Options for Modelling of Transboundary Water Quality

MRC (ENVIRONMENT PROGRAMME AND WUP WG-1)

Prepared by:
William Booty, PhD.
International Water Quality Modeling Consultant

Special Service Agreement No. PP01-144

for
Environment Programme
Mekong River Commission Secretariat

Final Report
TABLE OF CONTENTS

1. Introduction .................................................. 4
2. Transboundary Water Quality Issues ................. 4
4. Modelling Approaches .................................... 5
   4.1 Model Complexity versus Model Accuracy .... 6
   4.2 Deterministic and Stochastic ...................... 6
   4.3 Spreadsheet-Based Models ......................... 7
   4.4 Expert System (Knowledge based) .............. 8
   4.5 Artificial Intelligence (Pattern Recognition) .. 8
   4.6 Bayesian probability networks .................... 9
5. Nutrient Models ............................................. 9
   5.1 DOSTOC Model ........................................ 11
   5.2 NUSTOC Model ........................................ 11
6. Non-point Source Models ................................. 12
7. Toxic Chemical Models .................................... 15
   7.1 Generic Fugacity Model ............................. 15
   7.2 RICEWQ model ....................................... 16
   7.3 AQUATOX model ...................................... 17
      7.3.1 Overview ....................................... 17
      7.3.2 Object-oriented Structure .................... 18
      7.3.3 Temporal and Spatial Resolution ............ 18
8. Environmental Flows Modeling .......................... 19
9. Model Calibration/Verification .......................... 19
10. Decision Support Systems .............................. 19
    10.1 RAISON ............................................. 21
    10.2 Linkage of Water Quantity-Quality models - Halcrow package .... 21
11. Watershed Management Systems ........................ 21
    11.1 BASINS ............................................. 22
    11.2 RiverWare .......................................... 22
    11.3 WEAP .............................................. 23
12. Data and Knowledge Bases .............................. 23
    12.1 Water Quality Data ................................ 23
    12.2 Toxic Chemical Levels in Fish ................. 23
1. Introduction

The Water Utilization Programme (WUP), supported by the World Bank through the Global Environment Facility, helps the member states of the Mekong River Commission (MRC), Cambodia, Laos, Thailand, and Vietnam, implement key elements of the 1995 Agreement on Cooperation for Sustainable Development of the Mekong Basin, including the enhancement and protection of the environment, aquatic life and ecological balance within the basin. The WUP focuses on mechanisms to improve coordinated water quantity and quality management in the basin and by promoting reasonable and equitable water utilization amongst the riparian countries. It is anticipated that much of the forecasting of development impacts on water quality and quantity will be assessed through the use of mathematical models.

Water quality monitoring is carried out under the Environment Programme of MRC. Water quality monitoring (WQMN) was initiated in 1985 (1993 in Cambodia). This program is now undergoing a major review in order to refocus the entire program to ensure that it produces data relevant to the transboundary mandate of MRC. In the meantime, the four riparian countries continue to identify water quality as an important local and transboundary issue. There is, however, a dearth of information on what, exactly, the transboundary water quality issues are or should be, especially as the main stem of the Mekong remains of good quality.

The purpose of this contract is to provide to MRC and national representatives, an assessment of the types of modelling approaches and decision-support tools that may be appropriate for water quality assessment, given the range of issues that may be important and under the data-poor conditions that exist in the basin. The outputs of this contract will be used to guide the development of suitable modelling tools within the modelling platform and toolbox that are now being developed by Halcrow Ltd., under contract to MRC.

2. Transboundary Water Quality Issues

The WUP process has not yet resulted in the identification of specific water quality issues that will require modelling. Therefore, the following represent a range of issues that have potential water concerns in the Mekong River Basin.

- Downstream transport of nutrients from urban centers such as Vientiane (Lao PDR) and Phnom Penh (Cambodia)
- Contaminant impacts (mainly pesticides) on fish, and their downstream transport into Tonle Sap Lake and the Mekong Delta.
- Wetlands management and their interaction with water quality/quantity.
- Behavior of aquatic (including lake) ecosystems under various conditions of water quality.
- Ability to predict transboundary effects from tributary inputs in sections of the Mekong River where the international border runs down the center of the river (Thailand / Laos)
- Long distance transport of nutrients and contaminants, including transport from China, into the lower Mekong basin and the ability to predict the length of river sector where the greatest impacts (water quality, fishery, ecology) are likely to occur.
- Evaluation of land use change, and agricultural expansion or intensification, and their impacts on receiving water quality.
- Environmental flows and ecological health in the main stem of the Mekong River.
• Catchment management and water quality implications.

3. Key Questions for Water Quality Modelling Options

• To what extent do existing databases and knowledge bases limit the application of water quality models in the river basins?
• Which existing models include the processes relevant to the system being studied?
• Which physical, chemical, and ecological processes of these river basin ecosystems need to be understood better in order to further develop existing models or to develop new models?
• What level of accuracy is “good enough” for implementation of water quality policies?
• Is the model to be used for basic scientific understanding of the key physical, chemical and biological processes or is it solely to be used to provide reproducible outputs for given inputs?
• What are the spatial and temporal domains that must be considered?
• What are the relative costs of implementation of the different types of models (i.e. data required for inputs and calibration, public domain model versus private sector, time to implement, computer hardware required, etc.)?

Technical issues include:

• Regional installation of computer and communications technology to support data sharing amongst the various users of the modelling platform.
• Need for point and non-point source loadings data for the selected pollutants
• Standardized laboratory procedures for laboratory analysis of water quality samples
• Fully georeferenced sampling stations
• Availability of suitable water quantity and quality models for forecasting, planning, assessment and watershed management
• Adequate modelling expertise in MRC and at national levels to implement suitable models?

4. MODELLING APPROACHES

The following text provides a brief overview of the technical basis for models. The success or failure of various modelling approaches depends on a good understanding of these technical issues. This is a complex subject and is mainly written for those have some familiarity with modelling.
4.1 Model Complexity versus Model Accuracy

As shown in Figure 1, as the model complexity increases with an increased understanding of the processes occurring in a system, the model accuracy will also increase. However, there is inevitably a level of complexity that is reached where further parameterization of the system no longer provides added accuracy due to less certainty in the understanding of the processes and lack of measured data to calibrate them. In fact, for many models that have been developed for systems that are well monitored and understood, they will fall well to the far right-hand side of the curve in Figure 1 for regions lacking both data and knowledge about the processes. In most cases, the structures of these models are quite rigid and values must be entered as input whether they are known or not. This will ensure that model accuracy remains low.

Figure 1 Relationship of model process complexity to model accuracy

4.2 Deterministic and Stochastic

The majority of water quality modelling designs have focused on the development of simulating physical, chemical, and biological processes through systems of ordinary partial differential equations. These equations can be considered as deterministic if they provide a single response for each set of input variables such as flows, loadings, model parameters, initial conditions, etc. In a stochastic model, the processes are assumed to have an infinite progression of jointly distributed random variables. Most deterministic models usually contain empirical components. These models are very useful in increasing the understanding of how relevant variables change and interact. However, they do not consider model output variability caused by non-deterministic (stochastic sources). The main sources of uncertainty in water quality modelling can be associated with i) relationships among variables determining the behavior of the system (uncertainty of model structure), and ii) values of the
parameters appearing in the identified structure of the model. Sources of uncertainty and variation in natural systems include: site characteristics such as water depth, which may vary seasonally and from site to site; environmental loadings such as water flow, temperature, and light, which may have a stochastic component; and critical biotic parameters such as maximum photosynthetic and consumption rates, which vary among experiments and representative organisms.

In addition, there are sources of uncertainty and variation with regard to pollutants, including: pollutant loadings from runoff, point sources, and atmospheric deposition, which may vary stochastically from day to day and year to year; physico-chemical characteristics such as octanol-water partition coefficients and Henry’s Law constants that cannot be measured easily; chemodynamic parameters such as microbial degradation, photolysis, and hydrolysis rates, which may be subject to both measurement errors and indeterminate environmental controls.

Most deterministic models, which attempt to include uncertainty, use various forms of Monte Carlo techniques. Monte Carlo applications are based on special assumptions about system uncertainty. The differential equations describing the system are solved first using deterministic methods and then these deterministic solutions are “randomized” via Monte Carlo simulations. These models provide stochastic analysis of their deterministic solutions. Usually the mathematical objective is to minimize error and one model is often preferred over another if it can be shown that its error is smaller. So the calibration of a deterministic model reduces to minimizing its stochastic elements.

In a stochastic model, structure is derived to assure that certain statistical properties are preserved such as the probability distribution of the output or perhaps its mean, variance, skewness and serial correlation. The deterministic component of a stochastic model is usually not derived from physical, chemical, or biological processes, as is the deterministic component of a deterministic model. Consequently, stochastic models cannot be used for the same purposes intended for deterministic models. Nevertheless, stochastic and deterministic models have the same general structures because they are both made up of stochastic and deterministic components.

There is now being developed hybrid deterministic-stochastic models, which take advantage of both approaches. For example, the AQUATOX model (Park, 1999a) provides probabilistic modeling by allowing the user to specify the types of distribution and key statistics for a wide selection of input variables. AQUATOX uses a Latin hypercube sampling algorithm, which requires far fewer iterations than a brute-force Monte Carlo sampling. As many variables may be represented by distributions as desired, but the method assumes that they are independently distributed. A lognormal distribution is the default for environmental and pollutant loadings. Other distributions may be selected such as uniform (only 2 values known), normal distribution for well-sampled processes, triangular, etc.

### 4.3 Spreadsheet-Based Models

A spreadsheet does exactly what a computer language does, it lets people program computers. Most simulation models use high-level computer languages such as FORTRAN, Pascal, Visual Basic, C++, etc. The development of such programs can be difficult and time consuming. Models may be developed on standard spreadsheets such as Excel, or they may be developed using specialized software designed for model development based upon spreadsheet design such as Crystal Ball (Comtech) and Facet (Facet Decision Systems).
4.4 Expert System (Knowledge Based)

There are several different levels at which expert systems may be used in water quality modelling. Expert systems may be used to support numerical models through an interface, which supports the selection of a model from a hierarchy of models (Booty and Wong, 1994) based upon the nature of the pollutant, the environmental system being studied and the types of outputs required. An expert system may also be used to support the setup and application of a model, such as in the HSPEXP model (Bicknell et al., 1997). An expert system may also be used to assist in the interpretation of model outputs (Booty and Wong, 1994). At the final level, a fully rule-based simulation model may be developed, such as in the RiverWare (Fulp et al., 2000) and STREAMES.

An expert system contains two basic modules: the Knowledge Base (KB) and the Inference Engine (IE). The expert system requires two types of input data. The first is a set of parameters and their attribute values. There are two types of parameters: discrete and continuous (i.e., real values). Discrete parameters can either be crisp or fuzzy (see below). The parameters describe the domain that the data is in (i.e. water quality characteristics). The second type of input data is a set of rules or cases, which represents the KB. The KB contains the accumulated knowledge of the process (i.e. river nutrient behavior).

When the parameter is defined as fuzzy, each of its attributes has a membership function associated with it. A membership function is simply a function, which maps a single value to a number between zero and one indicating the degree (possibility) of membership. A degree of zero means that the value is not represented by the attribute while a degree of one means that the value is completely representative of the attribute. The type of membership function can be linear, cubic, S-curve (Sigmoid/Logistic) and Pi-curve. The IE is the software that controls the reasoning operation of the ES. The ES also has access to process data and external applications. It also has the ability to perform explanations or justifications through a user interface.

4.5 Artificial Intelligence (Pattern Recognition)

Pattern recognition methods have been used to help establish patterns of water quality. For example, pattern recognition methods have been used to develop a predictive capability and to identify periodicities of the processes, which determine the dissolved oxygen (DO) in rivers using existing DO data. The strength of pattern recognition methods is that they operate on the measured results, not on measurements of the factors that cause these results. Thus, pattern recognition methods are not dependent upon the measurements of the processes determining DO and nutrients, the variability of processes in the river, or the methods used to measure the independent variables.

The apparent weakness of pattern recognition methods is that they do not explicitly consider the factors that produce the results. Consequently, it is difficult to determine the impact of any particular independent variable on the result. For example, the relative importance of sediment oxygen demand, one of the factors in the DO prediction equations, cannot be determined using pattern recognition methods. Consequently, this type of model is best used for answering fixed management questions such as if the loadings of phosphorus are reduced by 25%, what will be the resultant change in phytoplankton biomass. This type of model can be used to predict the potential for eutrophication for example in a wetland along the Mekong River. It cannot be used to predict future changes based upon changes in dependent variables not originally used in the construction of the model.
4.6 *Bayesian Probability Networks*

These models use “Bayes nets”, which are based upon a graphical model, which is an expression by the scientific expert of the functional dependencies (and independencies) for the system of interest. Probability network models (Jensen 1996) maybe used to express uncertain, complex associations among variables using probability analysis. Data and expert judgment are used to probabilistically quantify all linkages. The relationships are quantified using historical data, models, and expert judgment. By incorporating expert judgment, the method is not handicapped by a lack of observational data. The network structure provides an integrated approach to uncertainty analysis, which also allows for easy updating of prediction and inference when observations of model variables are made. This is particularly important when applied to a natural system such as the Mekong River in which additional monitoring is likely to occur concurrent with the modeling effort.

In the following sections are presented summaries of models that are used for a range of typical water quality issues, including nutrients, non-point sources, contaminants and environmental flows. In view of the limited knowledge available for the Mekong system, the following summaries are also intended to draw the reader’s attention to the input requirements, including a suitable knowledge base, that are essential if the model(s) is to perform with reasonable confidence.

5. **NUTRIENT MODELS**

There are many models that have been developed to examine nutrients in rivers, a selection of which is listed below. These are mainly deterministic/stochastic models. Some have expert systems attached to them. Most are highly data dependent and have been developed for northern temperate latitudes.

- **CEQUALRIV1** (CE-QUAL-RIV1 one dimensional river model)
- **CEQUALW2** (CE-QUAL-W2 two dimensional river model)
- **DOSTOC** (Dissolved Oxygen STOChastic model)
- **DSSAMt** (Dynamic Stream Simulation and AssessMent model)
- **HEC5Q** (Hydrologic Engineering Center 5 water Quality)
- **HEC6** (Hydrologic Engineering Center 6 scour and deposition in rivers and reservoirs)
- **MIKE 11** (1-D, dynamic simulation package for simple and complex river and channel systems)
- **NUSTOC** (Nutrient STOChastic model)
- **QUAL2E** (1-D SS temperature and nutrient water quality model for rivers)
- **TOXCHEM** (TOXic CHEMical model)
- **WASP5** (Water quality Analysis Simulation Program)
- **WQRRS** (Water Quality for River-Reservoir Systems)
Before choosing one of these types of models, one must first assess which are the key controlling processes. In many models, phytoplankton biomass dominates and phosphorus is assumed to be the controlling nutrient. In contrast, for nutrient poor rivers the control can be either phosphorus or nitrogen. Investigative studies, such as flow-through mesocosm experiments, are normally required to determine the least number of processes needed to provide accurate predictions of water quality.

Due to the sediment erosion problems identified by some of the riparian countries, the selection of a model should also consider whether it employs sediment transport functions, which would be directly applicable to the Mekong River conditions. For example, in the MIKE 11 model, both cohesive and non-cohesive sediment transport are represented. In the non-cohesive sediment transport module, there are five separate sediment transport capacity functions that may be selected, depending on the characteristics of the river. The module also includes sediment grain size distribution and morphological (with feedback via sediment continuity and bed resistance) functions. Outputs include sediment transport rates, bed level changes, resistance numbers and dune dimensions.

Another point to consider is whether a model has nonlinear terms that will increase the tendency of a system to become chaotic. Many models require that the river flow dynamics be known. In most models both the flow dynamics and time of travel have nonlinear terms in the governing equations. Consequently, even if the water quality prediction model is simplified to linear form, the flow dynamics and time of travel are nonlinear. In this case, as nonlinear terms in the model increase, the “limits of predictability” will decrease. Therefore, the model should only be as complex as is needed, as was shown in Figure 1.

It is unlikely that adequate biological information for the Mekong River Basin will be available to construct a highly mechanistic predictive model, such as those above, concerning the effects of nutrient enrichment on water quality. Baseline information on the biota, their phenology, and spatial distributions is lacking, as well as adequate descriptions of energy flow or rates of biological production. In the absence of these data, it might be appropriate to investigate whether simple empirical models that describe the statistical relationship between response variables (such as algal biomass and/or composition) and independent variables (e.g., total phosphorus, nitrogen, nutrient ratios) could be used to predict the effects of nutrient enrichment.

One major limitation to the development of empirical models is that their predictive power depends to some extent on the range of independent variables. For example, is there a sufficient range of observed values of nutrients to establish statistical relationships with the biota? Also, the time-scale in the response of the biota to enrichment must be taken into account. It is implicitly assumed that in using any existing empirical relationships that they are “robust” with respect to time. The empirical relationships are static, implying that the biotas at a given nutrient concentration are in “equilibrium.” This may not be the case with systems that are being perturbed by nutrients, especially if the organisms considered have long generation times. This time scale problem could play a significant role, not only in applying existing empirical models to the Mekong River basin, but also in developing new empirical models to predict response to nutrient enrichment.

The following two examples demonstrate the complexity that is typical of nutrient models. For the Mekong, one must be quite certain that there is the knowledge base and input loadings data, to ensure that these types of nutrient models can produce reliable outputs. Due to the potentially high level of uncertainty in the results of the models being operated in a
data poor environment, it is particularly important to run models that produce a direct output of model uncertainty. Both the DOSTOC and NUSTOC models provide this information and this is another reason why they have been selected for specific discussion below.

5.1 DOSTOC Model

This is a one-dimensional, steady state model in which all equations describing selected processes are first-order stochastic differential equations with stochastic parameters and random initial conditions. The model determines first and second order moment of:

- Ultimate carbonaceous biochemical oxygen demand (BOD)
- Dissolved oxygen (DO)
- Nitrogen oxygen demand (NOD)

All rate constants, as well as respiration, photosynthesis, and diffuse source loadings are regarded as stochastic processes. The initial conditions upstream in the river and tributaries and the concentrations of BOD, DO, and NOD in the municipal sewage and industrial point sources are considered as random variables. Input data required include the saturation concentration for oxygen, loss rate due to respiration, photosynthesis rate, point and nonpoint source loads of BOD, DO and NOD, BOD decay rate, reparations rate, sedimentation and adsorption loss rate for BOD and NOD decay rate. Simplifying assumptions include:

- Longitudinal dispersion is negligible.
- Velocity is uniform for each river reach.
- Mean values of rate constants and other parameters are uniform for each river reach.
- Mixing is instantaneous and complete.
- DO saturation is temperature dependent only.

All of these will have to be evaluated as to whether they are appropriate for conditions in the Mekong River.

5.2 NUSTOC Model

NUSTOC is another stochastic, one-dimensional, steady state model that predicts organic and inorganic nitrogen as well as dissolved and particulate phosphorus concentrations in river waters. The nitrogen cycle includes decay of organic nitrogen to ammonia, with subsequent nitrification of ammonia to nitrate. The phosphorus cycle has been designed specifically for turbid rivers with conversion of dissolved to particulate phosphorus. Both the nitrogen and phosphorus components include biological uptake via primary producers (macrophytes and algae). Input data required include suspended solids concentration, ammonia oxidation rate, organic nitrogen to ammonia hydrolysis rate, benthos source rate for ammonia, organic nitrogen settling rate, organic nitrogen production rate due to respiration, primary producers respiration rate, fraction of algal uptake as ammonia, inorganic nitrogen uptake due to algal growth, rate of dissolved phosphorus from benthos, particulate phosphorus settling rate, algal uptake rate of dissolved phosphorus, linear partition coefficient, suspended solids settling rate, and growth rate of primary producers. Simplifying assumptions include:

- Dissolved phosphorus concentrations are primarily regulated through uptake by benthic algae and phytoplankton and adsorption to suspended solids.
• The partition coefficient between particulate and dissolved phosphorus is assumed to be linear.
• Settling is the primary mechanism for removal of particulate phosphorus from the water column.
• Decay of organic phosphorus to inorganic phosphate is not included.
• Desorption of particulate phosphorus to dissolved phosphorus is neglected.
• Conversion of organic nitrogen to ammonia and nitrification of ammonia to nitrate can be described by first order decay equations.
• Nitrite is rapidly converted to nitrate and is not simulated.
• Anaerobic denitrification of nitrate to ammonia is not simulated.
• Organic nitrogen can be lost from the water column due to settling.
• Photosynthesis and respiration rates are dependent upon algae/plant biomass and growth rate.
• Algal preference for uptake of ammonia or nitrate can be selected.

Despite the fact that this model was developed for turbid rivers, which is certainly the case for the Mekong River, conditions in turbid rivers of North America may not be the same as those in regions such as Asia. Consequently, the processes may have to be refined to better match these different conditions.

6. NON-POINT SOURCE WATER QUALITY MODELLING

In the Mekong River Basin, a large component of the loads, which input to the river, will be non-point source in nature. At the November 2001, MRC Regional Water Quality Workshop, non-point source issues were assigned an equal priority with point source problems. In order to evaluate the impacts of land use change and agricultural expansion or intensification on receiving water quality, non-point source models have been developed. Examples of these models include:

ACTMO  (Agricultural Chemical Transport Model)
AEAM SHELL  (Adaptive Environmental Assessment and Management Modelling Shell)
AGNPS  (Agricultural Non-Point Source pollution model)
AGSWAMP  (Agricultural Stormwater Analysis And Management Program)
ANSWERS  (Areal Nonpoint Source Watershed Environment Response Simulation)
ARM  (Agricultural Runoff Management)
BRASS  (Basin Runoff and Streamflow Simulation)
CMSS  (Catchment Management Support System)
CREAMS  (Chemical, Runoff, and Erosion from Agricultural Management Systems)
EGEM (Ephemeral Gully Erosion Model)
ELM (Ecosystem Level Model)
EPIC (Erosion/Productivity Impact Calculator)
GAMES (Guelph model for evaluating effects of Agricultural Management systems on Erosion and Sedimentation)
HSPF (Hydrologic Simulation Program - FORTRAN)
LASCAM (Large Scale Catchment Model)
MIKE SHE (MIKE Systeme Hydrologique European)
MULTSED (MULTiple Watershed SEDiment Routing)
NPS (Non-point Simulation Model)
NUTMOD (Daily load and concentration nutrient model)
PTR (Pesticide Transport and Runoff)
RUSLE (Revised Universal Soil Loss Equation)
SHAW (Simultaneous Heat and Water)
SLAMM (Source Loading and Management Model)
SWAT (Soil and Water Assessment Tool)
SWRBBWQ (Simulator for Water Resources in Rural Basin - Water Quality)
USLE (Universal Soil Loss Equation)
USGSREG (USGS REGression method)
WATERSHED (WATERSHED hydrographic program)
WATFLOOD (WATERloo FLOOD )
WEPP (Water Erosion Predicting Program)
WEM (Wind Erosion Model)

**Example:** As part of an integrated watershed management study for watersheds of Southern Ontario, Canada, all available NPS models were evaluated (Bowen et al., 1997). The Agricultural Non-Point Source (AGNPS) model was selected as the most appropriate model and interfaced with a decision support system (RAISON). By linking the model to a decision support system with a user-friendly technical interface, the model can now be applied very efficiently to different types of watersheds and for a wide range of planning scenarios and to evaluate best management practices. The combination is much more useful than just linking the AGNPS to a GIS system. The user-friendly interface has already allowed conservation authorities within southern Ontario to be able to apply the model very quickly and effectively for watershed management studies.

These NPS models have been developed to predict rainfall event-generated runoff, which is the main driving force behind non-point source runoff in temperate latitudes. This situation is
not, however, typical of the Mekong basin where rice production dominates. Here, irrigation water is held for long periods of time before being released by human control, and which has no direct correlation with rainfall events. Consequently, a different type of NPS modelling approach will be required. This may involve the use of empirically derived relationships or rules as the first attempt to provide preliminary modelling capabilities. These models could be operated within a GIS system, a spreadsheet or expert system shell. For example, an approach being used in the STREAMES (Stream Reach Management: An Expert System) project could be used to evaluate the Non-point sources and magnitudes of nutrient (nitrogen and phosphorus) load affecting river reaches of interest. This system has been developed to cerate a tool that will provide the most predictive power with the minimum data requirements. An alternative approach might be to calibrate the RICEWQ model, now developed for toxics runoff from rice production, for nutrient runoff (see #7.2)

The fact remains, however, that there is no “off-the-shelf” NPS model suitable for rice production and will require some research into linkages between rice management and pollutant generation. Other non-irrigated crops can probably be handled adequately with a selection of existing models providing that the input rainfall and elevation data are available.

Several other options exist for estimation of diffuse pollution loading which include unit loads, constant concentration, spreadsheet, statistical, regression and rating curve, and buildup/washoff (Donigian et al, 1995). Unit loads are perhaps the simplest concept, which consist of values of mass per area per time for various pollutants. Empirical models for load estimation can be based upon population density as a predictor of nutrient loads. Relationships may also be developed between nutrients and suspended sediments. The unit load values are, however, statistical abstractions and can include large errors for any specific crop or land area.

Constant concentration assumes that the concentration is constant for a given pollutant, and annual runoff volume can be multiplied by the constant concentration to produce an annual runoff load. The concept is useful because it may be used with any hydrologic models, but using one constant concentration needs careful selection of that value. The spreadsheet may be used to automate and extend the concept of the constant concentration idea. The spreadsheet approach is suited to the estimation of long-term load, but is hard to obtain the variation of predicted loads and concentrations.

The statistical method concept is a derived frequency distribution for expected mean concentration, and has been used extensively for runoff quantity but not much for quality predictions. The regression and rating curve approach is a special form of regression analysis in which concentration and/or loads are related to flow rates and/or volumes. The rating curves obtained from regression analysis of monitoring data may provide reasonable predictions, however, they are notoriously difficult to apply beyond the original dataset from which the relationships were derived.

The buildup/washoff concept involves buildup of pollutants during dry weather and washoff during subsequent storm events. This model may provide adequate comparison of control measures but cannot be used for prediction of absolute values of concentrations and loads without adequate calibration and verification data. Many of these options have been incorporated in computer models to estimate diffuse pollution loading from urban and nonurban areas.
7. Toxic Chemical Fate and Transport Modelling

AQUATOX (general ecological risk assessment model)
ATHMOD (ATHabasca river 2 dimensional toxics fate and transport MODel)
CEQUALRIV1 (CE-QUAL-RIV1 one dimensional river model)
CEQUALW2 (CE-QUAL-W2 two dimensional river model)
CHEMTRN (CHEMical TRaNsport model)
DYNTOX (DYNamic TOXics waste load allocation model)
DYNAMIX (DYNAmic MIXing model)
E4CHEM (Exposure Estimation for potentially Ecotoxic Environmental CHEMicals)
EGC (Equilibrium Criterion mode)
EXAMSII (Exposure Analysis Modelling System)
GFM (Generic Fugacity Model)
MINTEQA2 (Equilibrium metal speciation model)
ONEDIFIN (ONE-Dimensional FINite time model)
PHREEQM (PH-Redox Equilibrium Equations with Mixing)
QWASI (Quantitative Water Air Sediment Interaction)
RICEWQ (Pesticide Runoff Model for Rice Crops)
SARAH (Surface water Assessment model –Reductions in Abiotic Hazardous wastes)
SERATRA (SEDiment-contaminant transport in Rivers-Application to pesticide TRAnsport)
TOXCHEM (TOXic CHEMical model)
TWODIFIN (TWO-Dimensional FINite time model)
UNSTOC (Unspecified substances STOChastic model)
UTM-TOX (Unified Transport Model for TOXicants)
WASP5 (Water quality Analysis Simulation Program)
WQRRS (Water Quality for River-Reservoir Systems)

7.1 Generic Fugacity Model

This model is useful for determining the general behavior and features of new or existing chemicals in the environment. For example, the chemical can be examined to determine into which environmental media it will preferentially partition, the primary loss mechanisms and its tendency for intermedia transport. It can be used for organic chemicals and ions. The required input data are:

- Molecular mass
- Temperature
• Melting point
• Water solubility
• Vapour Pressure
• Log $K_{ow}$
• Dissociation constant
• For ions only, pH of environment
• Reaction half-lives in each medium
• Emission rates for Level III fugacity model

Model outputs include:
• Partition coefficients
• Fugacity capacity and intra-compartment transport values
• Fugacity of the system or of each compartment
• Reaction and advection loss rates
• Concentrations and amounts in each compartment (air, water, soil, biota)
• Residence times

7.2 RICEWQ model

Of the above models, only one has been developed to deal with water quality problems associated with rice production, which is one of the main agricultural activities within the Mekong River basin. The RICEWQ model was developed to deal with the flooding conditions, overflow, and controlled releases of water that are typical under rice production. It simulates pesticide transport from rice paddies based upon water and pesticide mass balance. The water mass balance takes into account precipitation, evaporation, seepage, overflow, irrigation and drainage. The pesticide mass balance considers dilution, advection, volatilization, partitioning between water/sediment, burial in sediment, and resuspension from sediment. The model uses a daily time step, with first order degradation rates. Input data required include the number of pesticides applications, dates of application, rate of application, wash off coefficient, water/sediment partition coefficient, degradation rate in water, degradation rate in sediment, diffusion rate and rate of volatilization. Other inputs include beginning and end dates of simulation, the surface area of the paddy, initial water depth, depth of paddy outlet, seepage rate of paddy, depth to initiate and terminate irrigation, date that the paddy is drained, crop emergence and maturation rates. Sediment properties include initial suspended sediment concentration, settling velocity, resuspension rate, porosity of bed sediment, and bulk density of bed sediment. Weather data include daily precipitation and daily or monthly pan evaporation. The model is extremely easy to use and has been intentionally designed to use input data and validation data that are fairly easy to obtain. This model has been examined and recommended by the U.S. EPA Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) Exposure Model Validation Task Force. However, all validations have only taken place in the U.S. The source code is available under copyright agreement from Waterborne Environmental, Inc.
7.3 AQUATOX model

7.3.1 Overview

The AQUATOX model (Park, 1999a) is a general ecological risk assessment model that represents the combined environmental fate and effects of conventional pollutants, such as nutrients and sediments, and toxic chemicals in aquatic ecosystems. It considers several trophic levels, including attached planktonic algae and submerged aquatic vegetation, invertebrates, and forage, bottom feeding, and game fish. It has the flexibility, as an object-oriented structured model, to operate as a simple model (i.e. as an abiotic flask) or as a complex food-web model. It can be used to model a food web rather than a food chain, for example to examine the possibility of less tolerant organisms being replaced by more tolerant organisms as environmental perturbations take place.

AQUATOX has been designed to be implemented for streams, small rivers, ponds, lakes, and reservoirs. It has been designed to consider various stressors including toxic organic chemicals, nutrients, organic wastes, sediments, and temperature.

The fate portion of the model, which is most applicable to organic toxicants, includes: partitioning among organisms, suspended and sedimented detritus, suspended and sedimented inorganic sediments, and water; volatilization; hydrolysis; ionization; and microbial degradation. The effects portion of the model includes: chronic and acute toxicity to the various organisms modeled; and indirect effects such as release of grazing and predation pressure, increase in detritus and recycling of nutrients from killed organisms, dissolved oxygen sag due to increased decomposition, and loss of food base for animals.

The abiotic and biotic state variables or compartments capable of being simulated in AQUATOX are shown in Figure 2. In the model biotic state variables may represent trophic levels and/or species. The model can represent a food web with both detrital- and algal-based trophic linkages. Driving variables such as temperature, light, nutrient loadings and pH and the state variables are treated similarly in the code, providing flexibility because external loadings of state variables, such as phytoplankton carried downstream into another reach, may function as driving variables; and driving variables, such as pH and temperature, could be treated as dynamic state variables in future implementations. Constant, dynamic, and multiplicative loadings can be specified for atmospheric, point- and Non-point sources.
7.3.2 Object-oriented Structure

The model is written in COM-based Pascal using the Delphi programming system for Windows. In an object-oriented system, an object is a unit of computer code of related variables and methods that can be duplicated; its characteristics and variables can be inherited by higher-level objects. For example, the organism object, including variables such as the $LC_{50}$ and process functions such as respiration, is inherited by the plant object; that is enhanced by plant-specific variables and functions and is duplicated for three kinds of algae; and the plant object is inherited and modified slightly for macrophytes. Inheritance provides a powerful and natural mechanism for organizing and structuring software programs. This modularity allows for higher flexibility of the model and includes the ability to add and delete given state variables interactively.

7.3.3 Temporal and Spatial Resolution

AQUATOX uses differential equations to represent changing values of state variables, normally with a one day time step. A simulation can begin with any date and may be for any length of time from a few days, corresponding to a microcosm experiment, to several years, corresponding to an extreme event followed by long-term recovery.

AQUATOX Version 1.0 is designed with the simplest spatial and temporal resolutions to be a general model for the fate and effects of pollutants in aquatic ecosystems. It is designed to represent average daily conditions for a well-mixed aquatic system. It can represent one-dimensional vertical epilimnetic and hypolimnetic conditions for those systems that exhibit stratification on a seasonal basis. For a large river, it can be modeled one reach at a time.
8. Environmental Flows Modeling

Environmental flows refer to water that is utilized in a river system, or released into it, for the specific purpose of managing ecosystem health. More than 30 countries now use environmental flows as a water management tool. Environmental flows are critical for maintaining the health and subsequently the level of water quality upon which ecosystems and society depend. The timing, quantity, and duration of flows and the quality of the water are inextricably linked and depend upon interactions between the catchments, floodplains, wetlands, ground waters and rivers.

Difficulties encountered in many areas include a lack of basic data, limited understanding of the relationships between flow and the ecological and geomorphologic components of the system, and an absence of adequate studies to demonstrate the outcomes of flow allocations. With the construction of dams on the Mekong, particularly the large ones in China, environmental flows will be a very important issue for the four riparian countries.

9. Model Calibration/Verification

The main goal of developing a model is to be able to simulate measured data for a system being emulated as accurately as possible. The process of improving the fit of the model output to the measured data is called calibration. Calibration typically involves a methodical “tuning” of the model coefficients, to obtain the best statistical goodness-of-fit. This often involves changing the model coefficients through acceptable ranges reported in the literature, or more rarely, using measured values from the system. This should be preceded by sensitivity analyses and followed by an evaluation of sources of model uncertainty or error propagation. Beck (1987) is an excellent reference on these topics.

Of primary interest in the application of models is how the model performs on a substantially different data set (verification data). Unfortunately such data sets are rarely available and there are few references in the literature demonstrating a truly rigorous verification with a complete error propagation assessment. As explained in section 4.1, poor prediction accuracy in complex water quality models is often the norm due to the lack of data to carry out satisfactory calibration and verification procedures. It is the author’s experience that the most useful predictive models are often those that most simply represent the system being modeled. Consequently, models written in a modular format such as in an object-oriented design, would be the most desirable model structure for the Mekong River, where components can be turned on and off depending on the amount and quality of calibration/validation data.

10. Decision Support Systems

An Environmental Decision Support System is a hybrid version of an Environmental Information System. It is designed to help decision makers, managers, and advisors locate relevant information and carry out optimal solutions to problems using special tools and knowledge.

There is a wide range of opinions of what constitutes an environmental information system or an environmental decision support system. One could argue that a database management system could be used as a decision support system for certain applications. Many people
consider Geographic Information Systems as very useful decision support systems. However, comprehensive decision support systems, such as RAISON (Lam et al. 1995), have been designed based upon a knowledge-based approach, which incorporates a hierarchy of tools, as illustrated in Figure 3. By having all of these tools available within a single system and being seamlessly linked to one another, custom applications to a wide range of problems can be easily and efficiently carried out.

It is recommended that the modelling program be developed with the end goal of including all of the models within a decision support system framework. This would provide a seamless system for data and knowledge acquisition, analysis, and presentation. To this end, it would be preferable if the models were built using an object-oriented approach, as most recent decision support system shells (RAISON, Facet, MMS and ESS) have been written in this form.

When developing an environmental decision support system, it is very important to know who the users will be and their expectations and technical levels of comprehension. The best way to do this is usually to build the system from the ground up, by interacting with the user groups during the development process to ensure an appropriate design and to foster interest and ownership of the product. This will be critical I believe for the WUP, with the different MRC member countries involved.

It is critical that the MRC has key personnel in place to adopt this package and implement it.

Figure 3 DSS hierarchy of tools
10.1 RAISON
The RAISON for Windows V 2.0 decision support system is probably the most widely used, comprehensive decision support system for water quality management in North America. Version 2.0 is the latest version of a system that has evolved over the last 15 years at the National Water Research Institute for use by Environment Canada. The component-based RAISON Object System forms the central core of the system. It includes a vector based plus raster GIS system, relational database system, spreadsheet, graphing, statistics, expert system, neural network, optimization and spatial visualization modules. The open architecture allows users to customize the functionality without having to go back to the developers. RAISON has been particularly effective in gaming with “what-if” scenarios and in interacting with the public as an information tool.

The RAISON expert system is a rule-based system with fuzzy logic. As such it may be used for data classification or prediction of data. It may also be used to advise on scientific processes and knowledge limitations (e.g. the choice of models or model coefficients), etc. A generic inference engine is used to organise the rule base and to make conclusions or a course of action such as search the database for further information, display results on maps, or call another expert system (Lam et al., 1995, Booty et al. 1993).

The spatial visualization module contains a number of tools unique to RAISON. They have been designed to effectively group data into classes and to allow the results to be viewed on a georeferenced snapshot.

The ROS contains a number of core G.I.S. objects. These include a spatial object engine, a spatial object engine wrapper, a rendering engine, a projection engine and a coordinate conversion engine. These are used to support the creation of model input data files, for comparing model outputs to ambient measured data from field sampling and remote sensing during the calibration and confirmation phases, and for model output visualization.

10.2 Linkage of Water Quantity-Quality models - Halcrow package
The Halcrow basin modelling package uses an open architecture design. This modular approach should provide the technical tools to provide the synchronization of the temporal and spatial data concerns for the models. A three-level user interface is being developed to provide the system user with access to the levels of tools they require. The knowledge base is used to store all of the data required for model inputs and model outputs. These are then available to the other models. The system is currently designed to allow a wide range of model formats. The interfaces have been created with Visual Basic and new interfaces for additional models should be able to be quickly implemented.

Models can be incorporated into the system by: (a) using the executable codes as given through appropriate interfaces for the model input and output, (b) emulating the model by a simplified version such as an input-output model, and (c) by converting the code to a programming language (e.g. Visual Basic) that can be run directly within the Windows environment.

11. Watershed Management Systems
There are specialized watershed management and modeling systems that have been developed in the United States such as BASINS, RiverWare, and WEAP, which may, in the future, be of use for watershed management considerations within the Mekong River basin.
11.1 BASINS

BASINS (Better Assessment Science Integrating Point and Non-point Sources version 2.0 (EPA, 1998)), is designed to assist watershed and water quality analysts and modelers in identifying key problem areas, analyzing spatially distributed point source and water quality data, and facilitating model setup and analysis of the output. Written in the Avenue scripting language, and run in the ArcView Geographic Information System (GIS) program, BASINS contains automated scripting functions to import and/or manipulate local data, run data analyses, create data reports, and populate models with georeferenced data. The three models in BASINS simulate water quality and/or Non-point source runoff, are automatically populated with BASINS GIS data, and come with Windows interfaces to facilitate the formatting of the remaining model input requirements. Toxiroute is an in-stream steady state flow and load, first order decay, screening model. QUAL2E simulates in-stream steady state flow and load for nutrients, algae, DO/BOD, temperature, fecal coliform, and user defined constituents and is the legacy model for point source permits for low flow conditions. The Non-point Source Model (NPSM) interface to Hydrologic Simulation Program Fortran (HSPF v.11) dramatically shortens the time to an initial watershed model simulation. NPSM/HSPF simulates dynamic point and Non-point source loads for nutrients, sediments, tracers, DO/BOD, temperature, algae, and user-defined constituents.

The GIS data in BASINS are all of conterminous U.S. scope, processed from the original data owner’s format to ArcView shape file format, and cut by watershed and U.S. EPA region for delivery on the web and CD, respectively. BASINS’ 32 data layers cover physical landscape features, base cartographic data, pollution sources, and environmental modeling data. All data layers supplied in BASINS are open to the user to manipulate with standard ArcView functions, customized BASINS scripts, user-derived Avenue scripts, and other programs.

Although this system has been used outside of the U.S., it requires a substantial amount of spatial, meteorological, hydrological and chemical monitoring data to operate. It is recommended that it is not appropriate for use in the Mekong River Basin at this time due to the lack of the extensive spatial and temporal data required. Model output uncertainties would be extremely high.

11.2 RiverWare

The Watershed and River System management Program, which is sponsored by the U.S. Bureau of Reclamation’s Science and Technology Research Program and the U.S. Geological Survey’s Water Resource Division, supports development of decision support systems to assist water resources managers. RiverWare is an object-oriented reservoir and river system modeling framework developed by the Center for Advanced Decision Support for Water and Environment Systems (CADSWEES) at the University of Colorado. It utilizes the Modular Modeling System (MMS), which was collaboratively developed by the USGS and CADSWEES. MMS provides pre-processors to access and prepare data, a library of models and modules to simulate hydrologic ecosystem processes and post-processors to display and analyze results. Applications have involved rule-based simulation, optimization of reservoir operations, river and reservoir water quality, stochastic hydrology, hydrologic routing algorithms and surface water/groundwater interactions. It is uncertain whether this type of system is required as a component of the WUP. It requires licensing of the software and consulting services for database and model development by Hydrosphere Resource Consultants, Inc. Development and application costs would be substantial. The Halcrow
modelling package should provide adequate support for models that will be required for the WUP.

11.3 WEAP
WEAP (Water Evaluation and Planning System) is a microcomputer tool for integrated water resources planning. It operates on the basic principle of water balance accounting. It consists of a schematic module with GIS tools for configuring the system, a data module that allows for the creation of variables and relationships through a link with Excel, a results module for flexible display of all model outputs as well as an overview module to collate results. It has been developed through the Stockholm Environment Institute with significant enhancements by the Hydrologic Engineering Center of the US Army Corps of Engineers and with project support from the UN, World Bank, USAID and the Global Infrastructure Fund of Japan. It is suggested that this system may be very useful for the MRC in which to run spreadsheet based water quality models that may be developed as part of the WUP. Its ability to link with other water quality models is uncertain. It also does not contain higher-level knowledge-based tools as found in other systems such as RAISON.

12. Water Quality Knowledge Base Information for the Mekong River Basin
The following section refers to key limitations of the current data and knowledge base for the Mekong River system insofar as model application is concerned.

12.1 Water Quality Data
The MRC water quality database analysis carried out by E. Barrios for the MRC in 2001, points out that there are nutrient and other basic cation/anion data that have been measured in the 4 riparian countries.

Except for high sediment concentrations, no obvious water quality problems appear to be documented in the main stem of the Mekong at this time. Concerns include potential increases in nutrient loadings, salinity problems, urban wastes, and agricultural pesticides.

The current database does not contain water quality data that would be required to calibrate deterministic toxic chemical fate and transport models.

The current database does not contain sufficient information to allow for the development of stochastic relationships for toxic chemicals.

12.2 Toxic Chemical Levels in Fish
Concentrations of persistent organochlorines (OC’s) such as PCBs, DDT’s, HCH, chlordane compounds and HCB have been determined in 27 species of marine and freshwater fish collected in Cambodia. Comparison with levels in other Asian and Oceanic regions show that Cambodia has one of the less-contaminated ecosystems (Monirith et al., 1999). Freshwater fish showed higher concentrations than marine, suggesting its usage for agriculture. It would appear that, except for perhaps some possible hot spot that may exist, that there is no current concern about levels of OC’s in fish of the Mekong River in Cambodia.
12.3 Loadings Data

12.3.1 Nutrient loads (point and non-point)
Currently there appear to be no programs in place within the 4 riparian countries to calculate point or non-point source loadings of nutrients within the Mekong River basin.

12.3.2 Persistent Organic Pollutants
Currently there are no programs in place within the 4 riparian countries to calculate point or non-point sources of persistent organic pollutants within the Mekong River basin. It is not known if there is a pesticide inventory in any of the countries, which would be useful for estimating applied pesticide loads.

12.3.3 Salts
Currently there appears to be no programs in place within the 4 riparian countries to calculate point or non-point sources of salts within the Mekong River basin.

12.4 Process Knowledge

12.4.1 Nutrient Cycling
Currently, there appears to be little research data on the key nutrient processes taking place in the Mekong River system. For example, it is unknown whether the river system and its wetlands are nitrogen or phosphorus limited, or if there is a seasonality to N or P limitation, or if there is alternating N and P limitation at different times of the year.

Although chlorophyll is the only means currently being used to directly measure phytoplankton biomass, it is well known that the chlorophyll-to-carbon ratio in phytoplankton varies by about a factor of 5 depending on the ambient light and nutrient levels. The use of eutrophication models as the basis for examining the transport and fate of toxic substances in lakes and wetlands requires specification of the amount and forms of organic carbon present.

12.4.2 Energy Pathways
Baseline information on the biota, their phenology, and spatial distributions is lacking, as well as adequate descriptions of energy flow or rates of biological production. There is a lack of any real research on the food chain of the Mekong River, which would be basic information required in risk assessment water quality modeling.

12.4.3 Kinetic Rates
Observational data for the Mekong River are extremely limited. Rates manuals have been published, such as Bowie et al. 1985, but these are based mostly on North American and European data, most of which will not be appropriate for use in models being applied to the Mekong River.

12.5 Spatial data
The DEM’s are currently 40-meter resolution, which need to be improved for very flat terrain such as exists in the delta. There is no land use mapping data newer than 1989 for Cambodia.
There are Radarsat images for 1999-2001 showing inundation along the Mekong River. Soil maps exist for Thailand and Vietnam. The soil maps for Laos are said to require significant corrections before they can be used. In Cambodia, the only coverage that exists seems to be for areas around Tonle Sap. The maps are only at either 1:500,000 or 1:1,000,000. The MRCS Integrated Database is now being developed with final integration of all current databases starting in Jan. 2002. This should eventually provide easy access to available data required for all modelling activities.

13. Conclusions

13.1 Nutrients and Dissolved Oxygen

- The current water quality data available in the MRCS database indicates that there currently is no significant nutrient problem for the mainstem of the Mekong River. Only during low flow conditions (Jan.-Mar.), in backwater wetland areas, do algal concentrations increase to cause taste and odour problems. Dissolved oxygen levels appear not to drop to levels sufficient to cause harm to fish. However, in areas such as Chau Doc in the delta, dissolved oxygen levels may drop to unacceptable levels during low flow due to excessive nutrient loadings from the city and possibly from upstream aquaculture.

- One of the critical inputs required for all nutrient models is loadings (point and non-point). At this point, there are no calculated loadings available to drive the models.

- There is very little to no scientific knowledge available for providing rate coefficients typically required by standard nutrient models. Investigative studies like flow-through mesocosm experiments are normally required to determine the least number of processes needed to provide accurate predictions of water quality and to determine the kinetics of the processes.

- While it is clear that modelling activities are to focus on general management and policy issues, the types of models normally used mainly require research inputs for kinetics, etc., MRC will have to decide if it requires such models enough to merit the kind of research that would be needed to fill critical knowledge gaps.

- Due to the very large amount of missing data required to set up and calibrate a deterministic nutrient water quality model such as QUAL2E, the expected uncertainties in the model outputs can be expected to be quite large. The high level of modelling expertise required to run this model effectively may not be available.

- Current water quality data does not support more than a 1-dimensional study of any of the river segments for nutrients.

- Typical North American non-point source models are not likely to be suitable in their current forms for application within the Mekong River Basin due to the very different agricultural practices, such as those for rice production. These will require extensive modification or new model development.

- There appears to be a significant amount of local knowledge on the behavior of the Mekong River ecosystem that could be captured within an expert system framework.
13.2 Salinity

- Salinity issues have been modelled in the Mekong delta and are quite well understood. Salinity models are widely available and can be easily integrated into the WUP modelling package. A hindcasting approach could be used in which a simple salinity model is run backwards, using some transboundary upper threshold criteria, and estimating how much current concentrations would have to rise at various upstream locations in order to reach the threshold level.

13.3 Toxic Chemicals

- The very limited amount of measured data for toxic chemicals in the Mekong River Basin will prevent the application of anything but a screening level model to be used initially within the WUP water quality modelling DSS. Very significant levels of error would be expected using detailed deterministic models such as WASP5. The cost to obtain the necessary data would also be quite high. As there appears to be little problem with toxicity in the main stem of the Mekong, a toxicity model per se is not recommended. MRC might wish to focus more on developing the knowledge base, especially on pesticide loadings and fish impacts, both to define the nature and extent of the situation, and as input data that will be required if, in the future, a toxicity model is requested.

13.4 Decision Support Systems

- When developing an environmental decision support system, it is very important to know who the users will be and their expectations and technical levels of comprehension. The best way to do this is usually to build the system from the ground up, by interacting with the user groups during the development process to ensure an appropriate design and to foster interest and ownership of the product. This will be critical for the WUP, with the different MRC member countries involved. A ground-up development approach can be accomplished within the framework of some existing decision support software such as RAISON.

- It is critical that the MRC has key personnel in place to adopt this package and implement it. This should provide technical modelling capacity for the Mekong.

13.5 Environmental Flows

- The very large impact of the wetlands within the Mekong River Basin on the filtering of nutrients and toxics needs to be considered. The sustainability of the wetlands may be modeled using environmental flows modelling techniques, however this type of modelling is not well advanced and requires a knowledge base that does not yet exist for the Mekong.

14. Recommendations

The following are recommended approaches to various issues that may be considered by the WUP and some of the key inputs that will be required.

However, the most important factor is that the WUP must decide first what water quality issues are to be included in the modelling package. This is not something that this consultant is able to resolve; therefore the following recommendations are descriptive and not prescriptive.
A second general recommendation is that MRC will have to make some hard decisions on the linkage between model selection and knowledge development (research) that will be required to operate the selected models appropriately. It is recommended that a group of experts be used to establish the linkage and recommend to MRC options for implementation both of the model and of the steps to acquire the knowledge base.

14.1 Nutrients and Dissolved Oxygen

- Given the current level of data and knowledge available, simple empirical or stochastic dissolved oxygen and nutrient water quality models such as DOSTOC (Zielinski, 1988) and NUSTOC (HydroQual Consultants Inc. and Gore and Storrie Ltd., 1989) should be run first, as part of a hierarchy of models that can be used for the WUP.
- Attempts must be made to determine loadings of nutrients to the system in order to be able to carry out mass balance modelling for the river.
- The AQUATOX model, because of its modular design, would be a very useful risk assessment model for implementation within the WUP water quality-modelling package. As data and knowledge become available, additional processes may be turned on in the model.
- Pattern recognition software may be used to quickly build up empirical relationships between the nutrient water quality parameters.

14.2 Salinity

- The current water quality model contained within the Halcrow Group modelling package is capable of dealing with salinity issues. There has also been a model developed in Vietnam to deal with salinity intrusion issues in the Mekong Delta caused by tidal effects during low flow conditions (Nguyen, K.D. et al., 1998). This is a transboundary issue as these intrusions can travel well up into Cambodia.

14.3 Toxics

Given the lack of any apparent toxicity problem in the main stem of the Mekong, a basin wide toxicity model is not recommended. However, locally, some problems may exist and the following should be considered.

- A fugacity model (Mackay et al. 1983a,b, Mackay, 1991) may be useful as an initial screening model to determine the fate of toxic chemicals within the Mekong River.
- In the few areas where point source loadings are available that discharge directly to the Mekong River, an ambient mixing zone model may be used to determine the distance downstream to achieve complete mixing and the concentrations in between. This approach can also be used in situations where cross-border situations exist as between Thailand and Laos.
- Pattern recognition software probably cannot be used to build up empirical relationships between the water quality parameters due to the very limited amount of measured data. This is also the case for its use in filling in data gaps.
- If a toxic risk assessment approach is required, then the AQUATOX model, because of its modular design, would be a very useful risk assessment model for implementation within the WUP water quality-modelling package. As data and
knowledge become available, additional processes may be activated in the model, such as bioaccumulation of contaminants in selected species in the Mekong River.

14.4 Environmental Flows

- In order to evaluate environmental flows in the Mekong Basin, an environmental flows decision support package similar to that developed for the Murray Darling Basin in Australia (Booty et al. 2000) could be considered as a component of the WUP. While the lack of detailed data and knowledge will be a serious handicap to practical implementation in the near term, a decision to use this type of approach would require that a basic framework be established. The framework will then accommodate the knowledge as it is generated.

14.5 Decision Support Systems

- It is recommended that the modelling program be developed with the end goal of including all of the selected models within a decision support system framework. This would provide a seamless system for data and knowledge acquisition, analysis, and presentation. To this end, it would be preferable if the models were built using an object-oriented approach, as most recent decision support system shells (RAISON, Facet, MMS and ESS) have been written in this form.

15. Overall Water Quality Modeling Matrix

In Table 1, some of the key models discussed in this report are summarized with respect to their applicability to water quality modeling in the WUP.
**TABLE 1: Selected water quality models and their applicability to the WUP.**

<table>
<thead>
<tr>
<th>Issue</th>
<th>Possible Modelling Approaches</th>
<th>Time Domain</th>
<th>Spatial Domain</th>
<th>Input Data Requirements</th>
<th>Suitability with existing data</th>
<th>Assumptions</th>
<th>Decision Support Options</th>
<th>Precision vs Cost Factor</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient downstream transport</td>
<td>QUAL2E</td>
<td>Steady state</td>
<td>1-D</td>
<td>River reaches, BOD, N,P, DO, coliform, etc.</td>
<td>Low</td>
<td>Best suited for point sources of pollution that do not have transient properties</td>
<td>Fortran program, not object oriented design</td>
<td>Low</td>
<td>Available from U.S. EPA</td>
</tr>
<tr>
<td>Toxic chemical fate and transport, Considers tidal effects</td>
<td>Organic Chemical Pathway and Fate Model</td>
<td>Dynamic</td>
<td>1-D, 2-D</td>
<td>Loadings of particulate and dissolved organic chemicals, river flows, and tides</td>
<td>Medium</td>
<td>Based on partition coefficient, biodegradation, photodegradation, settling, flows and tidal cycles</td>
<td>Fortran – not object oriented design</td>
<td>High</td>
<td>Environment Canada, National Water Research Institute</td>
</tr>
<tr>
<td>Wetlands management</td>
<td>Environmental Flows</td>
<td>Dynamic</td>
<td>2-D</td>
<td>Flows, water stage, rules</td>
<td>Low</td>
<td>Based upon expert rules</td>
<td>Operate with fuzzy expert system</td>
<td>Medium</td>
<td>Develop using expert system shell such as RAISON</td>
</tr>
<tr>
<td>River dissolved oxygen</td>
<td>DOStOC</td>
<td>Steady state</td>
<td>1-D</td>
<td>River reaches, flows, phosphorus and nitrogen loads</td>
<td>High</td>
<td>Stochastic application of Streeter-Phelps equations</td>
<td>Fortran program, not object-oriented</td>
<td>High</td>
<td>Obtain from Alberta Environment</td>
</tr>
<tr>
<td>River water quality (nutrients)</td>
<td>NUSTOC</td>
<td>Steady State</td>
<td>1-D</td>
<td>Stream reaches, flows and chemicals</td>
<td>High</td>
<td>Stochastic</td>
<td>Fortran program, not object oriented</td>
<td>High</td>
<td>Obtain from Alberta Environment</td>
</tr>
<tr>
<td>Lake water quality (toxics)</td>
<td>AQUATOX</td>
<td>Dynamic</td>
<td>1-D</td>
<td>Loads, system geometry</td>
<td>Medium</td>
<td>General ecological risk assessment</td>
<td>Object oriented design</td>
<td>High</td>
<td>Obtain from U.S. EPA</td>
</tr>
<tr>
<td>Transboundary mixing zones</td>
<td>Ambient mixing zone model</td>
<td>Steady state</td>
<td>1-D</td>
<td>River geometry, stream flow, effluent load</td>
<td>High</td>
<td>No discharge-induced mixing</td>
<td>Fully integrated</td>
<td>High</td>
<td>U.S. EPA</td>
</tr>
<tr>
<td>Non-point sources and BMP’s</td>
<td>AGNPS</td>
<td>Event based</td>
<td>1-D</td>
<td>23 parameters, of climate, soil, topography, chemical and land management</td>
<td>Medium</td>
<td>SCS, MUSLE, sediment associated chemicals, GIS linkage</td>
<td>Fully integrated with RAISON</td>
<td>Low-Medium</td>
<td>Obtain from USDA</td>
</tr>
<tr>
<td>Toxic chemical fate</td>
<td>QWASI</td>
<td>Steady state Dynamic</td>
<td>1-D</td>
<td>Emissions, physical-chemical properties</td>
<td>Medium</td>
<td>Partitioning a function of fugacity capacity of each chemical</td>
<td>Basic program which may run within RAISON</td>
<td>Medium-High</td>
<td>Canadian Environmental Modelling Centre</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>----------</td>
<td>----------------------</td>
<td>--------------</td>
<td>-----------------------------------------</td>
<td>--------</td>
<td>---------------------------------------------------------------</td>
<td>-------------------------------------------</td>
<td>-------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Nutrient/Toxic transport and fate</td>
<td>WASP5</td>
<td>Dynamic</td>
<td>1-D, 2-D, 3-D</td>
<td>Loads, boundary conditions, mass transfer rates, kinetic rates, segment parameterization</td>
<td>Low</td>
<td>Generalized model structure to allow site specific application</td>
<td>Fortran code, run as stand alone program</td>
<td>Low</td>
<td>U.S. EPA</td>
</tr>
</tbody>
</table>
16. Mission Summary

On November 19th, 2001 Dr. Booty arrived at the Mekong River Commission Headquarters in Phnom Penh at approximately 1:30 PM. Dr. Booty met with Dr. Anders Thuren (Programme Manager, Environment Division, MRC) and Dr. Ed Ongley (International Consultant) to go over the terms of reference for the water quality modeling assessment study for the WUP. One with Mr. Nguyen Than Tin followed this meeting to go over the practical aspects of the mission activities of Dr. Booty.

Later on the afternoon of Nov. 19th, Dr. Booty met with Dr. Ian Campbell (Senior Environmentalist) to discuss a wide range of ecosystem concerns in the Mekong Basin.

On the morning of Nov.20, 2001 Dr. Booty met with Dr. Riad Al-Soufi (Senior Specialist, Technical Support Division, MRC). This meeting was very informative in providing general background information on previous and ongoing environmental studies (i.e. Finnish study on Tonle Sap lake) at the MRC. Following this meeting, Dr. Booty met with Dr. Jon Wicks, who is a software integration specialist with Halcrow consultants. This meeting was very important in understanding the structure of the Halcrow modeling package, which will be used to link water quantity models with water quality models. Dr. Wicks gave Dr. Booty a demonstration of the Halcrow Basin Modeling Package, pointing out the 3 different interfaces levels, the hydrologic and hydraulic models, as well as a water quality model that is already implemented in the system that considers conservative parameters, salinity, temperature, DO, BOD, and pH.

On the afternoon of November 21, 2001, Dr. Booty accompanied Dr. Ongley, Mr. Tin and two representatives of the Ministry of Water Resources and Meteorology, Department of Hydrology and River Works, Water Quality Analysis Office to 2 wetland areas used to treat municipal sewage from Phnom Penh. It was noted that local farmers were harvesting morning glory directly downstream from the sewage pumping station and that it is then sold in the market.

On the morning of Nov. 22, 2001, Dr. Booty met with Mr. Chin Samouth (Programme Officer, Environment Division, MRC) in order to discuss different aspects of wetlands in the Mekong River Basin. Dr. Booty was shown maps that had been developed for inventories of fish, wildlife habitats, and wetland coverage maps. Mr. Simouth indicated that there still needs to be a baseline study done to look at loads to wetlands.

The next meeting was a general meeting of the WUP working group, headed by Mr. Chaiyuth Sukhsri (WUP-Team Leader). Dr. Booty answered questions put forward by the group with respect to the water quality modeling options that would be considered and how they would fit into the Halcrow modeling package. This meeting was immediately followed by one with Mr. Dirk Vanderstighelen (Senior System Analyst/ Database Administrator, Technical Support Division, MRC). This meeting was important to determine what spatial data was available to support Non-point source water quality modeling. Dr. Booty was particularly interested in land use/cover, soil type, and digital elevation maps. Land use/cover maps based on 1992-93 surveys have been developed for the entire basin at a scale of 1:250,000. Soil type maps exist at a scale of 1:250,000 for parts of Thailand, Vietnam and Lao PDR only, with significant errors that need to be corrected for Lao PDR. The current DEM does not have small enough spatial scale to use effectively for detailed Non-point source modeling. This is particularly important in the lower Mekong River delta, which only has several meters of elevation variation. A wetlands layer is currently being completed at a scale of 1:250,000 that covers the Mekong corridor in Lao and Thailand and the delta. Mr. Vanderstighelen also pointed out that he is about to implement the integrated database (MRC-Information System),
which will provide a regional information system for the riparian countries. This will be very useful in providing data to support the water quality modeling program.

On the afternoon of Nov. 22, 2001, Dr. Booty met with Dr. Chris Barlow (Senior Programme Officer, Fisheries Programme, MRC). Dr. Barlow pointed out the enormous economic value of the fisheries in the Mekong. He pointed out the very important part the flood pulses play on fish migration in the Mekong River system. Dr. Barlow indicated that there was a lack of any real research on the food chain of the Mekong River, which would be basic information required in risk assessment water quality modeling.

On the morning of Nov. 26, 2001, Dr. Booty met with 14 members of the LNMC to discuss the WUP water quality modelling issues that exist in Lao PDR. The LNMC have set up a modelling team, who at this point are only involved with hydrologic modelling. They have responded to a questionnaire sent to them by Halcrow concerning water use in Lao P.D.R. for such things as irrigation, hydropower, drinking water, etc. It was mentioned that they considered sediment erosion such as bank erosion as a serious issue. It may have some relationship to water quality issues but these were not specified. At the current time there are only 2 MRC stations that collect data on sediment on the main stem. It would be useful to have some suspended solids analyses carried out in order to determine the size fractions and the chemical characteristics for water quality modelling, such as fractions of inorganic and organic carbon, and sediment density. The same information is also required for riverbed sediments.

It was pointed out that turbidity is very high during the wet season. During low flow conditions in Lao PDR, rural areas have serious drinking water quality problems. These are due to high levels of nutrients and algae in the water.

At the meeting it was pointed out that in a town about 70 km north of Vientiane, water quality analyses were carried out using portable water quality kits. During March of 1998, poor water quality conditions were noted, possibly due to fertilizers and pesticides being used. Therefore it was suggested that samples be collected for analysis at a certified laboratory to verify this issue. Currently only the Ministry of Public Health carries out urban water quality testing.

There have been reports of fish kills near the border with China but no industrial type parameters have been measured during these events.

During the afternoon of Nov. 26, 2001, Mr. Keomany Luanglith (Project officer, WRDD) and Ms. Sonephet Phosalath (Hydrologic Engineer, LNMC) took Dr. Booty to visit one of the wastewater treatment ponds for Vientiane. There are two sets of 3 treatment ponds. Final discharge is to wetlands that are approximately 6 km from the Mekong River. Discharge BOD is apparently now down to 60 mg/L from an earlier 200 mg/L. Funds of $1.5 M US were obtained to deal with other household loads that still enter the wetlands without control. It was pointed out that better laboratory support would be required to deal with the wetlands improvements studies.

It is very clear that at the moment there is no way to directly measure the discharge from the wetlands to the Mekong. This Non-point source of potential nutrients and toxics from the Vientiane area could be a transboundary issue. Dr. Booty mentioned that there are models available, such as PREWET, which have been designed to estimate the amount of pollutant treatment provided by wetlands that the planning departments could use.

On the morning of November 27, 2001, Mr. Keomany Luanglith and Ms. Sonephet Phosalath escorted Dr. Booty to two industries in Vientiane that discharge effluent to the Mekong River. The first industry was the Asia Paper Mill Factory Co., Ltd. The manager, Mr. Lin Fu-
Lin, gave a summary of the operation of the plant, which is a recycling operation only. The process does not use any bleaching agents or dyes. The main chemical used is Al SO₄. The current effluent flow is 100 m³/day with a BOD of 82 mg/L and a TSS of 54 mg/L. The company has been ordered by the Dept. of Irrigation to now reduce the effluent concentrations to 30 mg/L for BOD and 32 mg/L for TSS. This will be accomplished by reducing the output from the factory, reducing the work force from 100 to 50 people.

The second industry visited was the Suh Hyun Tannery Lao Co., Ltd. The company manager, Mr. Kommanivanh, provided details on the operation of the plant, including a list of 19 chemicals used. The effluent discharge to the Mekong River is 15-20 m³/day. Mr. Kommanivanh was not aware of the BOD, TSS, or pH of the effluent. Key chemicals used include sulphuric and formic acids, ammonium sulphate, sodium metabisulphate, sodium hydrosulphide, sodium sulphide, soda ash, ammonium chloride, hydrogen peroxide, and a number of chemicals used as fungicides (i.e. Eurocide XL-2), and trademarked cell-expanding chemicals such as Truponat LA, Trupozym CN and Trupozym CH.

Due to the very small effluent discharge volumes from the above plants, they would not be expected to cause any transboundary water quality problems in the mainstem Mekong River, which has an average discharge of 14,000 m³/s.

On the afternoon of Wednesday Nov. 27th, 2001, Dr. Booty flew from Vientiane to Luang Prabang, Lao PDR to join the Regional Water Quality Workshop.

On Wednesday Nov. 28th, Dr. Booty took part in a field trip to visit the Bane Korvane irrigation project, and then a boat trip down the Mekong River from Tham Ting Cave to Luang Prabang. During the boat trip, it was observed that there is very little wildlife (birds, mammals, etc) along the river. This is probably due to the lack of macrophytes and other plants along this stretch of the river, which would be needed to support this kind of wildlife.

On Thursday Nov.29, 2001, took part in the WQ workshop. Key points noted during the day include:

- Currently there are very few measurements of industrial discharges in the Mekong River Basin.
- Need to establish transboundary locations for benchmark water quality.
- Possibly consider carrying out hindcast modelling for nutrients and salinity.
- In Vietnam, water quantity (hydrology, hydraulics) is the major controlling factor for water quality, including salinity and acidity issues.
- In Thailand, they wish to look at the whole basin and then select specific parameters for water quality modelling issues.
- Thailand suggested that more basic research needs to be carried out to support the water quality modelling as well as the development of biological and chemical indicators.
- Non-point sources of pollutants appear to be the most important sources in many regions.

Dr. Booty gave a presentation on water quality modelling options for transboundary water quality issues under the WUP. It was pointed out in the following plenary discussion that Dr. Booty’s mission was to provide recommendations on water quality modelling approaches to deal with the water quality issues being provided by the 4 riparian countries. This did not
mean that final, specific models would be recommended, as many of the water quality issues are still not well defined. However, a number of possible models to deal with specific issues were provided for consideration. These included two stochastic models, the DOSTOC model for dissolved oxygen, and the NUSTOC for nutrient cycling. A hybrid deterministic-stochastic general water quality risk assessment model such as AQUATOX was recommended and a fugacity screening level model for toxic chemicals. It was also pointed out by Dr. Booty that because the AQUATOX model is written in an object oriented language, it is possible to modify the model to match the level of model process complexity that can be supported by the current data and knowledge bases.

During discussions with members of the Vietnam MC (Mrs. Nguyen Thi Ky Nam, Mr. Pham Gia Hien), it was pointed out that the VNMC office in Hanoi had already acquired a copy of the AQUATOX model. However, it had not yet been applied to water quality issues. They also pointed out that there had also been a substantial amount of modelling carried out to examine salinity issues in the delta area of Vietnam.

Dr. Booty met with Mr. Sideth Muong, who is a project officer with the Cambodia Ministry of Environment. He is currently working towards a Ph.D. and is developing a decision support system for urban wastewater management strategies in Phnom Penh. He was in Luang Prabang to give a paper at a wetlands workshop. He is hoping to obtain assistance from the MRC in obtaining data required to support his modelling work. It is suggested that this research may be a very useful addition to the WUP and Environment Program in developing additional water quality modelling capacity.

On Dec. 01, 2001, Dr. Booty traveled from Luang Prabang to Vientiane. The next day Dr. Booty flew to Phnom Penh and then on to Ho Chi Minh City to begin a tour of the Mekong Delta.

On Dec. 02, 2001, Dr. Booty joined Mr. Nguyen Thanh Tin (MRC) and Mr. Nguyen Ngoc Vinh (Deputy Head of Station Network Division, Southern Region Hydro Meteorological Center, KTTVN) in Ho Chi Minh City for a 2 day trip down into the delta region of Vietnam. During the trip, most of the major Mekong River delta branches (Hau River, Tien River) were observed, including a large number of man-made channels built to divert water to the southwest in the Kien Giang and An Giang regions. In Chau Doc it was very clear that there was a significant amount of nutrient loading to the Bassac River (surface foam and odour). There is direct discharge of untreated sewage to the river from Chau Doc, which has a population of approximately 100,000. There are also extensive fish aquaculture operations along the banks of the river. These operations are predicted to expand by approximately 2-3 times by 2010 (Tien, P.V., 2001). It is very likely that DO levels in the river will decline to levels of concern for fish survival during low flow conditions.

It was observed during the trip through the delta region that the entire lengths of all of the roads are occupied by dwellings, which are built out over the canals. All of these dwellings discharge human and household waste directly into the waterways. Adjacent to these are the fields with rice and animals such as water buffalo, pigs, etc. All of these are adding significant loadings of nutrients, bacteria, parasitic organisms, and other household wastes to the waterways. It is possible to estimate these loads using basic census information and standard household/farm operations data that is known about these types of sources. These data can be combined with the measured flow data being collected in the region in order to model concentrations of DO, nitrogen and phosphorus compounds in the canals and branches of the Hau and Tien rivers. Various scenarios may then be modeled to examine what controls may need to be put in place to achieve water quality standards necessary to prevent ecological damage in the region. It was also observed that many of the homes were also
shops/businesses that carried out all types of services and produced products such as metal fabrication, vehicle maintenance, brick production, etc. It is not known if these would generate significant amounts of “industrial” type wastes. They would best be described as Non-point sources of pollutants.

Observed the 4 new channels under construction to divert Mekong River water to the southwest. These also included sluices to prevent saline water from moving upstream during low flow conditions and high tides. Most of the roads in the region are being raised by about 1 meter to match the flood stage that occurred in 2000. At least 4 new bridges were being constructed to meet the new flood level record along the Long Xuyen Quadrangle. It was also pointed out that the Vietnam government is building these new infrastructures in order to increase tourism in the area. These operations would not have any transboundary impacts. Stayed overnight in Long Xuyen and then traveled the second day to Ha Tien at the border with Cambodia. The high iron and sulphur soils located in the Dong Thap Muoi and Long Xuyen areas between the Tien and Hau Rivers were observed, which generate high acidity in the region. The only major industries in the area were the two cement factories just south of Ha Tien. In areas with strongly saline soils, shrimp farming is being developed. The KTTVNB has an extensive number of flow gauging stations (one at each bridge), which collect data on a one-hour interval. It was clear that at several of the MSC primary stations that local pollution would cause serious problems with water quality monitoring due to possible lack of complete mixing.

It was pointed out that a salinity model has already been developed for the Mekong Delta by the Vietnamese (Nguyen, K.D. et al., 1998) that apparently produced good results and that an acidity model had also been developed (T.V. Truong et al, 1996, T.V. Truong, 1998).

On Dec.05, 2001, Dr. Booty traveled from Ho Chi Minh City to Phnom Penh.

On Dec.08, 2001 Dr. Booty returned to Canada to carry out one week of home office work on the final report to the WUP.
17. References


Mekong River Commission Lower Mekong Hydrological Yearbook 1996.


STREAMES (Stream Reach Management: An Expert System), Project EVK1-CT-2000-00081 of European Commission’s 5th Framework Programme.

Waterborne Environmental, Inc. 897-B Harrison Street, S.E., Leesburg, VA 20175.

US Army Corps of Engineers, Engineer Research and Development Center, PREWET Version 2.3.