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POLLUTION REMEDIATION PLANNING IN DEVELOPING COUNTRIES: CONVENTIONAL MODELLING VERSUS KNOWLEDGE-BASED PREDICTION

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ABSTRACT

Increasing water scarcity in many developing countries is forcing investments into remediation of water quality at the basin or sub-basin scale in order to increase water availability. Remediation decisions involving complex aquatic environments are often made in data-poor and knowledge-poor situations. Remediation objectives are often poorly articulated, raise unrealistic expectations, and cannot be evaluated in cost-benefit terms. Mathematical modelling, as a means of determining remediation options, is the usual method of choice in data-rich developed countries and requires substantial investment in reliable data, scientific capacity and a sophisticated management culture that generally are not found in developing countries. Modelling is expensive, has numerous other technical problems in developing countries, requires a high degree of input by foreign experts, and rarely leaves residual capacity in the developing country. In contrast, new techniques in knowledge-based (K-B) prediction focus on use of local and domain knowledge to establish meaningful program objectives. K-B-based decision support systems (DSS) allow the client to game with alternative remediation options with outputs expressed in degree of uncertainty in the assumptions and analytical processes included in the DSS system. The K-B approach builds local capacity and, by providing access to domain knowledge, reliance on foreign experts diminishes as local experts assume similar tasks elsewhere in the country.

Key Words: developing countries, water pollution, water management, modelling.

Introduction

Water scarcity in many developing countries is now a fact of life and is rapidly becoming a primary limitation to economic development. According to the United Nations assessment of the global water situation [1] approximately one-third of world’s population now, or will very soon, face serious water shortage. This is predicted to rise to two-thirds of the world’s population by 2025. When coupled with issues such as food security for which agriculture must increasingly compete with urban and industrial requirements for water [2], the need for rapid action by national governments is self-evident. Indeed, the United Nations Commission on Sustainable Development at its sixth meeting (1998) focused on the need to develop an international action plan for sustainable management of freshwater.

For many developing countries, the option of increasing water supply is no longer physically or economically viable or, in some countries, socially acceptable. Therefore, remediation of water quality is destined to become a major factor in increasing available water supply. The shift in paradigm from resource development to allocation mechanisms and water quality management is now noted by the World Bank [3]. Yet, pollution of surface (and increasingly groundwater) water resources from uncontrolled urban, industrial and agricultural discharges remains catastrophically high in most developing countries. Pollution includes microbiological agents with major public health implications, nutrients leading to high levels of eutrophication, contaminants of all types with largely unmeasured [4] and often unknown ecological and public health implications, and other noxious substances leading to foul taste and odour consequences for riparian populations. According to some economic growth models [5] pollution levels will increase by up to x18 by 2025 in Asia, and by lesser amounts in Latin America and Africa.

The overall cost to national economies of water pollution is rarely known. In one of the few such studies, Smil [6] found that for 1991, the cost of water pollution to the Chinese national economy was approximately 0.5% of GDP -- or in dollar terms, equal to the value of Chinese exports in that entire year. Therefore, the challenge both for national water management policies and programs, and for foreign aid programs (ODA – overseas development assistance) in the water sector, is to place water pollution within the economic context of water management.

The challenge for developing countries is to develop pollution control strategies that are cost effective, are compatible with the state of social and economic development, and which provide demonstrable and achievable benefits. Our experience in developing countries indicates, however, that water pollution management is usually not developed within an holistic context such as an integrated water management program, too frequently seeks to use advanced “western” techniques that are incompatible with national capabilities, and often expresses the objectives or benefits in unrealistic terms. In this paper, we address the severe limitations, in developing countries, of conventional methodologies that are used in western countries to derive remediation options for large or complex aquatic areas, up to the river basin scale. The mis-match between conventional western methods and the ability to usefully deploy such methods in developing countries, highlights the need to find alternative approaches that address the continuing problems of cost, knowledge, capacity and sustainability in developing countries.

Water Quality Remediation -- The Context

Typically, large scale remediation issues involve assessing the relative importance of a variety of non-point and point sources, determining specific remediation objectives expressed in ecosystem and/or societal goals, evaluating different control/management options for source reduction in cost-benefit terms, and leading to a comprehensive solution for which the management options are clearly linked to the objectives of the program. In western countries the database is usually rich, the capacity to produce reliable and sophisticated information is excellent, and the affordable cost is high.

In developing countries, the database is almost always very limited and, too often, unreliable. The capacity for modern environmental chemistry and toxicology, including the range of metals and trace organic compounds now required to deal with modern contaminant issues, is extremely limited. The domestic knowledge base of chemical pathways, fate and effects, is usually inadequate, both from the point of view of academic knowledge and of reliable site information. The data problem and requirements for modernization have been discussed by Ongley [4] [7] [8]. Further complicating the situation are typical problems such as narrowly focused institutional mandates, lack of communication between institutions, an inadequate legal basis for setting or enforcing water quality standards, and severe economic restraint.

In the water sector, most developing countries train competent engineers, hydrologists, sedimentologists, biologists, mathematical modellers, etc.., that are qualified to deal with site or effluent-specific remediation. We find, however, that the domestic ability to deal with more complex and/or large scale remediation problems is often very limited for the reasons noted above. Consequently, remediation objectives are often poorly articulated, or inappropriate, or too narrowly focused. The objectives set unrealistic expectations and which frequently are not linked to specific management objectives.

As an example, the conventionally monitored variable (parameter) for industrial pollution is COD which is only an indicator variable. Yet water agencies attempt to make remediation decisions based on COD under complex situations, where the different chemicals that are included in COD have very different pathways, have differing impacts on ecological and public health, and have widely differing options for remediation.

Into this milieu, national agencies and overseas development programs insert western techniques that operate within a totally different paradigm. Conventional stand-alone mathematical modelling, which is the most common approach to remediation decision-making in western countries, is a data-rich approach. It relies not only upon an historically rich database by government agencies and scientific establishments but also upon the ability to fill any data gaps with accurate information. This approach depends upon a rich base of scientific understanding and of scientific and managerial capability. Also, the acceptable cost-base is far larger than in developing countries. Developing countries meet few of these criteria, hence, we argue that an alternative approach is much more suitable to the needs of these countries.

Knowledge-Based (K-B) Prediction versus Mathematical Modelling

The dilemma between conventional stand-alone modelling practices and the context of developing countries is met, we believe, by a new type of predictive technique that comes from the field of Information Technology as applied to environmental analysis. This approach, known as the "knowledge-base" approach usually will contain mathematical models, but approaches the problem quite differently. Therefore, here we discuss the pertinent technical aspects of these two alternative approaches and provide two comparative examples.

Mathematical Modelling: The conventional approach is to use mathematical models to link upstream sources with downstream consequences. There is now a vast array of public domain and proprietary mathematical models for predicting chemical transport through aquatic systems [9]. Typically, such models are constrained by the variables contained in the model, and usually have limited or no ability to add, reject or change these variables or processes. The working assumption by agencies or their consultants must be that the selected model is a realistic reflection of the variables and processes that apply to their situation. Usually there is no way to test this, especially when used by individuals who have little understanding of the assumptions and limitations of the model nor of the relevant environmental science. Once the model is chosen the modelled environment is forced into the constraints of the chosen model. Proprietary models owned by some consulting firms may be even more limiting in that the proprietary model may be the model of choice irrespective of better alternatives. Often the contracting agency, whether a national institution or an international financial institution, has not the experience to determine whether the approach recommended by the consultant is appropriate or not.

The expression of **uncertainty** in the outcome of any predictive technique is a major factor in recommending remediation alternatives. In conventional mathematical modelling, uncertainty is dealt with through sensitivity analysis wherein the sensitivity of the outcome to changes in the values of key variables is determined through simulation of potential ranges of values for those variables. Note, however, that uncertainty is expressed only in terms of variables contained within the model and not in terms of whether the model was the right choice, or contained the correct variables or processes, or correctly characterizes the process variables, or whether the input data are reliable.

In reality, uncertainty needs to be assessed within a much broader envelope of scientific and management concerns and unknowns. These include:

- Many process variables are poorly known in science and inadequately captured in mathematical models. A common example is the transport of hydrophobic contaminants (the majority of common trace contaminants fall into this category). The behaviour of the most important component -- the chemically-active silt-clay fraction during riverine transport, is only now being understood, yet all conventional transport models treat this fraction as if it were sand which, in fact, behaves entirely differently [10]

- The physical or biological system that is being evaluated may depart significantly from the precepts of standard models. For example, nutrient management modelling in the Asian context often requires a *nutrient-sediment-phytoplankton-macrophyte-fish culture* component because fish culture both uses and produces nutrient loadings. To our knowledge, there are no such models currently available that can deal with this typical situation, hence the need to factor in the uncertainty caused by poorly understood relationships and by absent components in the model.

- The processes that are being simulated may be poorly understood or poorly quantified in the environment being modelled. Using the Asian example, lakes are typically large yet very shallow, and eutrophic or hyper-eutrophic. The science that links nutrients with algal production and algal toxins is usually poorly understood in these environments, and the physics of lake circulation and sediment-water interactions are often unknown and may be impossible to assess in a remediation project. Indeed, the knowledge of eutrophication and nutrient-phytoplankton-macrophyte interactions is mainly from northern temperate climates and is often inappropriate in humid tropical environments. This means that assumptions used in conventional mathematical models cannot be assessed, leading to un-assessable levels of uncertainty. Often, this uncertainty implies that the "correct" model cannot even be identified.

- The data required to calibrate conventional models are often inadequate, unreliable, or lacking. Nutrient and contaminant management requires that point and non-point sources be assessed for loadings, for relative impacts, and for relative remediation costs. Yet, in developing countries, the knowledge of non-point source loadings assessment is usually unknown, the point source database is problematic due to limitations of the database and the number and shifting nature of point sources (loadings from rural enterprises in China, for example, are almost impossible to capture), and for lake environments the internal loading (nutrients and certain important contaminants that are retained in the bottom sediments – often in very large amounts) have never been measured. Therefore, the data required to calibrate models are generally not available. Additionally, data reliability can be a serious problem in developing countries and creates unknown levels of uncertainty when used in models.

- Management expectations of a remediation program are usually unconformable with the level of detail available for industrial and municipal effluents. For example, indicator chemistry, such as COD, contain no information on: speciation of metals, characterization of organic contaminants, or relative toxicities of effluent components. As each of these impacts on the type of environmental effects that are being modelled, the modeller is faced with either a major program of data collection, or a gross level of modelling which will not meet the expectations of the client.

A further problem with this conventional approach is that the link between the modelled processes and the remediation recommendations, is usually not transparent to the client. The outputs are expressed in mathematical terms which are translated by the consulting expert. The client becomes completely reliant upon the consultant to competently translate the modelled results into recommendations. The client can not easily evaluate the results, or game for himself with different remediation options, or test the working assumptions of the model.

Because of the complexity of the modelling process, and the requirement for reliable, high quality data, such projects almost always depend upon “foreign experts” (consultants) to manage the process leading to the final product. Typically, domestic agencies are used for routine tasks, or for tasks for which they already have particular expertise (typically, hydraulic modelling). When the project is completed, the consultant leaves a final report and recommendations, but typically leaves no net increase in domestic capacity. Moreover, when the same problem is faced elsewhere in the same country, the approach is not transportable because the same sets of data etc, must be gathered in order to calibrate and operate the model in the new location.

As an example of unrealistic project objectives for remediation and aquatic assessment using a modelling approach, consider the following terms of reference recently issued by an international financial institution. The significance lies in a proposal for a $US 10 billion engineering works that will have major and long term impacts on freshwater and marine systems. The terms of reference are derived from a prefeasibility study carried out by a western consulting engineering company.

Objective: Assess impact of pollution on water quality in the …….. Reservoir, as a result of addition of salts and pollutants from the upper catchment area and feasible pollution control measures with special reference to the feasibility of accrual of benefits of irrigation, municipal and industrial water supply and others envisaged in the Project.

Requirements: **One** foreign expert having knowledge and experience on quality, quantity and treatment of effluents generated by various industries such as chemical, pharmaceutical, petrochemicals, fertilizers, pesticides, dyes and dye stuff, textiles, refineries, pulp and paper, etc. as well as agricultural pollution of fertilizers, pesticides and sewage effluents and municipal waste. Experience in modelling of progressive quality changes in a reservoir due to effluents and water inflows of varying quality including salinity. … to serve as an advisor for a local working group comprised of local experts from different ministries for six months.

Our analysis of this requirement is that the objective of establishing management options to achieve water quality in the reservoir requires the following domain experience:

(a) Effluent and process control technologies for a wide variety of industries and industrial processes, including effluent characterization.
(b) Knowledge of non-point source runoff, including irrigation methodologies and alternatives that affect chemical runoff.
(c) Specialized knowledge on aquatic pathways, fate and effects of specific industrial chemicals (here, food web and ecological toxicity issues and potential endocrine disruption are highly relevant for dyes, dioxins and furans in pulp and paper effluents, PAH’s in refinery effluents, etc.).

(d) Lake (= reservoir) physics and chemical pathways including eutrophication and sediment-water interactions.
(e) Domain experience in modelling which will link all of the above.

In our experience, there is unlikely to be locally based expertise in at least three of these domain areas. There is also unlikely to be data available for point or non-point sources that will be required to drive a modelling process. Complicating the matter further is that the modelling is to predict impacts on a reservoir that has yet to be constructed.

We expect that the complexity of this issue is not fully understood by the project officer (often an economist) nor by the local experts, and quite probably not by the original consulting company; otherwise, the terms of reference would have been established quite differently. We note that engineering companies tend to adopt overly simplistic assumptions about causality in aquatic systems. In the six months allocated to this assessment we would estimate that, if the consultant and client are realistic, this project will not proceed much further than gathering information and evaluating sources and related control options, and evaluating alternative approaches for carrying out the river-reservoir assessment. If a full assessment is expected, then almost certainly the client will have wasted his money on results that will have little confidence in science and little bearing on management options. Unfortunately, the reality is that such studies set expectations that the client only finds to be inadequate long after the major investment decisions have been made. One might note that this same issue in, say, The Netherlands or the United States, would command a large group of experts, with a major budget allocation, over a (minimum) 2-3 years period.

Knowledge-Based Approach: The problems with models are not necessarily the models per se, but in the way modelling is approached. Therefore, we argue for a different approach that has the following characteristics:

- Recognizes uncertainty from the outset;
- Recognizes that the policy decisions are driven not by “exact” solutions provided by mathematical simulation of specific variables, but by confidence that the overall environmental performance of the aquatic system will shift from one level to another according to levels and types of remediation expenditures – for example, from hyper-eutrophic to mesotrophic state (as measured by a variety of phenomenon) and not simply from one level of phosphorous concentration to another as would be predicted by a model.
- Formulates a predictive methodology (modelling or otherwise) according to the existing domestic and domain (expertise in the field) knowledge and which anticipates the limitations of knowledge and of available (or collectible) data;
- Anticipates and incorporates uncertainty, both in what is known and what may be unknown (e.g. un-measured phenomenon) but can be evaluated using domain knowledge;
- Evaluates efficacy of predicted remediation options within the envelope of uncertainty;

- Selects the predictive approach through a transparent process involving the client so that the client understands and approves the methodology;
- Develops and applies the predictive methodology using accumulated knowledge which becomes part of local capacity that can be used elsewhere for similar issues;

This approach uses the following sequence:

1. Define meaningful, measurable and achievable objectives (e.g. health protection, ecosystem protection, fish production, etc.), with relative priorities, so that realistic expectations are established. In this scoping step the client is part of an interactive process so that he/she fully understands what is feasible and what is not, and what the likely level of resolution (certainty) will be. Unfortunately, this step is usually restricted to establishing a set of management objectives, carried out solely by the client or in concert with a project officer from an ODA or international financial institution. The consequence is that many remediation programs go badly wrong at this stage because the wrong expectations are established (see example above).

2. The components of a decision-support system (DSS) are identified that have potential to meet the objectives. This includes the identification of appropriate models, including scoping models that have less rigorous data requirements, that may usefully be included in the DSS system. It should be noted that models are usually an integral part of the DSS structure.

3. Relative to the objectives, evaluate the knowledge base (domestic and domain) and databases available or collectible with reliability. This step establishes the probable data costs, and begins to build an evaluation framework that focuses upon domestic capacity augmented by foreign expertise.

4. Using the domain knowledge, determine the likely uncertainty in types of data, pathways, fate and effects (as applicable), and methods of analysis, that can be used in the DSS.

5. With the client, make a final choice of the DSS components, develop the rule bases (ie. decision criteria used in the DSS), and link these into an integrated DSS system.

6. The client runs the DSS, either ***forward*** where the economic decisions drive the environmental objectives, or ***backwards*** where the downstream environmental objectives are set and which therefore condition the type of economic decisions that are made for remediation.

7. Local managers determine what level of cost is justified relative to an objective assessment of realizable benefits.

8. Outputs are often highly visual, with normative judgements so that the client can game with options, and use it as a tool for public participation, for interaction with senior management, etc..

A key element of the K-B approach is that of participation by the client at all steps so that local capacity is developed.

There is now technology available (from the field of information technology) which evaluates alternative model choices relative to uncertainty inherent in the choice of parameters or processes and method of analysis. Uncertainty includes a wide range of physical and bio-geochemical factors that may be poorly understood, or not easily (or not at all) incorporated into a model, or for which there are little or no data. Scientific understanding, especially of contaminant pathways, fate and effects, is very incomplete; yet that uncertainty is critical in the assessment of predicted outcomes. The K-B approach can capture these types of uncertainty and factor them into the outcome.

In contrast, local knowledge (as distinct from domain knowledge or data) may be very reliable. In contrast to mathematical models that cannot use such knowledge directly, K-B tools allow this knowledge to be coded into the analytical process and to be incorporated into the domain knowledge base.

In our discussion of the problems in the modelling approach we noted that such projects almost always depend upon “foreign experts” (consultants) to manage the modelling process leading to the final product. This is also true of the K-B approach, however the principal differences in the context of foreign input are in the degree of technical and judgemental input by the client, use of local knowledge, and the development of in-country expertise. This leaves an enriched technical capability that has as its logical conclusion a greatly reduced dependency on foreign consultants.

Finally, we note that while the technical components of K-B DSS systems are well known in the field of information science [11], their application in environmental DSS systems is only now emerging from research into practice (see, for example [12]) . Because the term “decision-support system” is now a popular marketing phrase by many companies that now claim to offer such systems in environmental analysis, the rule of *caveat emptor* applies.

Two Contrasting Examples

The following two examples of complex decision-making – one a typical remediation issue in developing countries, and the other a basin-scale planning issue, contrast the two approaches.

EXAMPLES OF THE K-B APPROACH

Case 1: Remediation of Contaminated River System In a Developing Country

Environmental Situation: High levels of COD in river system with taste and odour problems in drinking water supplies, low oxygen with fish kills, high levels of contamination in water, sediment and biota.

Management Objective: Improve water quality by investing in effluent treatment upstream.
Data Availability: COD is only an indicator parameter, but is often the only "hard" data available.

	Conventional Modelling Approach	Knowledge-Base (K-B) Approach
1.	Check for local data on COD and related chemistry within context of range of mathematical models available.	Evaluate local data, local knowledge and expertise, and domain knowledge for this category of problem. No assumptions are made about availability of models.
2.	Decide on target levels of COD (or related chemistry) to be achieved at various points in the river.	With local managers, evaluate whether management objectives are best expressed as in-stream chemical measurements that can be "modelled", or if they include measures of "effects" such as reduction of chemical burden in fish tissue, reduction in taste and odour, reduced levels of toxicity to test organisms, etc.. Finally, establish project outputs that reflect these management criteria.
3.	Chemical characterization of selected effluents, including loadings from the various effluents.	Use standard databases of effluent chemistry on grounds that chemical characterization is likely to be sufficiently variable that the cost of characterization is unlikely to be justified. Approximate loadings established using known factory size and manufacturing process.
4.	Select and calibrate hydraulic model.	Select and calibrate hydraulic model, if needed (follows Step 5).

5.	Select a water quality (transport/ fate) model that contains COD and, where possible, chemicals measured in effluents that contribute to COD. Obtain in-river chemical data for calibration and verification purposes.	Identify, or create, components of a decision-support system (DSS) that can address the management criteria of Step 2. Components, such as simulation of chemical pathways, will reflect the uncertainty in predicting answers for the management criteria from Step 2. DSS includes economic component that classifies approximate levels of remediation costs to achieve various levels of improvement in effluents.
6.	Carry out sensitivity analysis using chosen variables in model. Using calibration data, determine model response to different variables and establish model reliability.	Using the knowledge domain, determine likely levels of uncertainty in types of data, pathways and fate, and methods of analysis, that can be used within the DSS. This includes uncertainty imposed by too little data in one or more parts of the analysis and is used as a basis for costing the need for more data collection. Make final selection of DSS components that produce results that are consistent with inherent and/or expected uncertainty.
7.	Calibrate, verify and run models for chemical compounds selected in step 3 and 5.	Run DSS with outputs expressed in degrees of certainty (Step 5) for achieving alternative outcomes.
8.	Change model inputs to simulate alternative load reduction strategies.	The DSS can be run forward (economic decisions drive the environmental outputs) or backward (the environmental objectives are defined and are used to drive the economic choices).
9.	Develop an economic model that predicts the cost of alternative load reduction strategies.	Part of the DSS
10.	Run transport/fate models with economic model to arrive at optimal solution.	See Step 8.
11.	Present and discuss results with local managers.	Local managers participate in all steps and participating in decision process, thereby building local capacity.

12.	Make recommendations on effluent remediation based on predicted levels of chemistry at various points in the river, and in consideration of data uncertainty. Uncertainty in the decision process can be expressed only in terms of the modelled components.	Results reflect inherent uncertainty in scientific understanding of the process variables **and** data uncertainty. Recommendations on economic costs of effluent control strategies strongly reflect degree of uncertainty in achieving down-river benefits selected as management objectives. Recommendations also reflect the degree of certainty in achieving environmental benefits for selected levels of economic costs.
13.	Local management makes investment decisions on basis of advice from "external" experts.	Local managers can determine what level of cost is justified relative to an objective assessment of realizable benefits.

Case 2: Watershed (River Basin) Management

Environmental Situation: Single or mixed land-use functions, controlled or uncontrolled economic development; all have varying environmental impacts.

Management Objective: An optimal development and management plan for a river basin (watershed) which meets the criteria of: minimize water quality impacts and achieve other benefits such as wetlands, fishery, biodiversity, etc.; minimize development costs; maximize economic benefits; etc..

	Conventional Modelling Approach	**Knowledge-Based (K-B) Approach**
1.	Evaluate type and number of planning and environmental issues that can be incorporated into one or more models.	Evaluate type and number of planning and environmental issues as a basis for assessing available data, local and domain knowledge on issue(s). No assumptions are made about availability of models.

2.	Evaluate model(s) that link land use to environmental "effects".	Using domain knowledge, evaluate uncertainty in the management objectives established by the client. This includes evaluation of uncertainty in the linkages between land use and those environmental "effects" that had been originally identified by the client as management objectives. Then, agree on a revised set of management objectives that are achievable under the given set of conditions of scientific uncertainty, data availability and reliability, cost of new data, etc
3.	Provide client with model or selection of models, including option of building new models, if needed. Advise client of those environmental effects that cannot be included in currently- available mathematical models.	With client, agree upon what is to be included in a decision-support system (DSS) and upon the level of uncertainty that is acceptable within the predicted outcomes of environmental effects that arise from alternative land use choices.
4.	Evaluate quality of available data and collect new data required to operate model(s)	Evaluate quality of available data and select those variables that have significant impact on modelled results. Using IT techniques, optimize data choices where there is an imbalance between data-rich and data-poor variables. Collect any new data required to implement Step 3.
5.	Carry out sensitivity analysis of components contained in model(s).	Link rules and/or model and environmental expertise into a Decision Support System (DSS), including an economic component for evaluating economic costs for: (1) development options for desired levels of environmental effects; and (2) in-situ costs for achieving desired level of environmental quality (e.g. constructed habitat).
6.	Select and calibrate hydraulic model.	Select and calibrate hydraulic model, if needed.
7.	Select and calibrate water quality model and perform sensitivity analysis on model variables.	Select and calibrate water quality model if such a model is required for the analysis. The DSS contains a knowledge component that modifies mathematically modelled relationships, especially when the modelled processes are not well understood or are difficult to quantify.
8.	Develop an economic model that links the cost of alternative land use development scenarios with predicted environmental effects.	See Step 5.

9.	Experts run models that simulate different development choices and determine probable environmental effects.	Client runs the DSS: Forward: Development options determine environmental effects. Backwards: Environmental objectives are established, then development options are determined within predetermined range of acceptable environmental effects. The DSS guides the client through the various scenarios and provides judgmental information about the various options according to the experience lodged in the knowledge base. Client can control the linkages amongst physical, ecological and financial factors, and those socio-political factors that condition development options.
10.	Expert proposes development options based on modelled environmental effects.	Client chooses, or ranks, most appropriate development options with knowledge of the degree of uncertainty identified by the DSS for each option.
11.	Using modelled results, expert interacts with community during public consultation as a technical specialist. Little local capacity is developed except for transfer of model to client.	Client can game with different options, using visual outputs of DSS, as part of public consultations. K-B approach builds local capacity so that client can carry out much of the analysis.

A variation of the above is especially useful for development situations where the focus is sectoral – such as development of hydroelectric power installations. Sectoral decision-making is a common problem in developing countries. The K-B approach is particularly useful in data-poor environments where a knowledge domain can substitute for lack of comprehensive local data. This approach permits gaming with alternative development scenarios that may not have been considered by the project proponents. As examples:

- If, within the lifetime of the power project, food security issues require abstraction of water upstream for irrigation, what will be the probable impacts on the power scheme under different irrigation scenarios.

- If future industrial and municipal development requires increasing amount of water upstream, causing reduced amounts and a change in flow regime, what are the economic implications for the power investment.

- What are the economic tradeoffs between a proposed hydropower development and some other form of basin development. Visual outputs are easily understood by politicians and planners.

Conclusions

Remediation decisions involving complex aquatic environments in developing countries often have to be made in a data and knowledge-poor situations. Therefore, remediation objectives are often poorly articulated, raise unrealistic expectations, and often cannot be evaluated in cost-benefit terms. The conventional mathematical modelling approach, as a means of determining remediation options, is the usual method of choice in data-rich developed countries. It requires substantial investment in reliable data, scientific capacity and a sophisticated management culture that generally are not found in developing countries. Moreover, modelling is expensive, may not capture the physico-chemical and biological processes that exist in the different climatic and hydrological environment of the target country, cannot deal explicitly with uncertainty caused by poor knowledge of the processes or omission of important variables or site conditions, and cannot use local knowledge (as distinct from data). Finally, mathematical modelling requires a high degree of input by foreign experts and rarely leaves residual capacity in the developing country.

A different approach uses new techniques in knowledge-based (K-B) prediction. Initially, it focuses on use of local and domain knowledge to establish meaningful program objectives. It explicitly anticipates the short-comings of conventional modelling in order that models can be realistically used within a K-B decision support systems (DSS). It allows the client to game with alternative remediation options with outputs expressed in degree of uncertainty in the assumptions and analytical processes included in the DSS system. The K-B approach builds local capacity and, by providing access to domain knowledge, reliance on foreign experts diminishes as local experts assume similar tasks elsewhere in the country.

References:

1. United Nations, *Comprehensive Assessment of the Freshwater Resources of the World. Report of the Secretary General,* Commission on Sustainable Development, 5th Session, 7-25 April 1997. Document E/CN.17/1997/9.
2. Ongley, E.D. and Kandiah, A., “Managing Water Pollution from Agriculture in a Water-Scarce Future”, In *With Rivers to the Sea*, Proceedings of the Seventh Stockholm Water Symposium, Sweden, Stockholm International Water Institute (SIWI), Report #2, 1997, pp. 309-316.
3. Saleth, R.M., and Dinar, A., *Water Challenge and Institutional Response: A Cross-Country Perspective,* Preliminary Report of the Rural Development Department, The World Bank. Washington, D.C. April, 1998.
4. Ongley, E.D. “Global Water Pollution: Challenges and Opportunities”, In *Integrated Measures to Overcome Barriers to Minimize Harmful Fluxes from Land to Water*, Proceedings of the 1993 Stockholm Water Symposium, Stockholm, Sweden. 1994, pp. 23-30.
5. UNIDO, *Global Assessment of the Use of Freshwater Resources for Industrial and Commercial Purposes*, Industry, Sustainable Development and Water Programme

Formulation Technical Report. United Nations Industrial Development Organization, ISED/R.53 of January 22, 1996. New York.

6. Smil, V., "Environmental Problems in China: Estimates of Economic Costs", *East-West Center Special Reports* No. 5, East-West Centre, Honolulu, Hawaii. 1996.
7. Ongley, E.D., "Matching Water Quality Programs to Management Needs in Developing Countries: The Challenge of Program Modernization", *European Water Pollution Control* , Vol.**7**, 1997, pp. 43-48.
8. Ongley, E.D., "Modernization of water quality programmes in developing countries: issues of relevancy and cost efficiency", *Water Quality International,* Sept/Oct. 1998, pp. 37-42.
9. Booty, W.G. and Lam, D.C.L. "Freshwater Ecosystem Water Quality Modelling", In: A.M. Davies (ed), *Modelling Marine Systems*, Vol. II, CRC Press, Inc. 1990, pp. 387-432.
10. Droppo, I.G. and Ongley, E.D. "Flocculation of Suspended Sediment in Rivers of Southeastern Canada", *Water Research*, Vol. 28, 1994, pp. 1799-1809.
11. Booty, W.G., Lam, D.C.L., Wong, I.W.S., and Siconolfi, P. "Design and implementation of an Environmental Decision Support System", *Environmental Modelling and Software*, (in press).
12. Booty, W.G., Lam, D.C.L., Tseng, T., Smith, I., and Siconolfi, P. "Great Lakes toxic chemical decision support system". In Denzer, R., Swayne, D.W., and Schimak, G. (eds.) *IFIP Proceedings of the Second International Symposium on Environmental Software Systems,* Chapman and Hall, 1997, pp. 95-101.