PB-224 173

CHOOSING HYDROLOGIC MODELS FOR MANAGEMENT OF CHANGING WATERSHEDS

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Prepared for:

Agency for International Development

1972

BIBLIOGRAPHIC DATA SHEET

1. Report No. 333.91-F655

2.

PB 224 173 63

4. Title and Subtitle

"Choosing Hydrologic Models for Management of Changing Watersheds"

5. Report Date 1972

6.

7. Author(s) Martin M. Fogel, Lucien Duckstein, and Chester C. Kisiel.

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Arizona Univ.

10. Project/Task/Work Unit No. Proj. 031-11-120-114

11. Contract/Grant No. AID/csd-2457-211(d)

12. Sponsoring Organization Name and Address

Department of State
Agency for International Development
Washington, D.C. 20523

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstracts

Changes in the hydrologic behavior of watersheds can be voluntary, indirect, inadvertent or in any combination. Many of these changes will require environmental impact statements to reflect both beneficial and adverse effects. Man-made changes are planned to meet a particular goal. To choose the most appropriate hydrologic model for predicting these modifications, the standardized cost-effectiveness analysis is recommended. In this methodology, the following steps are included: definition of goals, identification of specifications for realization of goals, development of alternative models to achieve goals, establish measures of effectiveness for evaluation of alternative models, determine capabilities and analyze merits of models and perform sensitivity analysis on goals, specifications and measures of effectiveness. For predicting changes on ungaged watersheds, many hydrologic models encounter calibration, validation or extrapolation problems. It is possible, however, to obtain an approximation of these changes with the use of simple models of the rainfall-runoff process. Two such models are compared in determining the effect of urbanization on the return period of a flood of given magnitude.

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group 333

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US Department of Commerce
Springfield, VA. 22151

18. Availability Statement

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page) UNCLASSIFIED

21. No. of Pages 7

22. Price

FORM NTIS-35 (REV. 3-72)

USCOMM-DC 14952-P72

NATIONAL SYMPOSIUM ON WATERSHEDS IN TRANSITION

CHOOSING HYDROLOGIC MODELS FOR MANAGEMENT OF CHANGING WATERSHEDS

Martin M. Fogel, Lucien Duckstein and Chester C. Kisiel[1]

ABSTRACT. Changes in the hydrologic behavior of watersheds can be voluntary, indirect, inadvertent or in any combination. Many of these changes will require environmental impact statements to reflect both beneficial and adverse effects. Man-made changes are planned to meet a particular goal. To choose the most appropriate hydrologic model for predicting these modifications, the standardized cost-effectiveness analysis is recommended. In this methodology, the following steps are included: definition of goals, identification of specifications for realization of goals, development of alternative models to achieve goals, establish measures of effectiveness for evaluation of alternative models, determine capabilities and analyze merits of models and perform sensitivity analysis on goals, specifications and measures of effectiveness. For predicting changes on ungaged watersheds, many hydrologic models encounter calibration, validation or extrapolation problems. It is possible, however, to obtain an approximation of these changes with the use of simple models of the rainfall-runoff process. Two such models are compared in determining the effect of urbanization on the return period of a flood of given magnitude.

(KEY WORDS: Hydrologic models, forecasting, watershed management, cost-effectiveness, land use effects, urbanization, semi-arid watersheds.)

INTRODUCTION

Hydrologic folklore suggests that each watershed is a law unto itself in its native or pristine state. Consequently, the challenges of comparative hydrology are compounded when man intervenes by changing the state and response of a watershed. The magnitude of the situation is placed in proper prospective when it is noted that there are over 700 million acres in small watersheds, with an average size of 125 square miles, that are included in potentially feasible watershed projects (Nolte, 1972). These projects are needed to alleviate problems that involve floodwater, sediment and erosion damage, drainage, irrigation, municipal and industrial water supply, recreation, fish and wildlife habitat and water quality. In addition, many smaller areas or subwatersheds have water management problems for which improvements are also considered feasible. As a sign of the times, environmental impact statements will probably be required to encompass both beneficial and adverse effects of most, if not all, improvements or changes.

Such changes may be voluntary, indirect, inadvertent, or all in consonance. Voluntary changes include the burning and clearing of brush, timber harvesting, vegetative conversion, forest canopy alterations to increase snow accumulation, land treatment to induce runoff, and control of riparian vegetation. Among natural or indirect changes are those induced by disasters such as lighting-produced forest fires, earthquakes, landslides, plant and animal diseases, climatic shifts, heavy rainfalls, and the gradual evolution of weathering, erosion and sedimentation. Man-made changes are those induced by construction of dams highways and levees, urbanization, cloud seeding, agricultural practices and the pumping of ground water. In some instances, man-made changes are inadvertent as in the case of precipitation in and around heat islands or urban areas (Changnon and Schickedanz, 1971). The decomposition of the combined complexity of all these disturbances and their effects into simpler cause-effect relations is a substantial challenge to mathematical and field investigators in many disciplines.

In this paper the problem of choosing appropriate hydrologic models for management of changing watersheds is considered. The attack on the problem is cast into the standardized cost-effectiveness methodology (Kazanowski, 1968).

Definition of the Problem. That a model choice problem exists is apparent from the hydrologic literature (Kisiel and Duckstein, 1972; Linsley, 1971). These reviews of the problem focus primarily on stationary hydrologic systems with stationary inputs; stationarity signifies that model parameters are space-invariant and time-invariant. Spatial variability or inhomogeneity of these parameters is very real but only of late have attempts arisen to model this feature of hydrologic (ecologic) processes while maintaining time stationarity of input and process parameters. When the stationarity assumption is removed on both the input and process parameters, there is need to specify or derive, from logic or experiment, models for their temporal change. In this sense and, at least in theory, the model choice problem is aggravated in the case of changing watersheds.

A survey of the literature reveals that there are very few quantitative models available for predicting the effects of watershed changes (Hewlett, et al, 1969; ASCE Task Committee, 1972) and these few models cannot claim universal applicability to the many goals of watershed management (Hibbert, 1971). Process-oriented models, such as the various versions of the Stanford watershed model (Linsley, 1971) and the ecologic models of the International Biological Program, suffer from a lack of field validation of their forecasted responses to simulated watershed changes. They may give trends or overall directions of change and may suggest further field studies to arrive at better understanding of basic processes. But even here dangers lurk in the use of simulation results either to justify expensive field studies to detect watershed changes or to make important decisions to manipulate watersheds. To paraphrase Shubik (1972) in his critique of Forrester's model of world dynamics, insensitivity of a model to

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parameter changes is not always a merit. "If the model is too insensitive to parametric sensitivity analysis, then it may be concentrating on the wrong variables. If it is highly sensitive, then data sufficiently accurate for the purposes at hand are possibly impossible to obtain." Given the paucity of formal process models to forecast changes and given the social pressures to make those changes, one wonders to what extent are model "assumptions validated by their plausibility and greatly reinforced by the insensibility of the results to the details of the assumptions?" (Gabor, 1972). We believe that the cost-effectiveness approach provides a constructive framework for explicit consideration of criteria implied above: cost of data requirements, degree of validation, credibility, sensitivity and reliability in detecting changes.

Goals in Management of Changing Watersheds. Goals are generally given as a word statement. Watersheds are manipulated to achieve a variety of goals such as to increase water yield, reduce flood peaks and alter their timing, increase recharge to aquifer, reduce sediment yield, reduce evaporation, reduce effects of fires on hydrologic and ecologic properties of watersheds, dispose of reclaimed wastewaters, optimize timber and livestock production, increase recreational opportunities, preserve wildlife, and to preserve natural beauty.

Man has commonly resorted to models in one form or another (e.g., prescriptive or normative) in order to attempt to achieve goals. Quite often these goals have been evaluated through primitive mental models to make intuitive forecasts about the effects of each manipulation implied in the goals. Increasingly it is recognized that a combination of field experimentation, rational modeling based on physical principles, and computer simulation are necessary to evaluate the potential achievement of goals.

AVAILABLE MODELS FOR EVALUATING WATERSHED CHANGES

Models may be based on field data, or on principles from the disciplines of hydrodynamics, hydraulics, chemistry and biology, or on both. Relevant are change models of the input function and of the watershed itself. To establish such models, statistical inference techniques are valuable in identifying the nature of the nonstationarity (or change) by helping us to answer questions about significant differences between two mean values, variances, regression slopes, and other parameters in either the input or watershed.

At this time, it is useful to review some of the problems and approaches relevant to modeling changes.

Input Nonstationarities. It is important to differentiate between changes in input disturbances and changes in the watershed. Changes in inputs include those effected in rainfall and radiation by cloud seeding, air pollution, and climatic change; these are in addition to the normal seasonal variation in hydrologic and meteorologic inputs. Lumb and Linsley (1971) have used a digital watershed model to study the effects of rainfall augmentation; no changes in watershed behavior are presumed. They justify this approach by emphasizing that such effects on real watersheds cannot be measured easily by field experiments. However, as suggested earlier in this paper, the computer approach must continually be checked by actual field data. *The validity of a model is evaluated by the goodness of the predictions.*

Changnon and Schickedanz (1971) give an excellent overview of the problem of detecting nonstationarities in input functions. While their focus is on the statistical evaluation of precipitation anomalies, their reasoning is germane to the study of other input functions of interest to resource managers and earth scientists. If the detection of watershed changes is to be efficient (in some sense), then careful evaluation of changes in input is necessary; otherwise, nonstationary behavior in the input might be falsely assigned to the watershed.

Watershed Nonstationarities Coupled with Stationary Inputs. The great majority of "change" studies in watershed management has assumed stationary inputs and has considered a limited range of input classes. It is axiomatic in the study of electro-mechanical systems that system response to deterministic or stochastic inputs will generally vary because of the nonlinearity of most systems. Only if the system is closely linear does the system response to unit pulse, unit impulse, unit step, sinusoidal or random inputs remain mathematically the same. Within this context, we see a clearcut advantage to computer studies of system response to various inputs because of the substantial waiting time to observe nature's response to a great variety of inputs.

"Change" studies, either in the field or with computer models, have employed regression relations (Anderson, 1960; Bethlahmy, 1972; Hibbert, 1971) and conservation of mass relations (Hawkins, 1969; Satterlund, 1969). Hawkins employed lag-one autoregressive stochastic models of streamflow as a basis for changing inputs to a reservoir system; the objective was to evaluate changes in reservoir yield as a consequence of changes in volume and timing of the input hydrology. Satterlund used the Thornthwaite water balance model to evaluate the potential effect of simultaneous application of cloud seeding and vegetation modification of target watersheds. In both cases, the results are prescriptive and depend highly on the plausibility of the underlying models.

Many field studies employ the field data to set up a "rule of thumb" as a model of water yield. For example, as a consequence of reseeding a burnt chaparral area with productive grass, the water yield increased from 7 to over 23 percent of average annual precipitation for an Arizona watershed (Hibbert, 1971); one might be tempted to extrapolate these results directly to smaller or larger treated areas. In another instance, Bethlahmy (1972) uses a power law relation between mean annual flood and watershed area to reason about floods on other treated areas. In both cases, no other basis except area is used to reason about changes in other watersheds. These two examples suggest a need to carefully evaluate the basis of transferring results to ungaged catchments.

Other studies have focused on effects of vegetation treatments on various descriptors of the discharge hydrograph (Brown, 1965; Hewlett and Helvey, 1970). Brown studied the recession slopes of the hydrographs on the assumption that a linear system model is a good descriptor of decay; he found that all woodland recessions are steeper than pine forest recessions and summer recessions are much steeper than winter-spring recessions. Hewlett (1972) notes that it is common knowledge that low flows and summer flows are increased by clear-felling of forests. Hewlett and Helvey (1970) concluded that quick flow is the only flood hydrograph parameter that increases significantly following clear-felling of a forest in the southern Appalachians. The discussions between Bethlahmy (1972) and Hewlett (1972) serve to sharpen some of the issues in detecting change from field data. In debate was the significance level: 95% or 99%? Bathlahmy claims that 95% is "much too rigorous". The discussion is reminiscent of the role of Type I and II errors in drawing inferences about hydrologic data (Duckstein and Kisiel, 1971). In our judgement more rigid significance levels, like 80 - 90%, are necessary when the science is young and substantial uncertainty exists in process understanding (as is the case in detecting changes). The power and discrimination of the statistical test are often overlooked considerations when trying to detect changes; for the case of the linear regression models that relate descriptors on untreated areas to treated areas, Farley and Hinch (1970) give a statistical test for detecting a change in the regression coefficient. It does appear that more work is necessary on powerful statistical tests for detecting changes in the environment where only small samples exist.

Many "change" models are based on postulated simple or multiple linear regression models; process dynamics are not explicitly considered. The works of Hibbert (1971), Anderson (1960), and Bethlahmy (1972) are illustrations of this approach for estimating increased water yield, snow accumulation, snowmelt, rain-snowmelt floods, and sedimentation. Included as independent variables are percentage of land as roads, grassland, area below snowmelt line, area of young volcanics, treated area (clear-cutting of timber), cultivation, and so on. If a land use manager were required to make a decision today based on a prediction of the hydrologic effects induced by altering an ungaged watershed, the chances are that he would use some empirically-based relationship or model supplemented with as much information from field experiments on other watersheds as were available. Linear and non-linear system models, simulation models, and statistical models would be of limited use since a calibration period would be required to determine the parameter values for the particular watershed in question. Then, some procedure would have to be devised for testing the parameters that would be affected by the change.

The well-known rational method and the Soil Conservation Service (SCS) procedure are examples of the type of methodology field personnel would probably rely on to make decisions on ungaged watersheds despite the rather low ranking given these procedures by some researchers (Hiemstra and Reich, 1967; Fleming and Franz, 1971). While such procedures have their limitations, they do offer a solution for estimating the hydrologic effects of urbanization, vegetative conversion and land-use treatment on ungaged watersheds.

COST-EFFECTIVENESS METHODOLOGY

There is nothing mystical or substantially new to the concepts and techniques of cost-effectiveness. It extends benefit-cost analysis to include the explicit consideration of alternatives to reach the goals, of uncertainty and of qualitative factors and to exclude "a priori" weighting. Also, a logical step by step framework is set up to allow a common dialogue between the analysts and the decision makers. Land use managers are not only forced to make decisions under uncertainty but also they must do so in the face of social, political and legal pressures or constraints. These constraints are in many cases not quantifiable. While there is a tendency to include only measurable factors in benefit-cost analysis, in contrast, the cost-effectiveness approach considers qualitative elements explicitly.

Essentially, cost-effectiveness presents the decision maker with a means for selecting the "best" system among potentially distinct alternative systems. With a steady stream of new and improved concepts and techniques being displayed, the decision maker should be in a position to make a rational choice between established systems and newer, more efficient and more complex systems. With the proliferation of hydrologic models, coupled with the need for environmental impact statements it appears desirable to employ a methodology for choosing among appropriate hydrologic models as has been done with selecting systems.

The model choice problem may be defined as the tradeoff between the combined effectiveness and cost of one model as compared to the same tradeoff for some other model. The model's usefulness or effectiveness is generally a set of properties (including its forecasts or predictions) that are significant to its users but may not be measurable. Included in this category may be the convenience, availability, credibility or flexibility of models. There are measures of effectiveness that express the relevant factor on its own terms and not necessarily in monetary units. The cost in selecting a model is the dollar cost of personnel, facilities, equipment and materials that are used to setup, collect and process data, calibrate, validate and use the model.

To illustrate the standardized approach of cost-effectiveness as outlined by Kazanowski (1968) and described by Kisiel and Duckstein (1972), the model choice problem will be discussed using urbanization of a watershed in the semi-arid Southwest as an example.

Define Common Goals. In this the first step, the primary objective is to select a transferable (regional) model that is capable of predicting changes (turning points) in the hydrologic behavior of a watershed due to urbanization. The hydrologic parameters that may be used to determine the extent of the alteration are volume of flow, peak flow, time to peak, duration of flow and sediment production.

Identify Specifications. Here the requirements essential for attaining the desired goals are spelled out. The model may be required to develop a probability density function or a cumulative distribution function of the specified hydrologic parameters for the "before" and "after" conditions.

Specifications may require that the model should have a high signal to noise ratio. For example, in a linear model for estimating storm runoff from small semi-arid watershed, a satisfactory relationship for thunderstorms has been determined to be (Fogel and Duckstein, 1970)

$$Q = C(R - A) \qquad (1)$$

in which Q is runoff volume per unit area, R is depth of rainfall, A are the initial abstractions and a function of the watershed characteristics, and C is a coefficient known to be dependent on watershed characteristics and, to a lesser extent, on the maximum 15-minute intensity of the storm. With C dependent only on watershed characteristics, the effect of urbanization should result in greater variations in C than would the maximum 15-minute intensity.

Other specifications may include the amount and kind of data that are to be used in the model, whereas the allowable budget and the decision-making time schedule are additional requirements that may be placed on the model selection.

Develop Alternative Models. In a cost effectiveness study, the various models that are available for predicting the hydrologic effects of urbanizing a watershed would be listed in this the third step. As mentioned earlier, however, there are very few quantitative models currently available for such a purpose. Examples of models that may be adapted for this use are the linear systems model being developed at Purdue University (Delleur and Rao, 1971) and the MIT catchment model (Harley et al, 1970).

The incorporation of rainfall probability models into rainfall-runoff relationships such as presented in equation (1) or in the SCS procedure can lead into the development of the simplest possible models. For example, it was found experimentally that the coefficient C in equation (1) has a value of about 0.3 for small desert shrub watersheds (Fogel and Duckstein, 1970). The initial abstractions A were determined to be 0.4 inches. With urbanization, C is expected to increase and A to decrease. Ideally, then, experimental data could be gathered and analyzed to obtain the variation of C and A with urbanization. Before such work is undertaken, let us examine a possible use of equation (1) for design purposes, namely, let us consider how the return period $T_r(y)$ of a runoff event of magnitude y varies as a function of C and A.

If the number of point rainfall occurrences follows a Poisson distribution with mean m, the maximal distribution function of point rainfall is

$$\Phi_R(k) = \exp(-m[1 - F_R(k)]) \qquad (2)$$

where $F_R(k)$ is the cumulative distribution function of rainfall (Duckstein et al. 1972). Assuming an exponential probability density function for point rainfall with a mean 1/u, then

$$F_R(x) = 1 - e^{-ux} \qquad (3)$$

and equation (2) becomes

$$\Phi_R(x) = \exp(-me^{-ux}) \qquad (4)$$

which is a Gumbel-type extreme value distribution with parameters m and u.

Next if a transformation of random variables represented by (1) is introduced into (4), with the correspondance $Q \rightarrow y$, $R \rightarrow x$, we have

$$x = \frac{y}{C} + A \qquad (5)$$

and

$$\Phi_Q(y) = \exp(-me^{-u(\frac{y}{C} + A)}) \qquad (6)$$

By definition of the recurrence period of a flood of magnitude y (or greater), we have from (6)

$$T_r(y) = [1 - \exp(-me^{-u(\frac{y}{C} + A)})]^{-1} \qquad (7)$$

Equation (7) is represented in Figure 1 for two sets of conditions encountered in southern Arizona, one a desert shrub watershed (C = 0.3 and A = 0.4), and the other, an urban watershed (C = 0.6 and A = 0.3). The latter set of figures were obtained from Kao (1972). Two values of the rainfall parameter u, or rather its equivalent parameter p in the geometric distribution (u = 1/p - 1), are shown when m has a value of 6 events per year (Fogel and Duckstein, 1969).

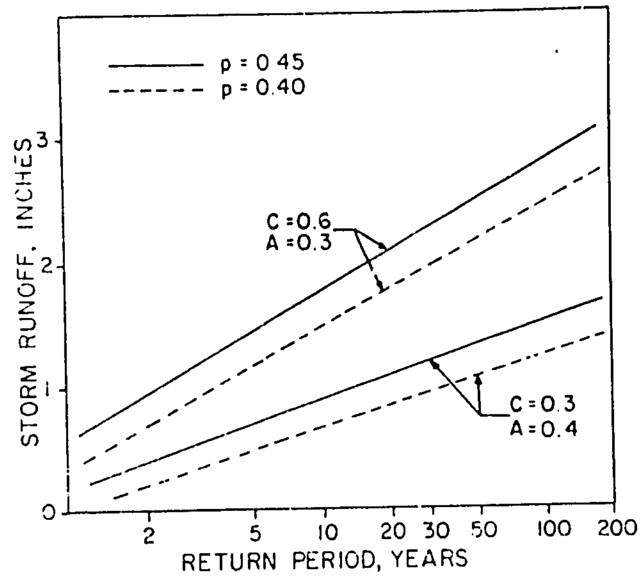

Fig. 1. Frequency distribution of storm runoff from small semi-arid watersheds using a linear rainfall-runoff model.

A similar transformation can be made using the SCS method of relating runoff to rainfall (Duckstein et al, 1972). Figure 2 illustrates these results for a desert grassland area and what might happen to the distribution function of storm runoff with the introduction of improved grass species. No experimental data are involved here; instead estimates of the runoff potential have been made by the following the prescribed procedure (U.S. Soil Conservation Service, 1964) to obtain values for S, a watershed parameter. An indication of the sensitivity of the method to the rainfall parameter m, the seasonal number of thunderstorm events is shown.

Implicit in the SCS model is that storm rainfall and resulting runoff have identical distribution functions. Inasmuch as the rainfall-runoff relationship is non-linear, this assumption is generally not valid.

A comparison between the SCS method and the linear model in determining the effects of urbanization on storm runoff volume is shown in Figure 3. Experimental data were used to determine the rainfall-runoff relationship (Fogel and Duckstein, 1970; Kao, 1972). Both models fit the limited range of available data equally well as determined by regression analysis. Extrapolating to the more extreme events results in the SCS method predicting more runoff than the linear model.

Establish Criteria for Evaluation of Model. With the

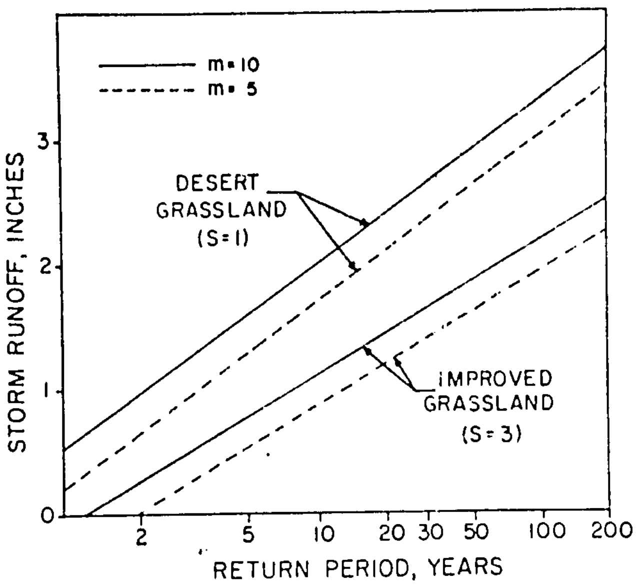

Fig. 2. Frequency distribution of storm runoff using the Soil Conservation Service method.

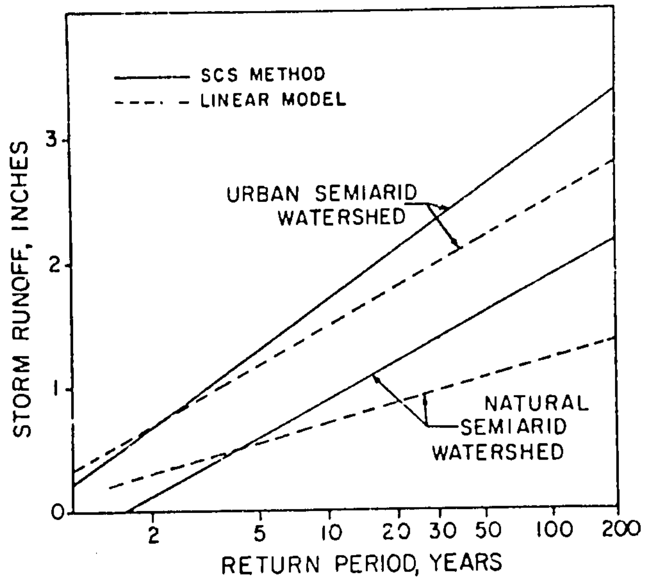

Fig. 3. Determining the effect of urbanization on the distribution of storm runoff by two methods.

assumption that there is a choice of alternate models that meet certain specifications in attaining the desired goals (forecasting change), it is now necessary to decide on measures of effectiveness for comparing models. Two classes of criteria are identified, namely, cost and effectiveness. Wherever possible they should be presented in quantitative terms.

Cost criteria may involve development of model (set-up costs), retrieving and processing of data, personnel requirements, computer requirements and maintenance or updating of model. Effectiveness criteria are often qualitative but nonetheless may be equally as critical as cost.

Here we are looking at, for example, the ability of the model to distinguish induced variability from natural variability above minimum accepted values. Statistical measures such as coefficient of determination, standard error of estimate, Kolmogorov-Smirnov and chi-square tests may be used as such criteria. The transferability of the model, the economic loss function associated with incorrect estimates and the waiting time for data, calibration and validation may all be critical items. The convenience, availability, credibility, and sensitivity of a model are all important qualities for which it may not be possible to assign a monetary value.

Determine Capabilities of Alternate Models. The merits of each of the models in predicting change should be spelled out in terms of the established criteria, both costs and effectiveness. One such procedure would be to do this for the hydrologic parameters (volume of flow, peak flow, time to peak, etc.) of interest. Then, the measures of effectiveness including costs could be ranked for each of the criteria. An overall ranking of the measures of effectiveness excluding costs and other quantifiable terms may then be possible. Thus, one model may have a low cost and a high effectiveness for the prediction of flow volume but a low effectiveness for peak flow. When all the models and the measures of effectiveness are arrayed in tabular form, the relative merits of the alternate models should be readily discernible.

Perform Sensitivity Analysis. To investigate the reliability of the models, a sensitivity analysis should investigate how the model predictions are affected by possible changes in its parameters. In addition, sensitivity analyses should be performed on goals, on specification and on ranking of the measures of effectiveness.

Document Assumptions. Finally, the analysis should include a statement of all hypotheses, the rationale for selecting goals and measures of effectiveness and similar pertinent information.

CONCLUSIONS

1. Only few quantitative models are available to predict the hydrologic effects of watershed changes prior to implementing the changes. While these models generally encounter calibration and validation problems, simple models may be used to predict the effects of watershed manipulations on hydrologic parameters. Care must be taken to distinguish between input and watershed non-stationarities.
2. Since many watershed projects deal with relatively small areas, transfer of results from one watershed are necessary but also questionable especially in view of many unresolved problems due to small sample size.
3. The standardized cost-effectiveness approach of Kazanowski provides a framework to choose between models to predict the effects of watershed changes; the methodology is readily able to include explicitly goals, alternative models, uncertainty and qualitative factors. It requires no explicit weighting of the measures of effectiveness.
4. The capabilities to predict the effects of urbanization using a linear rainfall-runoff model and the SCS method are compared in terms of return period of a flood of given magnitude. Preliminary data indicates that both methods yield reasonable results and allow at least a

rough estimate to be made of the effects of a changing watershed.

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