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MODELS FOR RIVER BASIN MANAGEMENT

by

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MANAGEMENT PERSPECTIVE

The paper was written in response to a request that NWRI make a presentation on the subject of water resources management and outlining selective NWRI activities in this field at the 6ths World Congress on Water Resources, Ottawa. The paper focusses upons modelling activities in support of basin management and addresses the special session topic, "Management of River Basin Systems". NWRI modelling research and applications covers most pertinent fields - nonpoint sources, contaminant pathways, fate and effects, eutrophication modelling, river-lake interactions, and hydraulic considerations. The NWRI "RAISON" model is highlighted, together with new research directions, such as fine particle transport. The paper focusses on the practical management implications of each modelling activity. The paper is a useful primer on modelling for management purposes and should be of interest to water managers in Canada and overseas. In addition to the List of References, a short bibliography of current literature is appended.

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ABSTRACT

River basin management requires prediction and optimization of complex interactions of natural and anthropogenic factors. Modelling, for management purposes, simplifies these interactions to resolve and predict the environmental consequences of important Canadian issues such as effluent discharges, eutrophication, urban and agricultural land use impacts, pathways, fate and effects of toxic chemicals in rivers, and hydraulic phenomena such as ice jams and sediment transport. Pre-packaged versus hierarchical models are compared, together with problems of optimization, post audit, and significant knowledge gaps. Expert systems with GIS capability have promise for comprehensive basin management.

INTRODUCTION

Different types of models achieve cost-effective solutions for a variety of river basin management concerns in Canada. Management modelling, to be effective, requires simplification of complex interactions of process and anthropogenic variables in time and space to resolve land-water interactions of concern. Not all river basin problems are equally tractable either due to unavailability of data as, for example, ice jam prediction, or because of lack of fundamental knowledge of biochemical processes as is the case for contaminant pathways and effects modelling. Typical basin management issues in Canada are point and nonpoint source concerns, fate and effects of chemicals in rivers, interaction of rivers with receiving water bodies, prediction of consequences in large lakes from management actions taken within the catchment, and prediction and control of hydraulic phenomena.

NONPOINT SOURCE MODELLING

Abatement of point sources of pollution has increased the relative importance of nonpoint pollution to such an extent that further improvements in receiving water quality are frequently unattainable without some control of nonpoint sources. Abatement of nonpoint sources of toxic chemicals is an important emerging issue. Nonpoint source models can provide loads in time and space to receiving water models, and can evaluate remedial alternatives. Runoff pollution models were first developed for two types of land use - urban and agricultural. Intense land use in urban areas combined with high rates of surface runoff strongly contribute to generation of high volumes of runoff and loads of pollutants typical for urban activities (Ellis, in Torno et al., 1986). Although less hydrologically active than urban land, agriculture covers substantial parts of river basins and produces pollutants specific to local soils and agricultural operations

Types of Models

Deterministic models reflect physical processes derived from theory; statistical models are based upon mathematical analysis of data. Typical models often combine both approaches. However, as basin area increases, the ability to track deterministic processes becomes so difficult and so expensive that wholly statistical models become more efficient (Ongley, 1987). Deterministic models use short-interval data related to specific events, whereas statistical models for large areas aggregate data at intervals such as seasons or years. Therefore, use of either approach to evaluate land management alternatives requires clear understanding of level of detail and of spatial and temporal resolution pertinent to the issue.

The physically-based approach is assumed to produce models with greater applicability, transferability, and better suitability for establishing the cause-effect relationships among the phenomena modelled. All such models rely to some extent on empiricism and require field data for model calibration and verification. Comprehensive models require large quantities of various types of input data. Typical physically-based nonpoint pollution models are the SWMM model for urban runoff (Huber, in Torno et al., 1986) and the HSPF model for agricultural runoff (Johanson et al., 1980).

Statistically-based models generally use locally collected experimental data and relatively simple mathematical formulations (Hemain, in Torno et al., 1986). The resources required to develop these models are generally smaller than for physically-based models. On the other hand, statistical models are not transferable to other areas and the spatial and temporal detail of modelling results is less exact than for physically-based models. For agricultural runoff, statistically-based models seem to predominate, certainly for larger watersheds. Typical examples of statistical modelling approaches are unit area loading rates used in both urban and agricultural areas (Novotny and Chesters, 1981).

Model Constraints

The concept of a design event used in hydrologic and hydraulic design is not particularly useful in water quality modelling where frequencies of pollutant fluxes generally differ from those of the climatic events forcing water quality events. Continuous modelling of pollutant concentrations and fluxes is far superior because it produces a continuous record of loading parameters which can be then analyzed, to identify exceedances of water quality criteria in the receiving waters and their durations (Johanson et al., 1980). In detailed modelling, proper modelling of catchment hydrology is quite important, because its output, namely runoff, drives all the other model components.

Soil erosion supplies large quantities of sediment which carry many chemicals originating from the native soil or from agricultural operations. In erosion modelling, it is not sufficient just to model the sediment yields, but also the composition of the eroded material and its transport. Although soil detachment in small experimental plots is understood, sediment transport to edge of field and to the drainage channel is one of the least understood processes. Observed upland soil losses are much greater than sediment yields at the watershed outlet (sediment delivery ratio) because of sediment storage along the transport route. The modelling of erosion on large areas is typically based on the USLE equation (Wischmeier and Smith, 1978) and more physically-based approaches are introduced for edge-of-the-field modelling typified by the CREAMS model (USDA, 1980). Sediment enrichment along the transport route is caused by a shift towards smaller particles with concomitant increased concentrations of pollutants adsorbed to the sediment (Novotny and Chesters, 1981). Enrichment is generally accounted for by simple empirical coefficients requiring verification with field data.

Nonpoint source models are needed for toxic chemicals having impact on water quality (Marsalek, in Torno et al., 1986). Although soil loss and nutrient production still dominate, more concern is now expressed about migration of agricultural chemicals, particularly pesticides. Better characterization of atmospheric deposition is needed, particularly in urban and industrial areas.

MODELLING FATE AND EFFECTS OF CHEMICALS IN RIVERS

Point Source Modelling

Modelling of pathways, fate and effect, especially of contaminants, in Canada's rivers is motivated, in part, by the forthcoming Canadian Environmental Protection Act and, in Ontario, the MISA program for assuring water quality downstream of major industrial outfalls. Modelling offers techniques for optimizing the often competing demands of regulation, environmental protection, and efficacy and cost of control measures within a regional or national economic framework.

Eutrophication Models: The problem of excessive nutrients causing algal bloom and oxygen depletion in rivers and large lakes is generally solvable by use of phosphorus removal methods. Research, including model development, in the past 25 years, has established load reduction guidelines (Sonzogni et al., 1986).

There are various types of DO models using statistical methods such as simple correlation and Kalman Filter techniques as well as those using mechanistic approaches such as DO-BOD kinetics or detailed nutrient-oxygen demand relationships. For many cases, simple DO models are as good as the more complex ones (e.g. DiToro and Winfield, 1984). Many models are capable of prediction within an error margin of 1 to 2 mg L^{-1} O_2, some even less. For river management, such models appear to be useful as in the case of the Thames River, U.K..

However, there are cases where the model predicted DO concentration well but model coefficients were not consistent with measured values. An example is the sediment oxygen demand (SOD) rate. Recently SOD experts concluded that both the observed data and model formulation had pitfalls (Hatcher, 1986). For example, the theoretical value for SOD obtained from a complex model (DiToro and Connolly, 1980) required an artificial inflation of 80% to predict the observed DO. Nevertheless, Simons and Lam (1980) show that, despite a wrong model formulation, sophisticated optimization techniques can select coefficients to make the model results fit the observed. Clearly, optimizing techniques are not a substitute for knowledge; the more complex the model the more likely the prediction will be in error.

For eutrophication modelling, there often exist ten or more years of data, enough not only for model calibration and verification, but also for post audit. For post audit, the same model is applied after the effluent load reduction is implemented (Sonzogni et al., 1986). Only a few models have undergone this final test (DiToro and Winfield, 1984; Lam et al., 1987a) to reveal weaknesses of the model not detectable with short-term data. Many eutrophication models predict reduced river chorophyll a concentration when phosphorus effluent load is reduced. Post audit of the Potomac River Eutrophication Model (Thomann and Fitzpatrick, 1982) showed that in-stream chlorophyll a was 250 µg L^{-1} compared with the predicted 100 µg L^{-1}. Thomann (1987) attributed this difference to a missing mechanism. A DiToro and Connolly (1980) model equated reduction in anoxia to reductions in phosphorus load in Lake Erie. This relationship was so generally accepted that the 1978 Great Lakes Water Quality Agreement included an objective that year-round aerobic condition was to be maintained in Lake Erie. Post audit showed that such an oxygen-phosphorus load relationship could not explain why anoxia still occurred long after the load reduction program was implemented. Anoxia is found to be more related to weather (e.g. solar heating, wind mixing) and sediment oxygen demand than phosphorus loading (Lam et al., 1987a).

Toxic Substances Models

Modelling provides important data for licensing of chemicals, effluent standards, water quality standards and/or environmental effects. Modelling input can be categorized as: ranking, pathway, fate, and effects of toxic chemicals.

__Ranking__: The toxicity of many new chemical compounds may not be known. The QSAR (Quantitative Structure Activity Relations) approach uses the physical and chemical properties of contaminants, measured in the laboratory or estimated from the molecular structure, to establish a toxic ranking. This ignores specific effects in the environment. The QSAR approach is improved by inclusion of knowledge of toxic pathway, fate and effects. For example, the model EXAMS (Burns __et al__., 1978) used measurements from a laboratory microcosm and QSAR techniques to define its model coefficients. Extrapolation of laboratory data to environment prediction remains a controversial subject due to inadequate understanding of biogeochemical dynamics of toxic substances.

__Pathways__: Since toxic chemicals have diverse physical and chemical properties, their interactions with other entities in the river systems are complicated and frequently do not behave according to textbook kinetics (e.g. Halfon, 1986). At NWRI, we have integrated the experimental study of key processes with model formulation. These include the air-water interface dynamics of the transfer fluxes of selected volatile organics, and fine-grained particle transport, the associated sorption mechanisms which are often ignored and other important processes such as hydrolysis, photodegradation, biodegradation sedimentation, burial, resuspension, and bioaccumulation.

Processes may be modelled in two ways. First, all processes are included in a generalized package (e.g. TOXIWASP, Ambrose __et al__., 1983). This has the advantage of covering a large number of processes so the user does not have to redesign the model. However, it: assumes the user can adequately define the coefficients (often not true); presumes that no important process is missing (Thomann, 1987); computes a large number of processes which may not be related to a given chemical; and lacks flexibility to allow reprogramming of new findings into the model.

In the second approach, a hierarchy of models is constructed. The user tailors the models to characterize only the important controlling variables. This more flexible approach is advantageous because it reduces model complexity, and it forces the user to assess the scientific variables pertinent to his situation and to acknowledge uncertainties both in data input and model output.

__Fate__: The interplay of frequency distribution of particles, sorption rates, nutrient availability, biota size, benthic and algal uptake, zooplankton grazing rates, etc., is central to the design of a toxics fate model. In the fugacity approach (Mackay and Peterson, 1981), the chemical fluxes among different compartments are computed and the fate evaluated based on a pathway structure from sediment, to water and to air. In general and especially for rivers, fate models are difficult to verify with field data because a large number of data are absent.

__Effects__: Prediction of effects (the "so what" question) is central to toxic chemical regulation and water quality standards. Although effects assessment using standard bioassays is widely utilized for end-of-pipe control, prediction of in-situ aquatic effects remains elusive due to complexity of aquatic ecosystems and knowledge deficiencies of chemical pathways.

Distance Effects

Although modellers attempt to account for all important biogeochemical transformations that occur during downstream transport, Ongley (1987) has demonstrated that data from any site represent the cumulative effect of source conditions, in-stream storage, lagging effects as well as transformations. Cumulatively, these represent "information loss" -- that is, an increasing (i.e. downstream) inability to account for upstream causes using downstream measurements. This implies that models of pathways of chemicals must expect increasing uncertainty as spatial scale expands.

Interactions Between Rivers and Receiving Water Bodies

Interaction of rivers with receiving water bodies are particularly important in the Great Lakes, and for other large Canadian rivers. Virtually all large lake problems originate in chemicals eminating from the surrounding basin. Traditionally, however, lake models have not been linked to fluvial models but have used forcing functions to simulate linkages to land management issues. As management alternatives become more complex and the trade-offs between point and nonpoint source controls become increasingly expensive, there will be a necessity to provide more specific linkages with spatially distributed sources of specific pollutants.

This will have management applications for large drainage systems, particularly interjurisdictional rivers such as those flowing across the Canadian prairies. For these, where apportionment of discharge is the vehicle for water quantity management, chemical apportionment is a possible scenario and will require prediction of chemical sources and pathways as a basis for equitable legislation and/or agreements.

One approach to comprehensive modelling is a general package such as TOXIWASP (Ambrose *et al*., 1983) where almost all the essential processes are incorporated, including processes applicable to estuaries or to receiving water bodies. For example, for the Fraser River and the St. Lawrence River, TOXIWASP does allow for one box or multi-segment representation of their estuaries. However, it does not allow for salt water intrusion, thermohaline stratification and three-dimensional hydrodynamics which are important for such large river estuaries.

An alternative to the pre-packaged model is an hierarchical modelling framework capable of including new knowledge or data. The use of expert systems permits integration of diverse data sets and identifies solutions according to a hierarchy of logic (artificial intelligence) programmed into the system. Combined with GIS (Geographical Information System) capability, such a system can integrate point data with areal data over time and provide both spatial and temporal analysis of: specified variables, variable interactions, time series, and submodels. The RAISON model (Regional Analysis using Intelligent Systems on a Microcomputer) developed by Swayne and Fraser (1986) and Lam et al. (1987b) combines expert systems and GIS capability to perform regional analysis plus simulation modelling of management alternatives. Developed for integrating atmospheric loadings, land use data, soil chemistry and water quality in studies of acid rain, RAISON has significant potential both for simple tasks such as State of Environment Reporting (both statistical and cartographic) and for complex concerns such as toxic chemical management in large drainage systems.

PHYSICAL PROCESS MODELLING

Traditionally, hydraulic modelling has concentrated on fluid phenomena in a fixed-boundary channel using single or multi-dimensional versions of the Reynolds equations of turbulent fluid motion. These models are used to address purely hydraulic questions such as flood forecasting, navigation concerns, and hydraulic design of river structures, and as modules in larger models dealing with more complex issues related to sedimentation, river ice, water quality and stream ecology. Environmental issues involving the interaction between hydraulics and other physical, chemical and biological processes, e.g. sedimentation, contaminant transport and fate, impact of ice, etc. motivate continued study of hydraulic phenomena in NWRI.

Sediment Transport

Extensive study of movement of sediment in turbulent river flows has led to development of complex models to handle irregular boundaries of natural streams for many applications related to erosion and deposition. Examples of well-documented models include HEC-6 and IALLUVIAL (steady-state); and MOBED and FLUVIAL 11 (unsteady-state). These one-dimensional models, because they operate with cross-sectionally averaged values of sediment concentration, flow velocity and depth, do not furnish any information on the lateral profile of the river. Such information is important for habitat management or to assess interactions amongst hydraulic properties, stream chemistry and benthic biota. Therefore, two-dimensional models have begun to appear recently.

Hydraulic engineers conventionally have focussed upon sand-sized material. Environmental concerns, especially contaminant pathways, require redirection of hydraulic research into the field of cohesive (fine particle) sediment transport. In many rivers, fine particles (<62.5 μm) dominate the suspended sediment regime (Ongley 1982). The fluid mechanics of fine particles, including the role of flocculation are not well understood in the relatively complex flow field of a river (e.g. see Partheniades, 1986). Existing models of fine sediment transport are few (e.g. see Hayter, 1986) and rely upon numerous empirical assumptions and coefficients that may change from site to site or from time to time. We expect our long-term field and laboratory study of the behaviour of fine sediments will permit development of more realistic physical transport models and better understanding of interactions with chemistry, bacteria, and boundary phenomena (e.g. filter feeders).

Mixing

Turbulent diffusion, secondary currents, and differential advection combine in rivers to produce a highly efficient mechanism for spreading and diluting dissolved or particulate contaminants. Modelling of river water quality must consider mixing processes and simulate them in a realistic fashion. Management decisions as to the effects of accidental contaminant releases or short- (transient) and long-term impact of waste discharges, depend on reliable estimates of pollutant concentration, C, as a function of space and time which is often unattainable without a capability to model river mixing.

Within the last 50 years, a good understanding of mixing processes has been utilized to build predictive models. As a rule, these models consider steady river flow and can be broadly divided into steady-state and transient mixing. "Steady-state" mixing results from continuous injection of a contaminant at constant rate. Very good two-dimensional models are available to predict the (depth-averaged) concentration as a function of transverse and downstream distance (e.g. RIVMIX, Krishnappan and Lau, 1983). Transient mixing is much more difficult and early work concentrated on the cross-sectionally averaged value of C. This one-dimensional analysis led to the concept of "Fickian"-type longitudinal dispersion and the associated dispersion coefficient, D. This concept is used in many one-dimensional water quality models and a constant D is assumed. This is a serious shortcoming because the "Fickian" character of dispersion is only attained for very large, and often impractical, downstream distance and elapsed time (e.g. see Beltaos, 1980). A challenge is to extend modelling capabilities to transient mixing in unsteady flow. While several two-dimensional, transient mixing models have emerged, a major problem is the numerical dispersion and diffusion introduced by the solution algorithms.

Ice Regime

Ice regime modelling is essential for water management decisions pertaining to flooding, winter navigation, northern development, hydropower production, etc.. A few proprietary river ice models have been developed, mainly by Canadian engineering consultants. To compensate for knowledge gaps, these models utilize many empirical, untested assumptions or crude rules of thumb. Hence, the models rely heavily on site-specific field calibration and verification prior to practical usage. We anticipate joint public and private sector development of a non-proprietary, comprehensive model of the ice regime that will include current knowledge and minimize arbitrary empiricism.

CONCLUSIONS

A variety of basin management issues to which models can be applied include effluents, urban and agricultural runoff and pollutant loadings, toxic chemical pathways, fate and effects, interaction of river with receiving water bodies, and the prediction and control of hydraulic phenomena such as sediment transport and ice jams. Modelling, for management purposes, simplifies complex interactions in time and space at a level of detail suitable for the problem at hand. Complex phenomena can be handled by pre-packaged models or by a hierarchical approach which allows tailoring to the problem. Sophisticated optimizing techniques will force-fit a complex model to observed variables, however the model may prove unreliable for prediction due to inherent uncertainty in model formulation. Models utilizing expert systems together with GIS capability already offer broad synthesis and modelling applications for a variety of basin management issues.

Water resource managers in Canada require predictive models of sediment transport, of channel change or instability due to engineering constructions, and of flooding due to ice jams. Habitat management and toxic chemical mitigation require greater resolution of interactions of sediment with the entire channel and of the fluid mechanics of silt and clay in rivers together with solution and adsorbed chemistry and associated microbiology. At the National Water Research Institute, modelling research combines the study of physical and biochemical processes with deterministic and mathematical synthesis and prediction techniques. Our work is predicated by practical management issues in Canada's rivers and river basins and attempts to provide a broad modelling capability to the nation's water managers.

REFERENCES

Ambrose Jr., R.B., Hills, S.I. and Mulkey, L.A. (1983). User's Manual for the Chemical Transport and Fate Model (TOXIWASP). Ver. 1. U.S. EPA-600/3-83-005, Athens, GA.

Beltaos, S. (1980). Longitudinal dispersion in rivers. ASCE J. of the Hyd. Div., 106 (HY1), 151-172.

Burns, R.R. Baughman, G.L. and Lassiter, R.R. (1978). Fate of toxic organic substances in the aquatic environment. In Jorgensen, S.E. (Ed.), State of the Art Ecological Modelling, Copenhagen, Denmark.

DiToro, D.M. and Connolly, J.P. (1980). Mathematical Models of Water Quality in Large Lakes. Part 2: Lake Erie. EPA-600/3-80-065, U.S. EPA, Duluth, Minnesota.

DiToro, D.M. and Winfield, R.P. (1984). Long time scale investigation of organic particle transport and fate in Lake Erie - a ten year post audit of the Manhatten College Eutrophication Model. NOAA Coop. Agreement Rep., NOAA, Ann Arbor, MI.

Halfon, E. (1986). Modelling the pathways of toxic contaminants in the St. Clair - Detroit River system using the TOXFATE model: the fate of perchloroethylene. Wat. Poll. Res. J. Can., 21(3), 411-421.

Hatcher, K.J. (Ed.) (1986). Sediment Oxygen Demand, Processes, Modelling and Measurement. Inst. Nat. Resources. U. of Georgia, Athens, Ga.

Hayter, E.J. (1986). Mathematical modelling of cohesive sediment transport. Proc., 3rd Int. Symp. on River Sedimentation, U. of Mississippi, 430-442.

Johanson, R.C., Imhoff, J.C. and Davis, Jr., H.H. (1980). User's Manual for Hydrological Simulation Program - Fortran (HSPF). U.S. EPA 600/900-80-015, Athens, GA.

Krishnappan, B.G. and Lau, Y.L. (1983). User's Manual for Model RIVMIX. National Water Research Inst., Environment Canada, Burlington, Ontario.

Lam, D.C.L., Schertzer, W.M. and Fraser, A.S. (1987a). A post-audit analysis of the NWRI Nine-Box Water Quality Model for Lake Erie. J. Great Lakes Res., 13(4), 782-800.

Lam, D.C.L., Fraser, A.S. and Bobba, A.G. (1987b). Simualtion and analysis of watershed acidification. In: Beck, M.B. (Ed.), Systems Analysis in Water Quality Management, Pergamon Press, Oxford, U.K., 85-96.

MacKay, D. and Peterson, S. (1981). Calculating fugacity. Environ. Sci. & Tech., 15, 1006-1014.

Novotny, V. and Chesters, G. (1981). Handbook of Nonpoint Pollution. Van Nostrand Reinhold Co., NY.

Ongley, E.D. (1982). Influence of season, source and distance on physical and chemical properties of suspended sediment. In: Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield, IAHS Publ. 137.

Ongley, E.D. (1987). Scale effects in fluvial sediment-associated chemical data. Hydrological Processes, 1, 171-179.

Partheniades, E. (1986). The present state of knowledge and needs for future research on cohesive sediment dynamics. Proc. 3rd Int. Symp. on River Sedimentation, U. of Mississippi, 3-25.

Simons, T.J. and Lam, D.C.L. (1980). Some limitations of water quality models for large lakes: a case study of Lake Ontario. Water Resources Res., 16, 105-116.

Sonzongni, W.C., Canale, R.P., Lam, D.C.L., Lick, W., MacKay, D., Minns, C.K., Richardson, W.L., Scavia, D., Smith, V. and Strachan, W.M.J. (1986). Uses, Abuses, and Future of Great Lakes Modelling. Report of the Modelling Task Force, Great Lakes Science Advisory Board, IJC, Windsor, Ontario.

Swayne, D.A. and Fraser, A.S. (1986). Development of an expert system/intelligent interface for acid rain analysis. Microcomputers in Civil Engineering, 1, 181-185.

Thomann, R.V. and Fitzpatrick, J.J. (1982). Calibration and Verification of a Model of the Potomac Estuary. HydroQual Inc. Final Report to D.C. Dept. Env. Sciences, Washington, D.C.

Thomann, R.V. (1987). Systems analysis in water quality management - a 25 year retrospect. In: Beck, M.B. (Ed.) Systems Analysis in Water Quality Management, Pergamon Press, Oxford, U.K., 1-14.

Torno, H.C., Marsalek, J. and Desbordes, M. (Eds.) (1986). Urban Runoff Pollution. NATO ASI Series, Series G: Ecological Sciences, 10, Springer-Verlag, Heidelberg.

U.S. Dept. Agriculture. (1980). CREAMS. A field scale model for chemicals, runoff and erosion from agricultural management systems. Conservation Research Report No. 26, USDA, Washington, D.C.

Wischmeier, W.H. and Smith, D.D. (1978). Predicting rainfall erosion losses. A guide to conservation planning. USDA-SEA Agricultural Handbook 537, Washington, D.C.