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ECONOMICS OF HYDROLOGIC MODELLING

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INTERNATIONAL SYMPOSIUM ON MATHEMATICAL MODELLING TECHNIQUES IN WATER RESOURCE SYSTEMS

ECONOMICS OF HYDROLOGIC MODELLING

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Abstract:

Proliferation of hydrologic models suggests either a situation wherein hydrologists are homing onto the "true" model or a situation wherein hydrologists are uncertain about the appropriate model. The latter condition seems more likely in the face of constraints on data availability, budgets, time, technology and capable manpower to build models. Any formal analysis of the cost of thinking that arises in model construction must set forward the goals of a model, goal specifications (on model and on constraints), and noncommensurate measures of effectiveness for judging model performance. These factors are embodied in the cost-effectiveness technique as outlined in the paper. This methodology is put forward as a logical basis for choosing models in the face of multiple goals for model use and multiple criteria of judging worth of the model. The use of the technique is outlined in terms of models for forecasting of water quality and quantity (floods). It is concluded that the analysis helps in the design of a model that will in turn help produce cost-effective plans, designs and operations.

1.0 The Problem

The proliferation of hydrologic models is the result of several factors:

(1) dissatisfaction with older and, perhaps, empirically-based and geographically-oriented models,
(2) development of computers,
(3) development of new mathematical tools for data analysis and model building,
(4) availability of research funds to evaluate old methods and to develop new methods,
(5) gaps in data on and understanding of different kinds of hydrologic systems,
(6) philosophical basis for the model, for example, deterministic or stochastic (1)*, non-mathematical,

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* Numerals in parentheses refer to corresponding items in the footnotes.

1. Kisiel, C.C., Efficiency of parameter and state estimation methods for lumped and distributed models of hydrologic systems, in Systems Approach to Hydrology, Ed. by V.Yevjevich, Water Resources Publication, Inc., Fort Collins, Colorado, 1971.

(7) complexity of the system to be modelled (for example, too many parameters),
(8) errors of forecast or prediction,
(9) cost of implementing the model.

Undoubtedly, other factors exist but these are representative. Both scientific and non-scientific factors are listed. Not every hydrologist or engineer gives the same ranking to these factors. Hence, it is quite natural to be uncertain about the best model for a given planning, design or operation situation. For some, the model choice problem does not exist because of habit in use of older "established" models or satisfaction with the results. Under these circumstances there may exist unknown opportunity costs or foregone benefits in having used the wrong model or in having used an expensive model. For others, there is a strong insistence on the supremacy of scientific criteria and at times a strident desire to "home" in on the "true" model at all costs. While such a viewpoint may be feasible for some natural hydrologic systems that closely conform to the model assumptions, most hydrologic systems do not conform to our mental constructions. Nature cannot be made to conform accordingly. Given this state of affairs it seems desirable to develop a methodology for attacking the model choice problem in the face of constraints on data availability, budgets, time and capable manpower to build the models. Such a methodology is proposed herein and outlined with an example.

2.0 Methodology of Cost-Effectiveness Evaluation

The cost-effectiveness technique (2) appears to offer a useful basis for choosing among appropriate hydrologic models. Even though it was initially developed for military systems, recent applications to civilian problems have been intensive (3,4) and include the evaluation of water quality surveillance systems, air and water pollution control, oceanographic data collection systems, and other areas of natural resource management. Basically, the technique entails a systematic

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2. Kazanowski, A.D., A standardized approach to cost-effectiveness evaluations, in J. Morley English (Ed.), Cost Effectiveness, New York: John Wiley & Sons Inc., 1968, pp. 113-150.

3. Dupnick, E. and L. Duckstein, Collective utility and cost-effectiveness in natural resource management, Paper presented at the 40th National Meeting of Operations Research Society of America, Anaheim, Calif., October 1971.

4. Cyrus W. Rice Division (NUS Corporation), Design of Water Quality Surveillance Systems: Phase I - Systems Analysis Framework, Water Pollution Control Research Series (16090-DBJ-08/70), 1971, U.S. Government Printing Office, Washington, D.C. 20402

evaluation of the alternatives with which goals might be achieved in the face of either fixed effectiveness or fixed costs (budgetary constraints). The word combination "cost-effectiveness" is relatively new and tends to create the impression of a new discipline; however, cost-effectiveness is a very old concept according to English (5).

In the context of the model choice problem in hydrology, it may be defined as the tradeoff between effectiveness and cost of one model as compared to the same tradeoff with some other model or of variants of the same general model (as the diffusion equation in groundwater hydrology). The effectiveness or usefulness of a model is generally a set of properties of the model (including its forecasts or predictions) that are significant to its users but may or may not be measurable. The cost is the dollar cost of personnel, facilities, equipment, materials, and so on that are consumed to develop, calibrate, validate and use the model. The word "effectiveness" denotes a desire to express every relevant factor in its own units, not necessarily in monetary units. With this important extra feature, cost-effectiveness appears as an extension of engineering economics (or cost-benefit analysis which was subsumed by cost-effectiveness in its evolutionary growth).

Kazanowski (2), in an effort to standardize cost-effectiveness evaluations, offers ten steps; below, these are paraphrased in the context of the model choice problem:

1. Define desired model goals, objectives or purposes.
2. Identify model requirements (specifications) that are essential to the attainment of the desired goals.
3. Develop alternative models for realizing the goals.
4. Establish criteria (measures) for model evaluation such that model capabilities can be compared to model specifications.
5. Select a fixed-cost or fixed-effectiveness approach (this will be dictated by the circumstances of the practical problem but is usually a non-trivial task).
6. Determine capabilities of all alternate models in terms of evaluation criteria.
7. Generate an array that classifies models in terms of the criteria.
8. Analyze the merits of alternative models.
9. Perform sensitivity analysis.
10. Document the rationale, assumptions, and analyses underlying the previous nine steps.

Implementation of the results and feedback are implied in the last two steps. Even though these ten steps may seem self-evident in retrospect, their systematic use is a challenge in the more complex systems being studied today.

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5. English, J. Morley (Ed.), Cost Effectiveness, New York: John Wiley & Sons, Inc., 1968, page 2.

3.0. Application to Forecasting Problems in Hydrology

To illustrate the foregoing steps, forecasting models for water quality and quantity are considered. Forecasting and prediction are taken as synonymous notwithstanding a recent report (6) which argues that deterministic models give forecasts and that stochastic models give predictions. No such differentiation is evident in the literature on estimation theory (7, 8).

Water quality and flow forecasting models have the following feasible goals:

1. A posteriori surveillance for legal or operational reasons (such as the determination of effluent charges or the use of 5-day BOD measurements to operate a waste treatment plant),
2. Real time surveillance for rapid decisions on health dangers in a stream,
3. Forecasting future stream conditions on a short-term, medium range or long-range basis for a variety of reasons, for example, such as the attenuation of flood peaks, delay of their arrival and reduction of duration of flow levels.

A different model may be the most cost-effective for each goal or one model may be acceptable for all goals. The achievement of the above goals requires development of effective systems that include not only the hydrologic model but also a data network, communication systems, data analysis and so on. In this paper, the focus is on alternative forecast models rather than on alternative control systems that employ those models.

3.1 Goal of the Cost-effectiveness Evaluation

Imbedded in the goals identified in the previous paragraph is the following goal: To compare alternate system models that forecast water quality and quantity. Thus for a specific forecasting problem, the goal is to find the most cost-effective system model.

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6. Ibbitt, R.P., Representative data sets for comparative testing of conceptual catchment models, UNESCO Working Group on Selection of Characteristics and Models in Representative and Experimental Basins, 1970.

7. Lee, R.C.K., Optimal Estimation, Identification and Control, Cambridge, Mass.: The MIT Press, 1964, 152 pp.

8. Wold, H., Time as the realm of forecasting, in Interdisciplinary Perspective of Time, Edited by E.M. Weyer and R. Kisher, New York: The New York Academy of Science, pp. 525-560, 1967.

3.2 Model Specifications

Specifications must be identified parametrically so as to reduce possible bias in subsequent steps. It is necessary to relate model specifications to the management and social use of model forecasts. Considering only short-term forecasts, properties of potential value include peak value, minimum value, time to peak, duration of deficiency and excess, and amount of deficiency and excess with respect to a fixed control or standard value. The model user may want one or more of these properties forecasted with substantial accuracy. One or more of these properties are specified for the water quality and flow control system as given below (each attribute suggests a model requirement):

1. Peak floods or stages produce damages irrespective of the duration of such flow. Overestimation of the peak results in unnecessary expenditures and apprehension by downstream residents, commerce and industry; underestimation produces a sense of safety when in fact slight or severe danger is impending. Evidently, the social loss function is nonsymmetric for equal errors of over-and underestimation.

2. Extremes of water quality parameters have varying effects. Of public health and ecologic importance is an excess of toxic elements, BOD, phosphates, pesticides and nitrates, to name a few. Of similar importance is a deficiency of dissolved oxygen, pH and alkalinity, to name a few.

3. Excess and deficiency of water quantity and quality must be measured in terms of both duration and amount. To rely solely on flow or quality duration curves in judging the adequacy of a water supply is a deceptive practice because the amount of the deficiency and excess can be a much more important contributor to the overall social costs. These issues have been explored in recent work on water quality (9) and water quantity (10)

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9. Davis, R.K., The Range of Choice in Water Management (a Study of Dissolved Oxygen in the Potomac Estuary). Baltimore, Maryland: The Johns Hopkins Press, 1968, pages 62, 77.

10. Domokos, M., Indices of water restriction and water deficiency tolerance, Proc. International Symposium on Mathematical Models in Hydrology, International Association of Hydrologic Sciences, Warsaw, Poland, July 1971.

and can be quantitatively evaluated in terms of crossing theory (11). Crossing theory allows for variable levels of water demand and water quality standards. Such levels or standards are usually specified on the basis of social, economic, or public health factors. These levels become specifications for the water quantity or quality control system: for example, a certain volumetric deficiency is allowed for only 5 days, or a certain excess of radioactive waste is allowed in the stream for only 24 hours particularly when the municipal water supply depends on the stream as a primary source. Thus, it is proper to expect a model to forecast these quantities either accurately or consistently on the "safe" side. If control levels or standards are for control of both excesses and deficiencies, then the model specifications may potentially be more demanding in relation to the full range of forecasts. One model may be better at the low end and another better in the upper ranges (9).

The model requirements increase as the specified scientific detail in forecasts is augmented. Quality may have to be forecasted between river banks and with depth. Detailed data on floods is required at many downstream locations for which very little data exists. On the other hand, forecasts may be required at only a few control points along a stream where substantial data has been amassed.

Model specifications may be dictated by circumstances confronting a small consulting office or hydrologists and engineers in developing countries. As such, the models may have to be simple, amenable to computation on slide rules or desk calculators, and not data-based while at the same time producing relatively reliable forecasts. The dilemna at this step is that these specifications may be incompatible. But the second step is not the place to prejudge the merits of one model over another. This is reserved to Step 8.

3.3 Alternative Forecast Models

To forecast either water quantity or quality, the models of the state transition function may be deterministic or stochastic; lumped or distributed; linear or nonlinear; stationary or non-stationary; explanatory or non-explanatory (8); and homogeneous or non-homogeneous in space. The model choice may be made from the following list:

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11. Nordin, C.F. and D.M. Rosjberg, Applications of crossing theory in hydrology, Bulletin of the International Association of Scientific Hydrology, Vol. 15(No.1), 1970, pp. 27-43.

1. Finite state machine (FSM) or simulation (12) - The model is quite general and may be concurrently deterministic and stochastic. It allows for rather general boundary and physical conditions that cannot be encompassed by partial differential equations. Considerable judgement is required in their implementation. The conservation laws are explicitly considered. Models based on these laws are generally presumed to have explanatory power to varying degrees in contrast to purely statistical models.

2. Partial differential equations (PDE) - Because the basic laws for conserving mass and momentum or energy are employed, forecasts based on these equations are usually considered most robust and applicable to most natural conditions. However, problems arise in estimation of parameters. Computer solution of the numerical difference equations is usually necessary for most natural conditions. In this context, the discrete form of the PDE can be generalized to the FSM. Bennett and Rathbun (13) have reviewed critically all available equations for forecasting dissolved oxygen in streams: PDE, ODE (ordinary differential equation such as the Streeter-Phelps equation and its improvements) and statistical (multiple linear regression). A similar choice of models exists to forecast stream temperatures and other water quality parameters. It is not the purpose of this paper to review these but simply to point up the choice. Harley, et al (14) and Harley and Dooge (15) give a rather comprehensive overview of the model choice problem in deterministic flow forecasting.

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12. Simpson, E.S., C.C. Kisiel and L. Duckstein, Space-time sampling of pollutants in aquifers, Proc., Symposium on Groundwater Pollution, 15th General Assembly of the International Union of Geodesy and Geophysics, Moscow, USSR, 1971.

13. Bennett, J.P. and R.E. Rathbun, Reaeration in Open Channel Flow, Open-file Report, Water Resources Division, U. S. Geological Survey, Fort Collins, Colorado, April 1971, 314 pp.

14. Harley, B.M., F.E. Perkins, and P.S.Eagleson, A Modular Distributed Model of Catchment Dynamics, Report No. 133, Ralph M. Parsons Laboratory, Dept. of Civil Eng., Mass. Inst. of Technology, Cambridge, Mass., Dec. 1970, 537 pp.

15. Harley, B.M. and J.C.I. Dooge, Systematic comparison of linear flood routing procedures, Paper presented at 1971 Fall Annual Meeting, American Geophysical Union, San Francisco, Calif.

3. Ordinary differential equations (ODE) - Here, generally only mass is conserved and the effects of momentum or energy are virtually neglected for both quantity and quality forecasting. Spatial variability is assumed to be minimal for the reach distances over which forecasts are projected.

4. Time series or stochastic models - In reality, the previous three models are time series in character. Furthermore, given the partial and ordinary differential equations as state transition functions, the initial condition (present state) in the stream and new disturbances in the stream or river basin, it is evident that the state that occurs at the end of the next time period depends only on the present state. This is the Markov condition (12, 16) that is used so extensively in stochastic models of streamflow and water quality (9); in this same vein, Jenkins and Watts (17) nicely demonstrate how ordinary differential (difference) equations give rise to these stochastic models (see Chapters 2 and 5) only because the input disturbances are stochastic. It should be emphasized that time series models may be purely deterministic as is the case with sum-of-harmonic models, for example, of stream temperature (18), purely indeterministic as is the case with white noise (see Chapter 5 of (17) and see page 287 of (19)), linear combinations of purely deterministic and indeterministic processes (19), or nonlinear combinations (19).

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16. Breiman, L., Probability and Stochastic Processes, Boston: Houghton Mifflin Co., 1969, pp. 152-155.

17. Jenkins, G.M. and D.G. Watts, Spectral Analysis and Its Applications, San Francisco, California: Holden-Day, Inc., 525 pp. 1968.

18. Kothandaraman, V., Analysis of water temperature variations in large river, Journal of the Sanitary Engineering Division, Proc. Amer. Soc. of Civil Engrs., Vol. 97, No. SA1, February 1971, pp. 19-31.

19. Cox, D.R. and H.D.Miller, The Theory of Stochastic Processes, New York: John Wiley & Sons, 1965, pp. 286-289.

5. Statistical models - Multiple linear regression (MLR) models have been used to estimate streamflows (20) and dissolved oxygen (13). Veitch and Shepherd (20) used principal components analyses to obtain a reduced number of new variates for use in subsequent MLR analysis, thus circumventing the problem of intercorrelation inherent in streamflow data at different time periods and at different control stations. Both the MLR and stochastic models have value when a reasonable amount of data is available at the control points and when the required updating of the model parameters is not too frequent. Nonetheless, they may not be transferable to ungaged sites.

6. No mathematical model - This alternative is listed to emphasize the value of the intuition of a competent hydrologist and the fact that a model has value only if it affects a decision. However, our subsequent comparison must assign this a very high cost because 20-50 years of experience may be necessary to acquire a high level of understanding. But this cost will not necessarily prompt a low ranking for experience. The methodology allows for one's value structure to make that judgment.

3.4 Measures of Effectiveness

Having decided on model specifications and alternate models for reaching the desired goal of forecasting, it is necessary to decide on measures or criteria of effectiveness for comparing models. The task is rather formidable because criteria are scientific and nonscientific or quantitative and qualitative. Too few or too many criteria might be chosen but at present the choice is largely arbitrary, a matter of experience, and a function of the forecasting problem. Too many criteria may lead to mental paralysis whereas too few criteria may result in choosing an inferior model. To test the adequacy or completeness of criteria for evaluation, Kazanowski (2, pg. 126) asks the following question: Could one model excel in most of the listed criteria and still not be judged "best"? A yes answer indicates absence of important criteria. The chosen criteria must somehow be related to the model specification, in this sense the analysis has a feedback loop.

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20. Veitch, L.G. and K.J. Shepherd, A statistical method for flow prediction, River Murray example, Water Resources Research, Vol. 7, No. 6, December 1971, pp. 1469-1484.

Two classes of criteria are identified: cost and effectiveness. Wherever possible, quantitative statements of the criteria should be made. Cost criteria include:

1. Development of model (setup costs) - analogous to capital investment. Costs of retrieving data, of transforming gage heights into discharge and of calibration and validation are included.
2. Acquisition of model (if proprietary).
3. Difficulty in implementation-cost of waiting for data and for computational results, level of professional training required to use model.
4. Computer requirements - slide rule, desk calculator, large scale computers.
5. Maintenance or updating of model.

Effectiveness criteria include:

1. Bias (measure of systematic inaccuracy)
2. Variance of forecast - arises because of errors in measurement and estimation of initial conditions, parameters and input disturbances and in model formulation. It cannot be overstressed that forecasts are made independently of the earlier calibration phase of model development. The calibration establishes the initial condition from which forecasting proceeds. The forecast variance concept is imbedded in Theil's inequality coefficient as used by Leuthold, et al (21) for choosing between two forecast models: an econometric model based on first economic principles versus a stochastic noncausal model based on time series analysis with correlograms. Based on the above criterion, Leuthold, et al suggest that the stochastic model may be cheaper to apply because of the data required to implement the econometric model. This may be food for thought in a hydrologic context, such as the example chosen here of water quality or quantity forecasting.
3. Economic losses associated with errors of overestimation and underestimation of floods, of droughts, of BOD. Bias and variance are simultaneously considered in the use of an economic loss function.
4. Transferability of model to ungaged sites - is a pollutant diffusion model in the Delaware estuary transferable to a Pacific Northwest estuary?

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21. Leuthold, R.M., A.J.A. MacCormick, A. Schmitz and D.G.Watts. Forecasting daily hog prices and quantities: A study of alternative forecasting techniques, Journal of the American Statistical Association, 65, March 1970, pp. 90-107.

5. Creditability of model - *a priori* acceptance by model user; a measure of salability of model to others. This is related to the validity of the model. Good forecasts serve to increase one's creditability in the model.
6. Fidelity of model in reproducing actual state transitions on *a posteriori* basis such as generating streamflow sequences as likely to occur as a given historical sequence; this is related to the calibration phase of model development.
7. Transferability of model from one use to another. In general, regression models would have low transfer value, whereas a time series approach may be transferable from hog prices to streamflow values.
8. Simplicity or parsimony - Models possessing this property may have few parameters or be based on compromises in the use of the conservation laws. For example, the classical Muskingum flood routing equations give good forecasts in certain low Froude number regimes with low frequency inputs, but only the more realistic diffusion-type model has the flexibility to approximate the response of the complete linear solution to higher frequency inputs (14, 15).
9. Sensitivity of model response to spatial and temporal variability of inputs. Certain models may respond poorly to moderate or rapid space-time changes in inputs; such is the case with a moving average water quality model based on many lags.
10. Sensitivity of model response to spatial and temporal variability of model parameters. Such sensitivity analysis may be used to decide on a lumped model as against a distributed model (1, 14).
11. Stability and degree of convergence of the numerical solution.

3.5 Remainder of the Cost-effectiveness Analysis

The remaining six steps will not be further detailed because of substantial difficulties in acquiring reliable cost information and in evaluating effectiveness criteria, in particular on bias, economic loss functions, variance of forecast, validation and calibration of flood or BOD forecasting models. The merit of the cost effectiveness analysis to this point is in its systematic identification of what we need to know (perhaps through further collective research) for continued rationalization of the model choice problem. There is need for pooling of our common experiences on use of models.

In the fifth step, a choice must be made between fixed cost and fixed effectiveness. Both cannot be "free" concurrently. Given fixed resources (time, manpower and budget), the model choice must be made in terms of the effectiveness criteria. Many consulting firms and government agencies find themselves in this situation. Given fixed effectiveness cirteria as may exist in a research and development context, the objective would be to develop a model satisfying these criteria at minimum cost. If the criteria in retrospect are deemed unrealistic, the cost of model building may be excessive. Nevertheless, the chosen model in either situation is not unique with respect to the same hydrologist or group of hydrologists because of subjectivity in the analysis. To some, the non-uniqueness of the model-building activity may be hard to accept but its recognition is essential to future progress.

4.0 Conclusions

Much remains to be done in developing mature guidelines for choosing hydrologic models for different management goals. Such research should realistically consider the circumstances for model use. Cost effectiveness methodology forces the profession to consider seriously the view that models have value only if they affect planning, design and operating decisions. It forces a serious evaluation of the tradeoff between complete scientific understanding of a given environmental situation and managerial need to make decisions in the face of incomplete data, imperfect models, and noncommensurate constraints (budgets, time, manpower, social). Even when a model has been chosen, there still is substantial difficulty in calibrating and, more so, validating forecasting models of water quantity and quality, which are fundamental components of water resource systems.

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