INTRODUCTION TO ENVIRONMENTAL MODELING

Environmental models are designed to simulate the responses of aquatic environments, such as aquatic ecosystems, under varying conditions. They are generally applied to help explain and predict the effects of human activities on water resources, such as lake eutrophication, dissolved oxygen concentrations in rivers, the impacts of acid rain on natural water bodies, and the fate, pathways, impacts and effects of toxic substances in freshwater systems.

The high degree of complexity of natural systems makes model development a difficult and highly skilled task. Data requirements for model calibration and for model use pose additional constraints on their widespread use. This complexity, together with the limited knowledge of the processes taking place in water bodies, require that a high degree of simplification and a number of assumptions must be built into any model. In truth, no model can account for all environmental variables and predict outcomes with 100% accuracy. However, a good model can tell us much more about an ecosystem or process than we might otherwise know from observation and data gathering alone.

Models can be designed along a variety of formats. Mathematical models, for example, are very useful tools for water quality and aquatic ecosystem management because they allow:

- The identification of important variables in a particular aquatic system, and help with the interpretation of the system's processes
- Forecasting of the impacts of developments on water bodies
- Policy testing and analysis.

The model user must be aware of the model's limitations, and its assumptions, in order to draw appropriate conclusions. At present, highly predictive models are not general, and general models are not highly predictive. A discussion of some model types and their functions follows.

CONCEPTUAL MODELS

A conceptual model is a written description and visual representation of predicted relationships between ecological entities and the stressors to which they may be exposed. These models represent many relationships and are frequently developed as part of an ecological risk assessment (ERA). They may include ecosystem processes that influence receptor responses or exposure scenarios that link land-use practices to stressors. Multiple conceptual models may be generated to address several issues in an ecosystem.

A good conceptual model will be iterative; in other words, it will be able to change as new information or new relationships are revealed. The complexity of the conceptual model depends on the complexity of the problem, including the number of stressors and the number or receptors. If the model is created to help determine the potential ecological risk posed by a particular substance or activity, it may be worthwhile also to create a model that represents expected ecosystem characteristics and functions in the absence of the stressor(s). In addition, the development of conceptual models has these benefits:

- The development a conceptual model serves as a powerful learning tool in the understanding of ecosystem elements and processes.
- Conceptual models are easily modified as knowledge increases.
- Conceptual models highlight what is known and can be used to determine data gaps and to plan future research They provide an explicit expression of the assumptions and understanding of a system for others to evaluate.
- Conceptual models provide a framework for prediction and are the template for determining research hypotheses.

THEORETICAL MODELS

If the physical, chemical and/or biological mechanisms underlying a process are well understood, a steady-state or dynamic model can be developed. When compared to empirical models, theoretical models are generally more complex. They require a longer period of observation for calibration and the number of variables and parameters to be measured are greater. They also require a significant amount of time for validation.

Uncertainty in Conceptual Models

Conceptual model development can potentially be one of the most significant sources of uncertainty in the determination of a stressor’s impact in an aquatic environment, such as DDT. If important relationships are missed or specified incorrectly, an accurate determination of the risk the DDT will be impossible. Uncertainty can arise from a lack of knowledge of how the ecosystem functions, from failure to identify and interrelate temporal and spatial parameters, or from omission of relevant stressors. In some cases, little may be known about how a particular chemical moves through the environment or causes adverse effects.

Environmental managers may not always agree on the appropriate conceptual model design. While simplification and lack of knowledge may be unavoidable, scientists and decision makers should: document what is known, justify the model and rank model components in terms of uncertainty.

Let’s imagine that an abandoned pesticide storage facility had released DDT into the environment through spills and mishandling. Due to erosion of contaminated soils, DDT has migrated into sediments of the Mekong River. Life cycle data on all potential receptors would be ideal for the development of a DDT exposure / transport / effects model. However, identification of known contaminant sources, pathways and suspected organisms where DDT could accumulate in body tissue would be sufficient to begin design of the conceptual model. As more knowledge is gained, more information could be added to the model, thereby reducing uncertainty.

EMPIRICAL MODELS

Empirical or statistically-based models are generated from analysis of monitoring data from specific sites. The relationships identified are then described in one or more mathematical equations. These models can be built relatively quickly when compared to theoretical models, and they are easier to use because they have fewer data requirements. Sometimes empirical models have to be generated from incomplete or scattered information about the aquatic system. In such cases the model output should be interpreted with caution. It is also important to remember that such models are not directly transferable to other geographic areas and to different time scales.

A Simple Empirical Model

Erosion is recognized as a serious environmental issue of the Mekong River. However, determining the rate and quantity of soil loss for a particular deforested site or ecosystem may prove difficult. The universal soil loss equation is an example of a basic yet functional model that can give scientists and environmental managers a fairly accurate idea of how much topsoil may be lost when a parcel of land is disturbed. The equation was developed from more than 40 years of data collection on a number of different soil types and hydrologic regimes. Relevant values for each factor have been determined for tropical soil types typical of the Mekong River Basin (MRB). The average annual soil loss from a site can be estimated by the following equation:

$$A = RKLSCP$$

where,

A = the average annual soil loss.

R = rainfall and runoff erosivity index by geographic location. R measures the erosive force of rainfall and run-off.

K = the soil erodibility factor. K is influenced by infiltration capacity, or the ability of the soil to absorb water rather than have water flow over it and take topsoil particles. The structural stability of the soil particles also plays a role; loose, unstable soil particles are more vulnerable to erosion. Soil erodibilty factors have been calculated for a number of different tropical soil types.

L = slope length. L is important because often the greater the inclined area, the greater concentration of flooding water.

S = slope gradient (steepness). In general, the steeper the slope, the greater the erosion.

C = cover and management. C refers to the amount and type of vegetative cover on the site. Bare, denuded soil will erode much quicker and in greater quantities than soil which maintains adequate vegetation. Humans frequently have a great deal of control over this variable.

P = erosion control practice. P refers to the type of site management in use to protect the land from erosion. Again, humans have a great deal of control here. P is particularly relevant to agriculture in the MRB, because the type of cultivation at a site can influence how much soil is lost from erosion.

Chemical Fate and Transport Modeling

Let's return to the example of DDT in the aquatic environment. Specific modeling can be conducted to determine the fate, residence time and transformation rates of this pesticide. In general, chemical fate and transport modeling will be more complicated than the previous soil loss example. More data are required, and more fields exist within the model that must be addressed. Table 1 gives a partial listing of some of the information required for a chemical fate model, as well as some of the potential model outputs. As the chosen model becomes more sophisticated, it is easy to see how models can help to identify further research needs.

Hydrologic Modeling

Hydrologic modeling is particularly valuable, both from an ecological and urban planning perspective. Environmental managers may want to be able to accurately estimate the quantity and velocity of stormwater run-off. Such capabilities would help in the planning of stormwater conveyance and storage systems.

As urban populations expand, sewer and stormwater infrastructure will need additions and upgrades. Hydrologic modeling can give scientists and environmental planners a picture of how flow volumes will change as more land is cleared and paved. Removal of surface vegetation and subsequent paving creates more impervious area. Surface run-off volumes increase, as stormwater can no longer infiltrate down through the soil. Stormwater storage and conveyance systems need to be designed to accommodate this increased drainage volume.

For practical estimation of rainfall excess or storm run-off volume, numerical representations (models) are required of rainfall and losses or of the relation of run-off to rainfall. Rainfall can generally be calculated with average rain intensity/duration data for the MRB riparian countries. Some common models for estimating storm run-off are:

- Loss (run-off) is a constant fraction of total rainfall in a given time period. If the storm has constant rainfall intensity, loss will be a simple proportion of the total rainfall. The model would use regional run-off coefficient specific to MRB soil types and landforms.
- Constant loss rate, where the rainfall excess is the residual after a selected

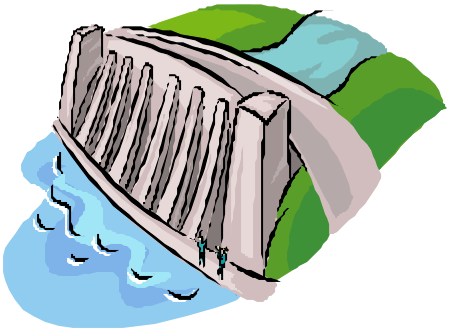
Table 1 Partial data requirements of a chemical fate model

DATA TYPE	SPECIFIC MEASURE
DIMENSIONS OF THE ENVIRONMENT	• Total surface area. • % water cover by area. • Average sediment depth. • Length of coastline.
VOLUME FRACTIONS	• Particles in air. • Particles in water. • Sediment pore water. • Sediment solids. • Fish tissue.
TRANSPORT VELOCITIES	• Sediment deposition. • Leaching from soil. • Sediment resuspension. • Soil water runoff. • Rain rate. • Sediment burial.
CHEMICAL PROPERTIES	• Chemical name. • Water solubility. • Reaction half-lives in water, soil, sediment. • Vapour pressure. • Molecular mass.
MODEL OUTPUTS	• Chemical residence times. • Concentrations in each compartment. • Transfer and transformation rates. • Partition coefficients. • Summary diagram.

constant loss rate or infiltration capacity is satisfied.

- Infiltration curve or equation representing capacity rates of loss decreasing with time.

The choice and validity of a rainfall loss model depends on the type of problem in question, the data available and the run-off processes that are likely to be dominant. Run-off is always dependent upon the length of time since the last rainfall event, and the amount of evapotranspiration that has occurred.



In the MRB, the rainfall run-off relationship is affected by Basin wetness during the rainy season. Natural storage capacities will be reduced during the rainy season, as reservoirs and depressions will be unable to drain for many months. The rate of soil water removal will be dependent on soil type, degree of vegetative cover, slope and season. These are all factors that need to be considered when deciding how to estimate run-off.

Reservoir Sedimentation

Estimating the effects of potential sediment accumulation in hydropower reservoirs is an important element in the planning and design of a dam project. Sedimentation of reservoirs is becoming more of a problem in the MRB, sometimes occurring much sooner than expected. Reservoir sedimentation often leads to:

- A reduction in the useful storage volume for water in the reservoir
- Change in water quality near the dam
- Increased flooding upstream of the dam, due to reduced storage capacity in the reservoir
- Degradation of the stream reach downstream of the dam
- A reduction in the volume of water available for crop irrigation.

Modeling reservoir sedimentation involves several steps. First, a flow duration curve must be calculated, which describes cumulative distribution of the stream run-off passing the dam. Next, a sediment rating curve is developed, which relates sediment concentrations to stream discharge. The sediment rating curve can be obtained entirely by sediment concentration and flow discharge measurements, but this method may not always be adequate. If stream flow is particularly high above a dam, sediment concentrations may be disproportionate to what the sediment rating curve may predict.

Average sedimentation concentration and flow duration can be determined from the two curves. The average total sediment load into the reservoir (by weight) per unit time is calculated with the following formula:

$$q_t = C_i Q_i \; P$$

where,

q_t = average total sediment load in weight per unit time

C_i = sediment concentration per unit time

Q_l = average flow duration per unit time

P = equal divisions of the flow duration curve. For example, the flow duration curve could be divided into 20 equally spaced sections of 5% each

The average total sediment load can be converted into a measurement of sediment load per year. Not all of the sediment passing through the dam section will be deposited in the reservoir because part of the load will pass through the spillway and other diversion flow releases from the reservoir. The relative size of the reservoir, its shape and operation, and the sediment particle size are all factors that will determine the amount of sediment trapped in the reservoir.

Modeling the sediment load in a reservoir can be very useful when selecting a method for reducing sediment accumulation. Some common methods include:

- Reduction of sediment flow through soil conservation. Soil conservation is generally used to reduce sediment yield from a watershed.
- By-passing heavy sediment-laden flows. This is an excellent option if an appropriate by-pass system can be constructed.
- Trapping of sediment with a vegetation screen. Periodic removal of sediment at the trapping site is required to maintain the effectiveness of this method.