tillage systems; fertilizer, pesticide, and irrigation application rates; point source loads; and feedlot management can be evaluated.

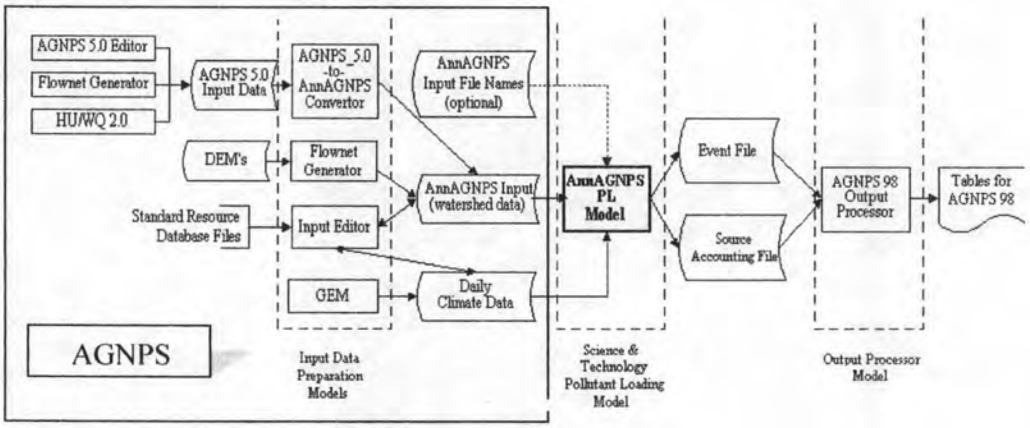


Figure 2-1 AnnAGNPS workflow diagram

Table 2-3 Summary of the components of the AnnAGNPS model

Characteristics	Incorporated in Model	Comments
spatial scale	watershed	limited by data availability and computer memory, drainage areas up to 300,000 ha
discretization	Cells	square grid or hydrologic boundaries
temporal scale	daily time step	unlimited number of years
Water		
surface runoff	Yes	SCS curve number and extended TR55
irrigation	Yes	water with dissolved chemicals and sediment with attached chemicals
ground water	future development	
Sediment		
sheet and rill erosion	Yes	RUSLE technology
gully erosion	Yes	function of surface runoff volume
stream-bed and bank erosion	Yes	by transport capacity
transport	Yes	Einstein deposition equation with Bagnold transport capacity
impoundments	Yes	settling time and dilution due to permanent storage
particle size classes	Yes	five
Nutrients		
nitrogen	Yes	dissolved and attached
phosphorus	Yes	dissolved and attached
organic carbon	Yes	dissolved and attached
pesticides	Yes	unlimited number, dissolved and attached
feedlots	Yes	dissolved nutrients only
point sources	Yes	water and dissolved nutrients
gullies	Yes	sediment and attached chemicals
snow-melt	under development	based upon thermodynamic balance of snow-pack with surrounding environment
frozen soils	under development	thermodynamic balance and heat transfer within soil column, includes effect on USLE soil "K" factor
economics	under development	minimization of pollutant loadings

Source: Bingner *et al.*, 2003

Table 2-4 Inputs required by AnnAGNPS erosion Model

1. Cell number (from)	12. Support practice factor
2. Receiving cell number (to)	13. Surface condition constant
3. SCS curve number (CN)	14. Aspen (direction of drainage)
4. Land slope	15. Soil texture
5. Land slope shape factor	16. Point source indicator
6. Filed slope length	17. Gully source level
7. Channel slope	18. Chemical Oxygen Demand (COD)
8. Channel side slope	19. Impoundment factor
9. Manning's roughness coefficient	20. Channel indicator
10. Soil erodibility factor	21. Fertilization level
11. Cover and management factor	22. Fertilization availability factor

Inputs required for AnnAGNPS are summarized in Table 2-4. AnnAGNPS calculations are performed on a daily time step. AnnAGNPS simulates water, sediment, nutrients, and pesticide transport at the cell and watershed levels. Special components are included to handle concentrated sources of nutrients from feedlots and point sources, concentrated sediment sources with attached chemicals from gullies, and irrigation (water with dissolved chemicals and sediment with attached chemicals). Each day the applied water and resulting runoff are routed through the watershed system before the next day is considered. No water except for that contained within the soil column is carried over from one day to the next.

The model partitions soluble nutrients and pesticides between surface runoff and infiltration. Sediment-transported nutrients and pesticides are also calculated and equilibrated within the stream system. Sediment is subdivided into 5 particle size classes (clay, silt, sand, small aggregate, and large aggregate). Particle sizes are routed separately in the stream reaches. Additional detail can be found in Cronshey and Theurer (1998), Geter and Theurer (1998), Theurer and Cronshey (1998)

2.5.1 Surface Runoff and Soil Moisture

For purposes of runoff generation and soil water storage, the soil profile is divided into two layers. The top 200 mm are used as a tillage layer whose properties can change (bulk density, etc.). The remaining soil profile comprises the second layer whose properties remain static. A daily soil moisture water budget considers applied water (rainfall, irrigation, and snow-melt), runoff, evapotranspiration, and percolation. Runoff is calculated using the SCS Runoff Curve Number equation (Mockus, 1972), but is modified if a shallow frozen surface soil layer exists. Curve numbers are modified daily based upon tillage operations, soil moisture, and crop stage. Actual evapotranspiration is a function of potential evapotranspiration calculated using the Penman equation (Penman, 1948) and soil moisture content.

Time of concentration in each cell can either be input or calculated by the model. If calculated, cell time of concentration is the sum of the travel times from the hydraulically most distant point for overland flow, shallow concentrated flow, and concentrated flow within the cell. Calculations for the three flow types are based upon the NRCS TR-55 (SCS, 1986) procedures, modified by Theurer and Cronshey (1998). The first 50 m of flow length are treated as overland flow. The next 50 m are treated as shallow concentrated flow, while the length beyond this is treated as concentrated flow.

2.5.2 Erosion

Overland erosion of sediment is determined using RUSLE (Renard *et al.*, 1997) and was modified to work at the watershed-scale in AnnAGNPS (Geter and Theurer, 1998). RUSLE is an erosion model predicting longtime average annual loss resulting from raindrop splash and runoff from specific field slopes in specified cropping and management systems and from rangeland. However, it is currently considered to be the best sheet and rill technology suited for continuous simulation of watershed sediment yield. RUSLE is used to determine the delivery ratio for the sheet and rill erosion for each cell. The delivery ratio for the individual particle-size classes is proportioned according to their respective fall velocities. The resulting sediment is called the sediment yield to the stream system.

2.5.3 Nutrients

A daily mass balance for nitrogen (N), phosphorus (P), and organic carbon (OC) is calculated for each cell. Major components considered are plant uptake of N and P, fertilization, residue decomposition, and N and P transport. Soluble and sediment adsorbed N and P are calculated. N and P are further partitioned into organic and mineral phases. Plant uptake of N and P are modeled through a simple crop growth stage index.

Relatively new information (Sharpley, 1995; Sharpley *et al.,* 1994; Sharpley *et. al.,* 1992; Edwards and Daniel, 1994; Edwards and Daniel, 1993; Coale and Olear, 1996) on fate and transport of phosphorus from areas with high soil test phosphorus has not yet been incorporated. Hence, predictions of phosphorus loss from fields with high animal manure applications may be conservative.

2.5.4 Pesticides

A daily mass balance adapted from GLEAMS (Leonard *et al.,* 1987) is computed for each pesticide. AnnAGNPS allows for any number of pesticides, each with their own independent chemical properties. Each pesticide is treated separately, independent equilibration is assumed for each pesticide. Major components of the pesticide model include foliage wash-off, vertical transport in the soil profile, and degradation. Soluble and sediment adsorbed fractions are calculated for each cell on a daily basis.

2.5.5 Reach Routing

The methods used to route sediment, nutrients, and pesticides through the watershed are outlined in Theurer and Cronshey (1998) and briefly discussed here. Peak flow for each reach is calculated using an extension of the TR-55 graphical peak discharge method. Sediment routing is calculated based upon transport capacity relationships using the Bagnold stream power equation (Bagnold, 1966). Sediments are routed by particle size class where each particular size class is deposited; more entrained, or transported unchanged depending upon the amount entering the reach, availability of that size class in the channel and banks, and the transport capacity of each size class. If the sum of all incoming sediment is greater than the sediment transport capacity, then the sediment is deposited. If that sum is less than the sediment transport capacity, the sediment discharge at the downstream end of the reach will include bed and bank material if the user has indicated that it is an erodible reach.

Nutrients and pesticides are subdivided into soluble and sediment attached components for routing. Attached phosphorus is further subdivided into organic and inorganic. Each nutrient component is decayed based upon the reach travel time, water temperature, and an appropriate decay constant. Soluble nutrients are further reduced by infiltration. Attached nutrients are adjusted for deposition of clay particles. Equilibrium concentrations are calculated at both the upstream and downstream points of the reach. A first-order equilibration model is used.

2.5.6 Calibration

As with all physical-process models, the model input can be refined by comparing model simulations to observed data. The selection of the curve number largely controls runoff volume in models which use SCS curve number technology. Because of the impact of runoff volume on all other hydrologic processes, it is expected that the curve number may be one of the most sensitive parameters in the AnnAGNPS model.

2.5.7 Input / Output

AnnAGNPS includes 34 different categories of input data (Cronshey and Theurer, 1998). These can be further grouped into the following major classifications: climate, land characterization, field operations, chemical characteristics, and feedlot operations. The climatic data consist of precipitation, maximum and minimum air temperature, relative humidity, sky cover, and wind speed. Land characterization data include soil characterization, curve number, RUSLE parameters, and watershed drainage characterization. Field operation data include tillage, planting, harvest, rotation, chemical operations, and irrigation schedules. Feedlot operations include daily manure production rates, times of manure removal, and residual amount from previous operations.

There are over 400 separate input parameters necessary for model execution. Some of these parameters are repeated for each cell, soil type, land use, feedlot, and/or channel reach. Separate parameters are necessary for the model verification section. Default values are available for some of the input parameters. The daily climate data input set includes 22 parameters, 8 of which are repeated for each day simulated. A climate generator, GEM, can be used to generate the precipitation and min/max air temperatures for AnnAGNPS. The development of other input data can be simplified because of duplication over a given watershed. Some of the geographical inputs including cell boundaries, land slope, slope direction, and land use, can be generated by GIS and digital elevation models.

Input is facilitated by an input editor which is currently available with the model. The input editor provides for data input in a page type format, with each of the 34 major data categories on a separate input page. Input and output can be in either all English or all metric units. Separate input files for watershed and climate data allows for quick changing of climatic input. Extensive data checks (with appropriate error messages) are performed as data are read and, to a lesser extent, after all data are read. Brief explanations of the input parameters are provided in the editor.

Output is expressed on an event basis for selected stream reaches and as source accounting from land or reach components over the simulation period. Output parameters are selected by the user for the desired watershed source locations (specific cells, reaches, feedlots, point sources, and gullies) for any simulation period. Source accounting indicates the fraction of a pollutant loading passing through any reach in the stream network that came from the user identified watershed source location. Multiple watershed source and reach locations can be identified. Additionally, event quantities for user-selected parameters can be output at desired stream reach locations. Output analysis can be simplified by using the output editor.

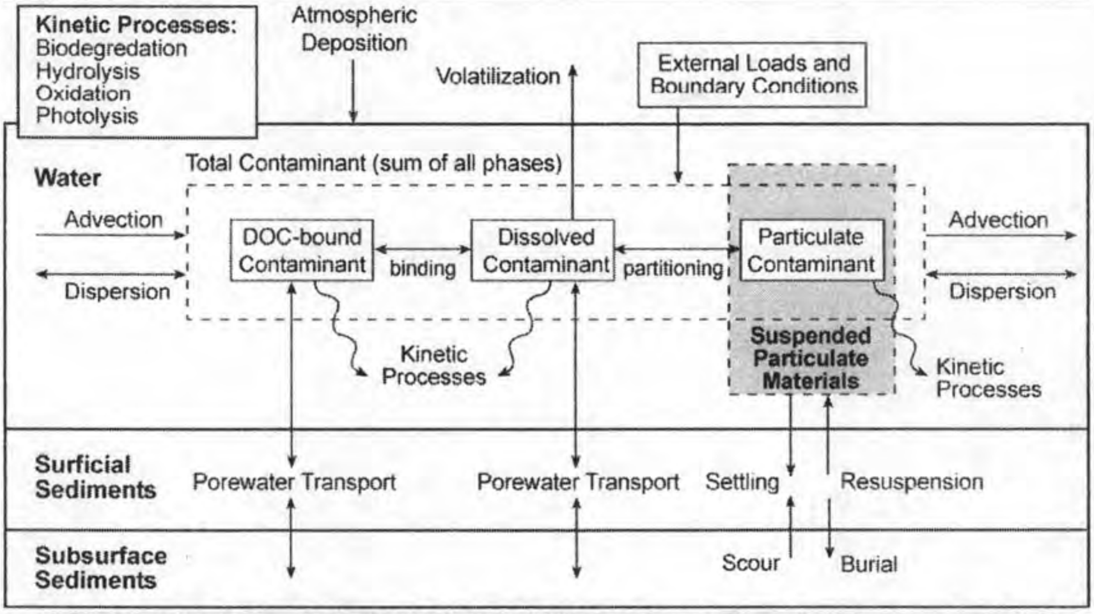
2.6 TREX MODEL

TREX is a fully distributed numerical modeling framework to simulate the transport and fate of chemicals particularly metals across watersheds. An overview of TREX features and numerical implementation follows.

2.6.1 Generalized Conceptual Model

A generalized conceptual framework for TREX is presented in Figure 2-2. The model focuses on the event transport of metals in surface waters. Consequently, several possible processes in the general conceptual framework can be neglected because storm events are short-lived, lasting no more than a few hours. In particular, mass transfer and reactions processes such as volatilization, biodegradation, hydrolysis, and photo degradation can be neglected because of the short time scale for simulations or because these processes do not occur for metals. Other processes, such as dispersion and diffusion can also be neglected because at the time scale of event simulations transport processes are expected to be dominated by advection. At the event time scale, subsurface transport is also neglected. As a result, the transport and fate processes most important for the event simulation of metals are:

- Advective water column transport;
- chemical partitioning between water (truly dissolved), dissolved organic compounds (DOC) (or other binding agents) (bound), and solid (particulate) phases;
- Transport (erosion, deposition, net burial) of solids and particulate chemicals;
- Infiltration of dissolved and bound (mobile) phase chemicals;
- External sources and sinks of water, solids and chemicals.



Partitioning between dissolved, particulate and DOC phases occurs in the sediments as conceptualized in the water column. Biodegradation, hydrolysis and oxidation can also occur in the sediments as conceptualized in the water column.

Figure 2-2. Generalized Conceptual Model Framework

In their most general form, these mass balance equations form a system of coupled partial differential equations that are functions of time and space. These equations describe the relationship between material inputs (precipitation or loads) and mass (water depth or constituent concentrations). To solve these equations, three simplifying assumptions were made and the equations expressed in finite difference form (Thomann and Mueller, 1987; Chapra, 1997):

1. Water column volumes are constant with respect to time during any interval ($\partial V/\partial t = 0$);
2. Surficial sediments do not move horizontally within the sediment bed
3. Chemical partitioning to solids and binding is rapid relative to other processes (local equilibrium).

The state variables in the model framework for the overland plane (denoted with the subscript "ov") and channel network (denoted with the subscript "ch") are: water depth (h), solids concentration (Cs), and chemical concentration (Cc). The corresponding equations for the water column and bed are:

Water Depth in the Overland Plane and Channel Network

$$\frac{\partial h_{ov}}{\partial t} = i_e - \frac{1}{B_x}\frac{\partial Q_{ovx}}{\partial x} - \frac{1}{B_y}\frac{\partial Q_{ovy}}{\partial y} - \frac{q_l}{L_c} + \frac{W_w}{A_c} \tag{2-2}$$

$$\frac{\partial \left(h_{ch} B_c\right)}{\partial t} = q_l - \frac{\partial Q_{ch}}{\partial x} + \frac{W_w}{L_c} \tag{2-3}$$

Solids in the Water Column of the Overland Plane and Channel Network

$$\frac{\partial C_{s,ov}}{\partial t} = v_r C_{sh,ov}\frac{A_s}{V_w} - v_{se} C_{s,ov}\frac{A_s}{V_w} - v_x C_{s,ov}\frac{A_c}{V_w} - v_y C_{s,ov}\frac{A_c}{V_w} - v_f C_{s,ov}\frac{A_c}{V_w} + \frac{W_s}{V_w} \tag{2-4}$$

$$\frac{\partial C_{s,ch}}{\partial t} = v_r C_{sh,ch}\frac{A_s}{V_w} - v_{se} C_{s,ch}\frac{A_s}{V_w} - v_x C_{s,ch}\frac{A_c}{V_w} - v_y C_{s,ch}\frac{A_c}{V_w} - v_f C_{s,ch}\frac{A_c}{V_w} + \frac{W_s}{V_w} \tag{2-5}$$

Solids in the Soil and Sediment Bed

$$\frac{\partial C_{sb,ov}}{\partial t} = v_{se} C_{s,ov} \frac{A_s}{V_s} - v_r C_{sb,ov} \frac{A_s}{V_s} \tag{2-6}$$

$$\frac{\partial C_{sb,ch}}{\partial t} = v_{se} C_{s,ch} \frac{A_s}{V_s} - v_r C_{sb,ch} \frac{A_s}{V_s} \tag{2-7}$$

Total Chemical in the Water Column of the Overland Plane and Channel Network

$$\frac{\partial C_{c,ov}}{\partial t} = v_r C_{cb,ov} f_{pb} \frac{A_s}{V_w} - v_{se} C_{c,ov} f_p \frac{A_s}{V_w} - v_x C_{c,ov} \frac{A_c}{V_w} - v_y C_{c,ov} \frac{A_c}{V_w} - v_f C_{c,ov} \frac{A_c}{V_w} \tag{2-8}$$

$$- v_{i,ov} C_{c,ov} \left(f_d + f_b \right) \frac{A_s}{V_w} + \frac{W_c}{V_w}$$

$$\frac{\partial C_{c,ch}}{\partial t} = v_r C_{cb,ch} f_{pb} \frac{A_s}{V_w} - v_{se} C_{c,ch} f_p \frac{A_s}{V_w} - v_x C_{c,ch} \frac{A_c}{V_w} + v_f C_{c,ov} \frac{A_c}{V_w} \tag{2-9}$$

$$- v_{i,ch} C_{c,ch} \left(f_d + f_b \right) \frac{A_s}{V_w} + \frac{W_c}{V_w}$$

Total Chemical in the Soil and Sediment Bed

$$\frac{\partial C_{cb,ov}}{\partial t} = v_{se} C_{c,ov} f_p \frac{A_s}{V_s} - v_r C_{cb,ov} f_{pb} \frac{A_s}{V_s} \tag{2-10}$$

$$\frac{\partial C_{cb,ch}}{\partial t} = v_{se} C_{c,ch} f_p \frac{A_s}{V_s} - v_r C_{cb,ch} f_{pb} \frac{A_s}{V_s} \tag{2-11}$$

Where h = flow depth of water column [L]

C_s, C_{sb} = solids concentration in water column and bed [M/L^3]

C_c, C_{cb} = total chemical concentration in water column and bed [M/L^3]

Q_x, Q_y = flow in the x- or y- direction [L^3/T]

q_l = lateral unit flow from overland plane to channel (floodplain) [L^2/T]

L_c = length of channel in flow direction [L]

A_c, A_s = cross sectional area in flow direction, bed surface area [L^2]

V_w, V_s = volume of water and sediments [L^3]

v_x, v_y, v_f = flow direction in the x- or y- direction and between overland plane and channel (floodplain) [L/T]

v_r, v_{se}, v_i = Resuspension (erosion), effective settling (deposition), and infiltration (or transmission loss) velocities [L/T]

f_d, f_b, f_p = dissolved, bound, and particulate chemical fractions [dimensionless]

$W_{w,s,c}$ = material point source/sink: water[L^3/T], solids or chemical [M/T]

Each term in the mass balance equations represents a process in the conceptual framework. The variables in each term represent model parameters. Thomann and Mueller (1987) and Chapra (1997) provide more detailed presentations of mass balance equations for chemical transport.

2.6.2 Numerical Implementation

To simulate hydrologic, sediment, and chemical transport, values must be assigned to each model parameter and the mass balance equations defined by the conceptual model framework must be solved. Numerical integration techniques are needed to solve the model equations. TREX uses a finite difference control volume implementation of the generalized mass balance equation. To generate solutions, the framework computes dynamic mass balances for each state variable and accounts for all material that enters, accumulates within, or leaves a control volume through precipitation excess, external loads, advection, erosion, and deposition. TREX also features a "semi-Lagrangian" soil/sediment bed layer submodel to account for the vertical distribution of the physical and chemical properties of the overland soil and channel sediment columns. These equations are solved using Euler's method for numerical integration (Chapra and Canale, 1985):

$$s\big|_{t+dt} = s\big|_t + \frac{\partial s}{\partial t}\bigg|_t dt \qquad (2\text{-}12)$$

Where $s\big|_{t+dt}$ = value of model state variable at time $t + dt$ [L] or [M/L^3]

$s\big|_{t}$ = value of model state variable at time t [L] or [M/L^3]

$\left.\frac{\partial s}{\partial t}\right|_{t}$ = value of model state variable derivative at time t [L] or [M/L^3]

dt = time step for numerical integration [T]

2.6.3 TREX Framework Features

The starting point for TREX development was CASC2D. As part of TREX development, CASC2D's underlying hydrologic and sediment transport submodels were significantly enhanced before chemical transport and fate components were added to create the TREX framework. An overview of TREX features is presented in Table 2-4. The entire body of TREX source code is organized to significantly improve code structure and modularity and includes line-by-line documentation. Beyond allowing development of basic chemical transport and fate features, TREX is structured so future categories of model features can be added to the framework without having to reconstruct the basic code. As presented in Figure 2-3, the code is designed so that the calculations for each process at any time level are independent and information is carried forward from hydrology to sediment transport to chemical transport in order to generate a solution.

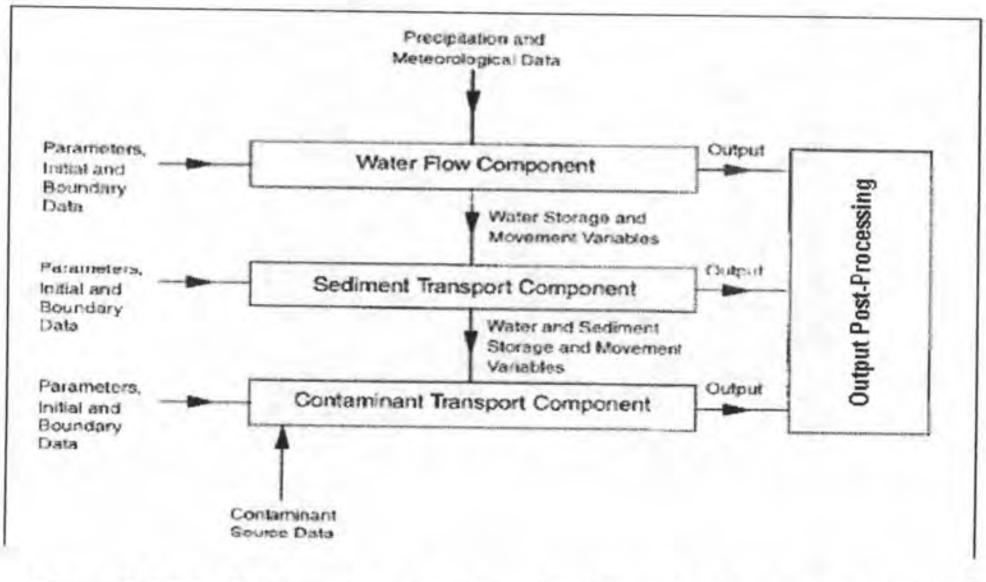


Figure 2-3 TREX Hierarchy and information flow (after Ewen *et al.*, 2000).

Model Component	*Prior CASC2D Code*	*TREX Code*
Number of particle types	Limited to three: sand, silt, clay	Unlimited
Floodplain sediment transport	None: solids passing through overland part of a flood plain cell instantly move to channel	Occurs whenever water depth in overland part of flood plain cell exceeds zero
Channel erosion	Limited: only solids deposited during simulation erode; net bed elevation change never < 0	Not restricted; channels can incise and net change in bed elevation can be < 0
Solids point sources and sinks	None	Point sources for overland plane and channel network
Chemical Transport Submodel		
Number of chemical types	None	Unlimited
Chemical transport and fate	None	Three-phase partitioning with advection, erosion, deposition
Chemical point sources and sinks	None	Point sources for overland plane and channel network

At any time level, flow is assumed to be unaffected by sediment and chemical transport and sediment transport is affected by chemical transport, so calculations for these three components have a natural hierarchy. The organization of hydrologic, sediment, and chemical transport and fate process functional units within TREX is presented in Figure 2-4.

Table 2-5 Comparative overview of TREX features

Model Component	***Prior CASC2D Code***	***TREX Code***
	General Model Controls	
Numerical integration time step	One time step limited to critical value regardless of flow	Series of time step values that can be optimized based on flow
	Hydrologic Submodel	
Water depth initial condition	Assumed to be zero but recent code allowed a non-zero flow depth in channels (dry start)	User can specify any value for depth overland, in channels, or infiltrated (wet or dry start)
Flow outlets and downstream boundary conditions	Limited to one outlet, assumed normal depth	Any number of outlets possible, downstream control or normal depth can be specified
Floodplain interaction	Present in initial code (Julien *et al.*, 1995) but not in recent code (Rojas, 2002).	Restored feature and enhanced to compute flooding from water surface elevations
Channel topology: orientation	Channel connections limited to four(N-S or E-W) directions	Channel connections in all eight raster grid directions
Channel topology: branching	Converging branches only, limited to two branches upstream	Converging and diverging branches with 2-7 branches
Flow point sources and sinks	None	Point sources for overland plane and channel network
	Sediment Transport Submodel	

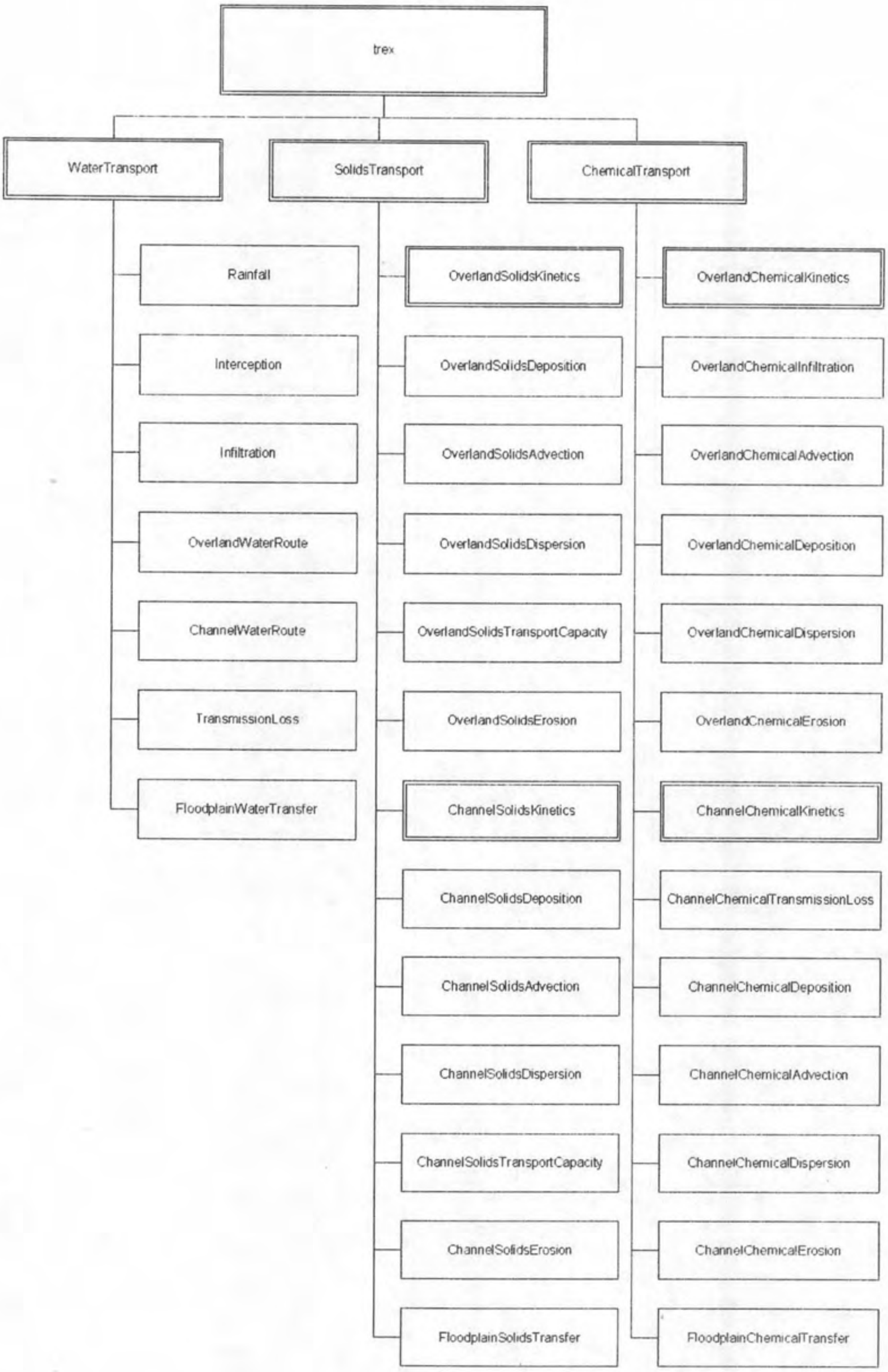


Figure 2-4 Organization of transport and fate process functional units in TREX.

Table 2-6 Inputs required by TREX erosion Model

1. Cell number (from)	12. Support practice factor
2. Receiving cell number (to)	13. Surface condition constant
3. SCS curve number (CN)	14. Aspen (direction of drainage)
4. Land slope	15. Soil texture
5. Land slope shape factor	16. Point source indicator
6. Filed slope length	17. Gully source level
7. Channel slope	18. Chemical Oxygen Demand (COD)
8. Channel side slope	19. Impoundment factor
9. Manning's roughness coefficient	20. Channel indicator
10. Soil erodibility factor	21. Heavy metal level
11. Cover and management factor	22. Heavy metal distribution coefficient

Inputs required for TREX are summarized in Table 2-6. As part of TREX development, many features of the original CASC2D code were significantly enhanced and many entirely new features were added. In particular, the TREX code is designed to simulate multiple watershed outlets and to also allow channel network branching in the upstream and downstream directions. This permits simulation of braided tributaries and distributary flows that might occur around alluvial fans or where a stream system on a high slope meets a large receiving waterbody on a low slope. Another significant enhancement is the addition of flow point sources and sinks. Note that TREX does not consider groundwater flow processes other than water loss at the surface by infiltration or channel transmission loss. However, to account for other water losses or gains, groundwater interactions could be represented as a series of time-variable point sources and sinks. In effect, this feature allows TREX to be externally coupled with groundwater flow and transport modeling tools such as MODFLOW (Harbaugh *et al.*, 2000), HST3D (Kipp, 1997), and MT3DMS (Zheng and Wang, 1999).

Another key feature of TREX is the representation of the bed and bed processes. The bed itself is presented as a vertical stack (layers). Typical water quality modeling approaches use an Eulerian (fixed) frame of reference for all compartments. In contrast, TREX uses what is termed a "semi-Lagrangian" (floating) frame of reference (Velleux *et al.*, 2001). In the semi-Lagrangian approach, the control volume of the surface bed layer is allowed to expand or contract in response to erosion or deposition. This allows for improved simulation of the dynamics of chemical distributions in soils and sediment. Velleux *et al.,* (2001) and Imhoff *et al.,* (2003) present further descriptions of the semi-Lagrangian approach and its details. The approach allows for dynamic simulation of both transport capacity limited and supply limited sediment and chemical transport.

Beyond these enhancements, TREX is fully-distributed and is designed to be compatible with data from raster GIS sources. In particular, data describing elevation, soil types, land use, and contaminant distributions can be processed in a GIS and used as model inputs. Model outputs are also designed to be compatible for use with a GIS.

2.6.4 Features to Visualize Chemical Transport and Fate

TREX has a number of features specifically designed to aid visualization of chemical transport and fate simulation results. Expanding on the approach described by Rojas (2002), TREX can provide outputs in several different formats including point-in-time, point-in-space, cumulative-time, and mass balance reports.

2.7 SONGKHLA LAKE BASIN

Songkhla Lake and its basin are spread over 3 provinces of Thailand: all 11 districts of Phattalung Province, 12 (out of 16) districts of Songkhla Province and 2 (out of 23) districts of Nakhon Si Thammarat Province. The lake covers approximately an area of 1,042 sq.km. and the drainage, an area of 7,687 sq.km. The basin spans approximately 150 km. from north to south, and approx. 65 km. from east to west. Songhkla is the only lake in Thailand where fresh water from precipitation, via streams and overland flow, draining into the lake, mixes with saline water from the sea, making Songkhla Lake a large lagoon system. The Basin is bounded by two mountain ranges. To the west is Banthad mountain range, which lies in north-south direction, and to the south is part of Sangala Kiri mountain range. The higher grounds of the two mountain ranges are covered with rainforests, constituting an upstream portion of the catchment area. Further down from the Banthad mountain range, from north to south of the Basin parallel to the mountain range, are undulating plains alternating with low hills. The area towards the east approaching the Lake is a large flat plain, most of which are paddy rice farms. North of Songkhla Lake is a large wetland called "Phru Kuan Kreng" which covers approx. 137 sq.km. The east of Songkhla Lake, which lies between the Lake and the sea, is a large flat plain. Physically, Songkhla Lake consists of 4 parts: Thale Noi in the northernmost of the Songkhla Lake system; Upper Songkhla Lake; Middle Songkhla Lake and Lower Songkhla Lake. The latter is connected to the Gulf of Thailand at Muang District, Songkhla Province.. The majority of SLB land, 5,660 sq.km. (3,537,827 rais – approximately two-thirds of the Basin area) is used for agriculture. Most of the agricultural land, 60% and 30%, respectively, is used for rubber plantation and paddy rice. Second land use category is forest, which occupies 1,164 sq.km. (727,426 rais - 13.7% of the Basin area); most of which is the rainforest covering upstream area on the hillsides, the remaining areas are mangrove and swamp forest. Other land use categories are natural water body (1,060 sq.km. or 661,848 rais or 12.5% of the Basin area); residential area (224 sq.km. or 139,837 rais or 2.6% of the Basin area). The remaining are for miscellaneous purposes, such as industrial area, man-made water body, roads and undeveloped land. The average rainfall during 1992-2002 was at 2,043 mm. with annual average temperature between 26.7 and 29.1 Celsius and relative humidity at 77 percent (Thai Meteorological Department, 2005).

2.7.1 Sub-Watersheds

The Royal Irrigation Department divided Songkhla Lake Basin into 12 sub watersheds based on major rivers that flows into Songkhla Lake as follows (Figure 2-5) Klong Pa Payom, 2. Klong Thanee, 3. Klong Nathom, 4. Klong Tachiad, 5. Klong Pa Bon, 6. Klong Phru Poh, 7. Klong Rattaphum, 8. Klong U-Tapao, 9. Eastern Coast sub-basin 1, 10. Eastern Coast sub-basin 2, 11. Eastern Coast sub-basin 3 and 12. Eastern Coast sub-basin 4.

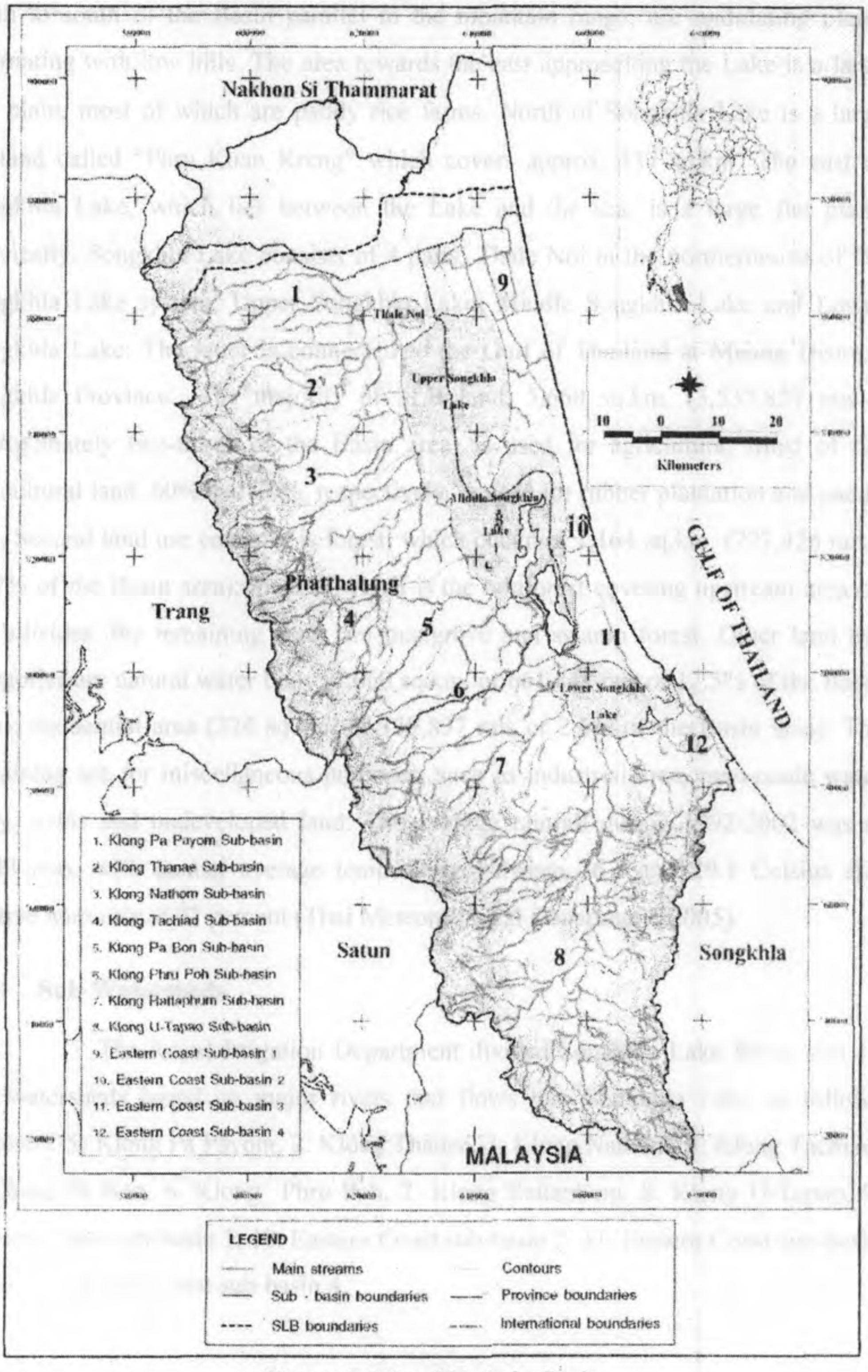


Figure 2-5 Songkhla Lake Basin

2.7.2 Current Water Quality Status of the Lake

Nutrient concentrations measured once a year in the Upper, Middle and Lower Songkhla Lake are shown in Tables 2-7, 2-8 and 2-9 respectively. The criterion for lake eutrophication is either having phosphate more than 0.02-0.1 mg/l (Pierzynski and Logan, 1993; Sharpley *et al.*, 1994 and Lory, 1999) or indications of Chlorophyll *a* more than 10 μg/l (Sin *et al.*, 1999; Sompongchaiyakul *et al.*, 2004). Phosphate was found higher at the lower Songkhla Lake, whereas Chlorophyll *a* was higher in the upper and middle Songkhla Lake. U-Tapao canal located in the Lower Songkhla Lake contributes to the heavy loading of nutrients and wastewater to the lake due to dense population and industries along the canal (Emsong, 1998). Studies of cadmium in Songkhla Lake basin's soil (Sae-Eong *et al.,* 2002) found that cadmium concentrations in the plough layer ranged from <1-90 ppb with an average of 24 ppb, and < 1-54 ppb with an average of 14 ppb. Recent report (Leekpai, 2006) shows that cadmium content was found to be < 1.33 ppm throughout the basin. Cadmium in the outer Songkhla lake was also found to be conservative in dissolved phase (Sirinawin, 1998). Thus, if the situation still continues, accumulated cadmium in the basin could pose a treat to the population.

Although the water quality in general in the Lake is within acceptable ranges, eutrophication and nutrient levels in the Lake is suspected to be higher than stated. The area of most critical concern is the upper lake system, consisting of Thale Noi, Thale Luang, and Thale Sap. According to calculations with the Integrated Surface Water Model established for the Songkhla lake basin (ISWM) (Emsong, 1998), the upper lakes are at the limit of their carrying capacity. These calculations indicate that Songkhla lake is not at risk presently, having excess capacity under current conditions. However, careful monitoring of the lower lakes system is warranted as the analysis suggests eutrophication levels in Songkhla lake are likely to continue to rise due to expected increased loading (Emsong, 1998).

Table 2-7 Upper Songkhla Lake nutrients during 1999-2003

Year	PO_4^{3-}	TP	$NO_3^-+NO_2^-$	NH_3	TN	DO	pH	Chlo *a.*
	mg-P/l	mg-P/l	mg-N/l	mg-N/l	mg-N/l	mg/l		μg/l
1999	0.004	0.12	0.021	0.024	0.54	7.54	8.14	34.3
2000	0.006	0.10	0.020	0.027	0.60	7.10	8.03	36.0
2001	0.004	0.09	0.023	0.036	0.72	7.69	8.08	37.0
2002	0.004	0.07	0.029	0.086	0.72	7.52	8.10	44.5
2003	0.004	0.06	0.023	0.040	0.70	7.76	7.59	21.3

Source: Sompongchaiyakul, 2005

Table 2-8 Middle Songkhla Lake nutrients during 1999-2003

Year	PO_4^{3-}	TP	$NO_3^-+NO_2^-$	NH_3	TN	DO	pH	Chlo *a.*
	mg-P/l	mg-P/l	mg-N/l	mg-N/l	mg-N/l	mg/l		μg/l
1999	0.005	0.07	0.053	0.058	0.49	6.66	7.44	8.0
2000	0.011	0.09	0.061	0.057	0.43	6.33	7.53	14.3
2001	0.007	0.08	0.073	0.041	0.60	6.88	7.54	13.1
2002	0.003	0.05	0.045	0.023	0.73	6.60	7.60	6.0
2003	0.002	0.05	0.017	0.028	0.42	7.32	8.01	5.4

Source: Sompongchaiyakul, 2005

Table 2-9 Lower Songkhla Lake nutrients during 1999-2003

Year	**PO_4^{3-}**	**TP**	**$NO_3^-+NO_2^-$**	**NH_3**	**TN**	**DO**	**pH**	**Chlo *a*.**
	mg-P/l	mg-P/l	mg-N/l	mg-N/l	mg-N/l	mg/l		μg/l
1999	0.063	0.17	0.722	0.384	0.97	4.88	6.97	11.2
2000	0.064	0.16	1.042	0.251	1.39	4.98	6.99	5.4
2001	0.056	0.17	0.713	0.214	1.43	6.55	7.15	12.6
2002	0.076	0.15	1.438	0.510	1.19	4.70	7.15	16.4
2003	0.081	0.20	0.905	0.661	2.18	3.61	7.11	13.9

Source: Sompongchaiyakul, 2005