Hydrologic and Watershed Modeling–State of the Art

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PRESENT concern of society for environmental quality requires consideration of water as a transporting medium for pollutants. Symbolic hydrologic models provide a quantitative, mathematical description of the transport processes within a watershed. A conceptual model of a watershed as a continuous system in three space dimensions is presented. Examples are given of mathematical formulations of this model as a distributed system (partial differential equations) and as a lumped system (ordinary differential equations). The structure of several currently used watershed models is examined briefly.

Penman (1961) proposed a concise definition of hydrology in the form of the question: "What happens to the rain?" This is the general question we are trying to answer through the use of material or symbolic watershed models. As society becomes more aware of the environmental problems that may result from man's activities on a watershed, we must direct our activities toward answering the questions: "What happens to the fertilizer?" or "What happens to the pesticides?" Because nutrients or pesticides may be carried by running water or may be adsorbed by sediments transported by runoff, the last two questions can only be answered through the use of hydrologic models.

A watershed is an extremely complicated natural system that we cannot hope to understand in all detail. Therefore abstraction is necessary if we are to understand or control some aspects of watershed behavior. Abstraction consists in replacing the watershed under consideration with a model of similar but simpler structure. There are two classes of models: material and symbolic. (Rosenblueth and Wiener, 1945). A material model is the representation of the real system by another system that is assumed to have similar properties but is not as complicated or difficult to work with. A symbolic model is a mathematical description of an idealized situation that shares some of the structural properties of the real system.

Material models include the iconic or "look alike" models and analog models. For example, lysimeters or rainfall simulators can be classified as material models. Symbolic or mathematical models are sometimes subdivided into theoretical models and empirical models. This is a rather arbitrary subdivision because one man's empiricism may be another man's theory. However, the point can be made that an empirical model merely presents the facts—it is a representation of the data. If conditions change, it has no predictive capabilities. The theoretical model, on the other hand, has a logical structure similar to the real world system and may be helpful under changed circumstances.

All theoretical models simplify and therefore are more or less wrong. All empirical relationships have some chance of being fortuitous and in principle should not be applied outside the range of data from which they were obtained. Both types of models are useful, but in somewhat different circumstances.

If anyone wishes to develop a model to aid in understanding a process, they should choose the theoretical model. However, if they wish to make a decision based upon answers obtained by using the model, the choice is not necessarily obvious. For example, engineering models contain components derived from the social science of economics as well as physically based components. Because the objective of engineering design is stated in economic terms, the physical fidelity of the model components is irrelevant. Net benefits of any project are a function of design costs. Therefore if an empirical component gave equal accuracy at a lower cost, it would be preferred to a theoretical model.

Symbolic models may be classified further as lumped or distributed, stochastic or deterministic. In general, a lumped model can be represented by an ordinary differential equation or a series of linked ordinary differential equations. A distributed model includes spatial variations in the inputs, parameters and dependent variables and consists of a partial differenital equation or linked partial differential equations.

Stochastic models describe processes occurring in time governed by certain probability laws. A model is deterministic if when the initial conditions, boundary conditions and inputs are specified, the output is known with certainty.

The purpose of this paper is to briefly review currently used watershed models and to examine how they might be used in understanding and predicting transport of pesticides, plant nutrients or other substances that might affect water quality. Other important aspects of the environment such as scenic beauty are not considered because hydrologic modeling does not seem to be directly involved in their evaluation.

A GENERAL DISTRIBUTED WATERSHED MODEL

Consider the general distributed model of a watershed shown in Fig. 1.

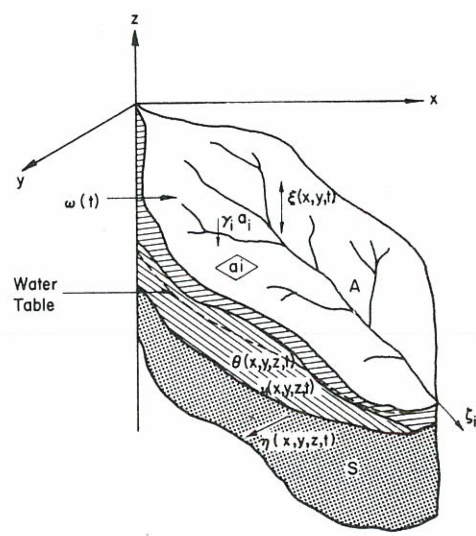

FIG. 1 Schematic drawing of watershed as a distributed system.

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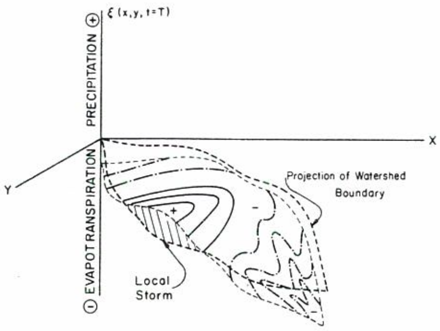


FIG. 2 Schematic representation of sample distribution of surface flux (x,y) over a watershed.

This open system is bounded by impervious rock on the bottom, by the imaginary surface S on the sides and by the imaginary surface A on the top. If we knew the flux of water in liquid and vapor form and the volumetric moisture content at all points within this volume, we could answer the question "What happens to the rain?" Vertical flux through the surface A consists of precipitation (positive) and evapotranspiration (negative) and is designated as $\xi(x,y,t)$. This flux through the surface may be considered as a stochastic process because even though we know its value at some instant t_o, we can only make probabilistic statements regarding its value at $t_o + \Delta t$.* Sample functions of this process at a time $t = T$ and at a point (x,y) are shown in Figs. 2 and 3.

The flux of water in a direction normal to the surface S is designated $\eta(x,y,z,t)$. This function includes both groundwater (saturated) flow and unsaturated flow. Where the groundwater catchment corresponds exactly with the surface water catchment $\eta(x,y,z,t) = 0$, if the position of zero gradient is time invariant. The surface streamflow from the system is more concentrated than the other fluxes and so will be considered as the point process $\zeta_1(t)$. Streamflow includes both surface runoff and water contributed to the stream from the saturated zone. Let the mass rate of sediment transport out of the watershed be $\zeta_2(t)$. Imported water, which is always a possibility if not a fact, will be represented as the process $\omega(t)$. The volumetric moisture content at any point in the system is $\theta(x,y,z,t)$. The continuity equation or the water balance for this system can be expressed as

$$P_T + \omega_T - E_T - Q_T - \zeta_1(T) = \frac{ds_T}{dt} \quad \ldots\ldots [1]$$

where

$P_T = \int_A \xi^+ (x,y,t=T)dA$ = precipitation rate (vol./time)

$E_T = \left| \int_A \xi^- (x,y,t = T)dA \right|$ = evapotranspiration rate (vol/time)

$Q_T = \int_S \eta(x,y,z,t) = T)dS$ = net subsurface outflow rate (vol/time)

$S_T = \int_V \theta(x,y,z,t = T)dV$ = total storage. (volume)

Finally consider some substance i added to an area a_i at a rate of γ_i per unit area. If this material is added as part of an agricultural operation, the area, the amount and the intervals between applications may be deterministic or nearly so. It may also be possible to treat the input as instantaneous. The total mass per unit spatial volume is denoted as $\nu_i(x,y,z,t)$. After some time lag, the substance added will be transported past the mouth of the watershed and will appear in streamflow at a concentration $c_i(t)$. The mass rate of transport of substance i out of the watershed is

$$\zeta_i(t) = \rho c_i(t)\ \zeta_1(t) + \psi[\zeta_2(t)]\ ;\ i = 3,4, \ldots \quad \ldots\ldots [2]$$

where ρ is density of water and $\psi[\zeta_2(t)]$ represents the amount of material carried by sediment. If we are primarily concerned with the outputs of a watershed, we will confine our attention to the multidimensional stochastic process $\zeta_i(t)$; i = 1,2,...N which represents the instantaneous rate of transport of water, sediment, and other substances out of the watershed. In some situations we may be interested in the processes $\zeta_i(t)$; in others we may be more concerned with the total transport during a time interval (0,t)

$$X^{(i)}(t) = \int_0^t \zeta_i(s)ds \quad \ldots\ldots [3]$$

To evaluate alternate courses of action, we need to have some information about the historical processes $\zeta_i(t)$ or $X^{(i)}(t)$ and also the processes $\zeta_i'(t)$ and $X^{(i)'}(t)$ after some changes have been made in the system. If we have long periods of record, we can estimate the parameters of the unmodified processes from historical data. If records are short, it may be necessary to use a model in conjunction with longer records of precipitation to estimate the parameters of the existing process. It will always be necessary to use a model to estimate the parameters of the modified processes $\zeta_i'(t)$.

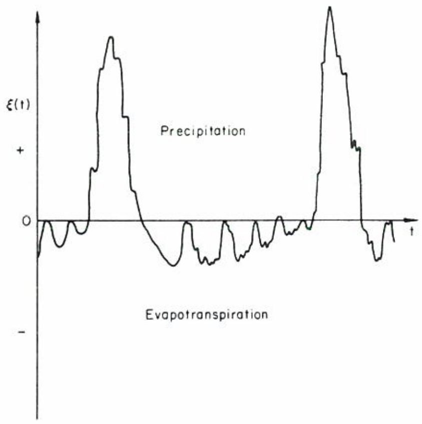


FIG. 3 Sample function of vertical flux at a point x, y.

ALTERNATE MATHEMATICAL FORMULATIONS OF THE CONCEPTUAL MODEL

Although the conceptual model presented in the previous section is an abstraction of reality, it presents a very general description of the behavior of a watershed. In fact it is too general to be of much use in any particular situation. To develop a more detailed formulation, it is quite natural to begin with the partial differential equation of continuity for flow of water in porous media or for free surface flow in streams. These equations can be derived quite readily and, along with Darcy's law for saturated flow in porous media and the momentum equation for free surface flow, constitute a rather rigorous mathematical description of transport of water within the system. Conceptually, these equations along with initial and boundary conditions would enable one to solve for the streamflow process in a deterministic manner if the rainfall and factors affecting evapotranspiration are given. These partial differential equations are a distributed model of the system. Unfortunately these equations either do not have analytical solutions or can be solved only for very simple geometries or boundary conditions. The equations may be written in finite-difference form and solved numerically, or a more abstract model may be

*It could be argued that this process can be reduced to a deterministic one if a detailed meteorological model is included. Considering present skill in weather forecasting utilizing numerical models, the surface flux model will remain stochastic for Δt on the order of days or hours. As Δt decreases to the order of minutes, we might consider the process to be deterministic, although a realization of the process will retain an apparently random component.

postulated. The more abstract model would be simpler than the distributed model but hopefully would have a similar structure and would retain most of its important characteristics.

As an example of this process of abstraction, let us consider various models for the description of unsteady flow over a plane—the "overland flow" problem. If we make the assumption that a one-dimensional formulation of the problem is adequate, we can describe unsteady, free surface flow on a plane by the continuity equation

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} = q(x,t) \quad \ldots\ldots\ldots [4]$$

and the momentum equation:

$$\frac{\partial u}{\partial t} + \frac{u\partial u}{\partial x} + \frac{g\partial h}{\partial x} = g(S_o - S_f) - \frac{qu}{h} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [5]$$

where:

u	=	local mean velocity in x direction
h	=	local depth
$q(x,t)$	=	lateral inflow rate per unit area
g	=	acceleration of gravity
S_o	=	bed slope
S_f	=	friction slope

and x and t are space and time coordinates respectively.

The above model distorts reality in many ways and its application to flow over a rough, natural surface is subject to greater doubt than its application to flow on a parking lot.

It has been found that in most hydrologic circumstances the above equations can be very accurately approximated by the kinematic wave equation (Woolhiser and Liggett 1967). In the kinematic wave equation, the momentum equation is simplified to

$$\left.\begin{aligned} S_f &= S_o \\ \text{or} \quad u &= \alpha h^{n-1} \end{aligned}\right\} \quad \ldots\ldots\ldots [6]$$

where α and n are parameters which include the effects of slope, roughness and the regime of flow (laminar or turbulent).

As a further abstraction, we might propose that overland flow be approximated by a cascade of N non-linear storages, each receiving inputs from rainfall, q_i, and the output from the upstream storage, Q_{i-1}. This system can be described by the following series of linked ordinary differential equations:

$$\left.\begin{aligned} \frac{dS_1}{dt} + bS_1^c &= q_1(t) \\ \frac{dS_2}{dt} + bS_2^c &= q_2(t) + bS_1^c \\ &\;\vdots \\ \frac{dS_i}{dt} + bS_i^c &= q_i(t) + bS_{i-1}^c \\ \frac{dS_N}{dt} + bS_N^c &= q_N(t) + bS_{N-1}^c \end{aligned}\right\} \; .[7]$$

where bS_i^c represents the outflow, Q_i, from the i^{th} storage element. Dooge (1967) used equation [7] to represent a "uniformly nonlinear system." There is an obvious similarity between the series of nonlinear storages and the kinematic model. During the rising stage due to uniform lateral inflow, the solution within the zone of determinacy for $0 < x < L_o$ for the kinematic model is given by

$$h = qt$$

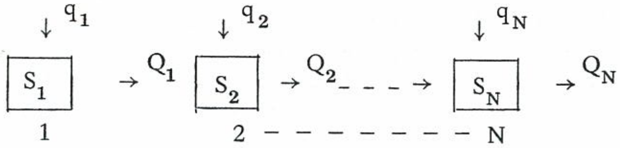
or

$$Q = \alpha(qt)^n \quad \ldots\ldots\ldots\ldots\ldots [8]$$

Kibler (1968) has shown that if a storage element is considered to be analogous to a length of plane equal to L_o/N that the discharge from the N^{th} element can be written as

$$Q_N = \alpha \left[\frac{N}{L_o} S_N\right]^n \quad \ldots\ldots\ldots [9]$$

as N becomes large. This expression is similar to equation [8] and is a very good approximation for $N \geqslant 10$. If N is large, the parameters in the storage model have a direct equivalence to those in the uniform flow relationship for the kinematic model. If overland flow on a plane is represented by a single storage element, however, this equivalence disappears although there is likely to be a relation between the number of storages and the ratio of the parameters for the kinematic model and the lumped-system model. This suggests the possibility of obtaining general relationships for parameter estimation through numerical experiments on distributed models and lumped system approximations to them.



As a further abstraction we might represent overland flow as a general system where the output (runoff) is assumed to be related to the input (precipitation) but where no explicit assumptions have to be made regarding the internal structure of the system. This approach was first applied to hydrology by Amorocho and Orlob (1961) and several investigators have worked on this problem in the following decade: (Amorocho 1963, 1967; Jacoby 1966; Bidwell 1971; Amorocho and Brandstetter 1971). A special case of the general system approach, the theory of linear systems, has found hydrologic application since Sherman's (1932) unit hydrograph theory was proposed. It was not until Dooge's classic paper (Dooge 1959) that most of the implications of the linear assumption were clearly stated.

As we consider this example of formulation of successively more abstract models, it is obvious that many of the model classifications tend to be rather indistinct. A certain amount of lumping of inputs and parameters is necessary for the distributed model because we can only obtain discrete data and because we must use discrete mathematical methods to solve the partial differential equation. It is readily apparent, however, that the general systems approach is valid only for time-invarient systems while in principle one might use the partial differential equation model to predict the runoff response if the watershed surface were changed provided one had independent information on the friction relationship for the changed surface condition.

This example demonstrates that the partial differential equations, the finite-difference equations, the ordinary differential equations describing lumped systems with decreasing N, and the general linear and nonlinear systems can all be looked upon as successively more abstract models of the real physical system. They share some common properties and all inevitably involve distortion. This distortion or the lack of physical significance of model parameters is the price we pay for simplicity and reduced data requirements.

STATE OF THE ART — WATERSHED MODELS

The Stanford Model (Crawford and Linsley — 1962, 1966) is certainly the

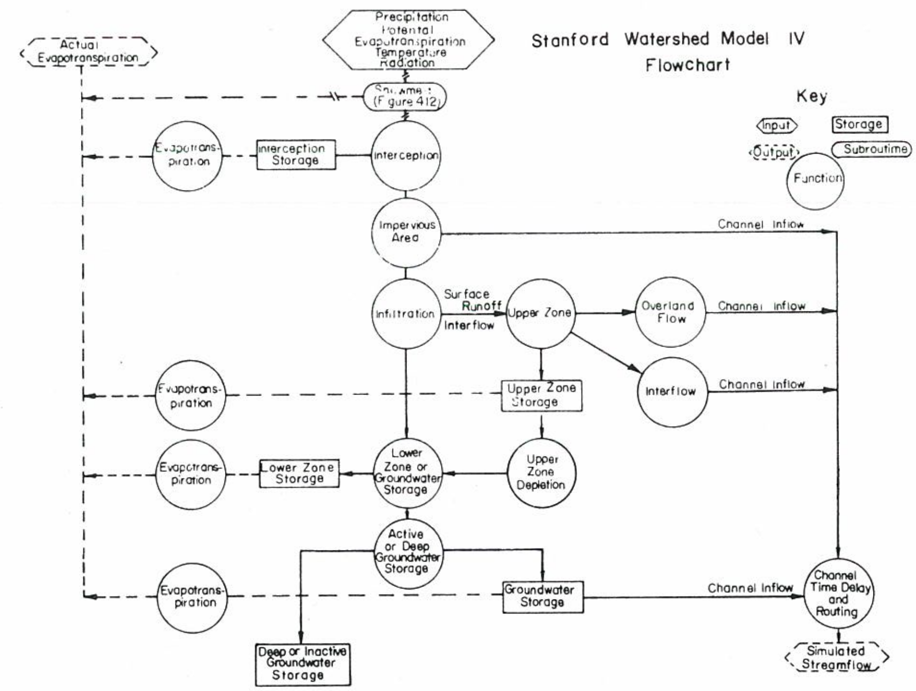


FIG. 4 Flowchart of the Stanford Watershed Model IV (from Crawford and Linsley 1966).

best known general watershed model in current use. A flow chart for this model is shown in Fig. 4. This is basically a lumped-parameter model, although large, heterogeneous watersheds can be divided into subwatersheds if sufficient data are available to estimate the parameters for the subwatersheds. The essential structure of the Stanford Model and lumped parameter models in general can be expressed in the following concise notation:

$$\frac{dS_i}{dt} + Y_i + \sum_{\substack{j=1 \\ j\neq i}}^{N} Y_{ij} = X_i \; ; i = 1,2, \ldots N \qquad [10]$$

where S_i is the amount of storage (state variable) in the i^{th} storage element; Y_i is output from the i^{th} element; Y_{ij} is the flow from storage i to storage j; X_i is the exogenous input to the i^{th} element. The Y_{ij} will usually be functions of the S_i and S_j and may be dependent on certain threshold parameters. The inputs X_i are independent of the state of the system, but the outputs, Y_i, depend upon the state of the system and may also depend upon current values of some inputs. For example, evapotranspiration rates may be a function of incoming solar radiation as well as soil moisture storage. The above system of equations are solved by finite-difference techniques on a digital computer. The methods by which infiltration and evapotranspiration are computed infer spatial variability in these fluxes but they are considered to be independent of position on the watershed. The Stanford Model has been used by many investigators and many different versions are available. However, the basic structure of the model is essentially the same in all versions. Because of the extensive experience with this model, it is quite appropriate to compare any new model structure with it to ascertain if there has been an improvement.

Holtan and Lopez (1971) have described the USDAHL-70 model of watershed hydrology. Although their objective is to develop a distributed watershed model, the present model is primarily lumped although, like the Stanford Model, a watershed can be broken down into smaller homogeneous areas. Spatial variations in soil properties and slopes are accounted for by dividing the watershed into land capability classes which correspond to uplands, hillslopes and bottom lands. The percentage of outflow from each capability class that is contributed to the other classes or the channel is estimated from topographic maps. Overland flow is simulated with a lumped, nonlinear storage model.

Although there are many similarities between components of the Stanford Watershed Model and the USDAHL-70 model, the USDHAL-70 model attempts to incorporate some aspects of spatial variability by dividing the watershed into land capability classes with specified spatial relationships. The USDAHL-70 model also puts more emphasis on a *priori* estimation of parameters, particularly for the infiltration component.

Dawdy et al (1970) have recently developed and tested a lumped system model describing surface runoff from small watersheds. The model structure is similar to parts of the Stanford Model and it can be described by equation [10]; however, there are differences in the functional relationships.

A distributed watershed model including overland flow, porous media flow and open-channel flow is not yet available. Freeze and Harlan (1969) proposed a three-dimensional approach which has not been completely implemented as yet. (Fig. 5). Freeze (1971) has presented a three-dimensional model for unsteady, saturated or unsaturated flow in a groundwater basin. His model is physically based in that it has a structure based upon the theory of flow in a porous medium. Models that include a part of the hydrologic system have been presented by others (Kibler and Woolhiser 1970; Brakensiek 1967; Henderson and Wooding 1964; Machmeier and Larson 1967; Morgali and Linsley 1965; Schaake 1965; Harley et al 1970; Amisial et al 1969; Huggins and Monke 1970; and Smith and Woolhiser 1971).

The parameters in the lumped system models have little direct physical significance and, therefore, can be estimated only by using concurrent rainfall and runoff data. In principle, the parameters in the distributed model have some physical significance and the possibility exists that they can be evaluated by independent measurements. However, in practice the partial differential equations describing distributed systems must be solved by finite difference methods. This representation requires the specification of parameter values at a finite number of points. If the number of points is large, the cost of measurements of the parameters becomes prohibitive. If the number of points is reduced drastically, the measured parameter values will not necessarily give good predictions of watershed behavior because of the distortions introduced by the order of approximation.

Because the structure of equation [10] is general enough to include an extremely large number of different models, the question arises "How do I choose the best model for my particular application?" Dawdy and Lichty (1968) suggest four criteria of choice that might be used: (a) accuracy of prediction, (b) simplicity of the model, (c) consistency of parameter estimates and (d) sensitivity of results to changes in

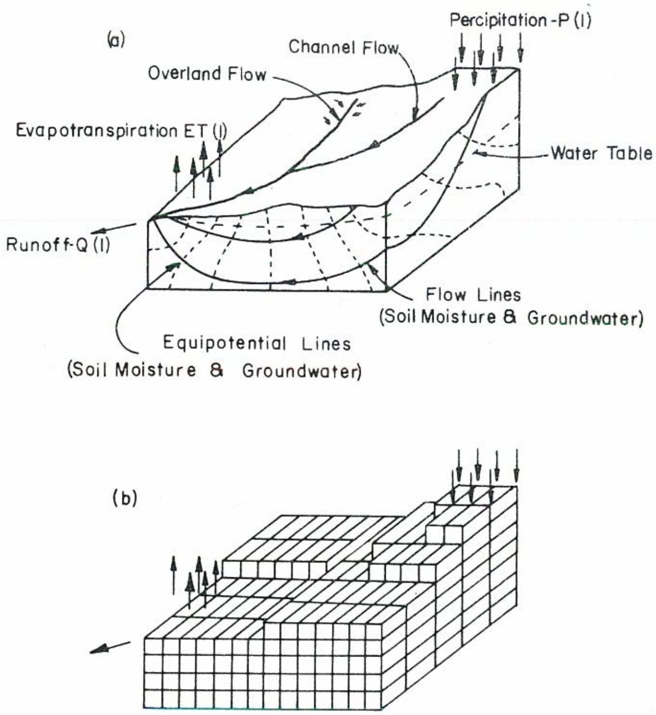


FIG. 5 Schematic diagram of (a) watershed and (b) three-dimensional, discrete model of the watershed (from Freeze and Harlan).

parameter values. Although it is impossible to obtain an unambiguous ranking with multiple criteria, these criteria are obviously related to a criterion which might be to maximize net benefits through use of a model in a design situation.

WATER QUALITY COMPONENTS OF WATERSHED MODELS

There have been many investigations concerning water quality in certain restricted segments of the conceptual watershed discussed previously. Perhaps the earliest and most widely used mathematical model describing water quality is that proposed by Streeter and Phelps (1925) to describe the dissolved oxygen relationship in a stream. The Streeter-Phelps model considers a particular reach of a stream with an initial biochemical oxygen demand (BOD) and dissolved oxygen content at the upper boundary. Under the assumption that biochemical oxidation and reaeration by absorption of atmospheric oxygen are first-order processes and the streamflow process is pure translation at constant velocity, the Streeter-Phelps model enables the prediction of oxygen deficit at any point within the reach. The Streeter-Phelps model considers only the first stage of biochemical oxidation and ignores the second or nitrification stage which may also utilize significant amounts of oxygen. Several more complete models have been proposed—Camp (1963), Churchill and Buckingham (1956), Dobbins (1964).

These refinements include the effects of photosynthesis, sedimentation, bottom scour and surface runoff on the dissolved oxygen balance. More recently O'Connor (1967) developed a model including, in addition to the above, artificial aeration, photosynthetic production of oxygen, temporal and spatial variations in flow rates, and diurnal variation in photosynthetic activity. Goodman and Tucker (1969) utilized a time-varying model in studying effectiveness of treatment plants.

All of the previously cited works have either considered steady-state situations or have considered time-varying cases as a series of steady states. This approach is probably adequate for nontidal rivers where streamflow and oxygen-demanding inputs do not vary rapidly with time.

Recognizing the possible inadequacy of the series of steady states or the quasi-steady state case used in earlier water quality work on esturaries, Dresnack and Dobbins (1968), Bella and Dobbins (1968), Harleman et al (1968) and Dornhelm and Woolhiser (1968) devleoped methods for predicting water quality based upon the partial differential equation of unsteady free surface flow and longitudinal dispersion for the one-dimensional case. Solutions were obtained using finite-difference or finite element methods. Unsteady, two-dimensional cases have since been considered by Fischer (1969).

Orlob and Woods (1964) studied water quality aspects of an irrigated area by computer modeling of the water transport system and concurrent transport of conservative pollutants. They used a lumped-system model which could be described by equation [10]. They used a time step of one month. Their investitagion demonstrated the possible effects of over-irrigation and recirculation of drainage waters on concentration of pollutants.

Another model using the lumped system approach to describe transport of a substance from the point of deposition on a watershed to the outlet of the watershed is that developed by Huff (Huff and Kruger 1967 (a, b)). In his initial work at Stanford University, Huff used the Stanford Watershed Model to describe the movement of water through a basin and expanded it to include the transport of radioactive aerosols (Sr^{90}). Subsequently, he and his associates at the University of Wisconsin (Huff et al 1970) are attempting to modify the radionuclide transport model to include the transport of nutrients (Watts et al 1970). The initial attempt in this area is the modeling of the transport of nitrogen in an effort to discover mechanisms by which nutrient enrichment of lakes and streams is related to human activity.

Bloom et al (1970) used a very elementary lumped storage representation of soil water and surface water as elements of a mathematical model to evaluate the transport and accumulation of radionuclides. Their model was very comprehensive in that it attempted to include the transport of radionuclides from deposition on plants and soil, transport by water, ingestion by fish and finally ingestion by man. This complex system was subdivided into ten "compartments." From continuity considerations, the behavior of the system was described by the system of equations:

$$\frac{dy_i}{dt} + \lambda_{ii} y_i = \sum_{\substack{n=1 \\ n \neq i}}^{N} \lambda_{in} y_n \,, \quad i = 1,2, \ldots N; \qquad [11]$$

where

y_i = the amount of radionuclide in the i^{th} compartment
y_n = the amount of radionuclide in the n^{th} compartment
λ_{in} = the transfer rate coefficient
λ_{ii} = the elimination-rate coefficient
N = the total number of compartments in the system.

Equation [11] is obviously a special case of equation [10].

The authors contend that this simple, linear, lumped-system model is justified because sufficient experimental data are not available to estimate parameters of more complex models.

Two models that use a distributed system approach toward describing water quality in an urban environment have been reported recently (Metcalf and Eddy, University of Florida and Water Resources Engineers 1971, University of Cincinnati 1970).

Hyatt et al (1970) developed a simulation model of the transport of salts in the upper Colorado River Basin. The hydrologic transport model used was similar in structure to the Stanford model but was solved by an analog computer. The salt transport model ignored ionic exchange and chemical precipitation phenomena within the soil and therefore is only applicable to steady-state situations. The basic time unit was one month and the smallest spatial unit was a sub-basin of the Colorado River. In further work at Utah State (Thomas et al 1971) a salt transport model has been developed that includes reactions occurring in the soil such as ionic exchange and chemical precipitation of gypsum and line. Both of these models are intended to aid management decisions with regard to water quality effects of irrigation.

If we consider only the lumped parameter storage models, adding a water-transported pollutant requires a parallel system of flows and storages similar in structure to that describing the flow of water. The parameters of the quality model include the hydrologic model parameters plus certain reaction rate parameters to describe transformation of the substance under consideration. Certain elements of the hydrologic model may be more important in predicting water quality than they were in predicting streamflow rates.

SUMMARY AND DISCUSSION

In this paper, I have briefly discussed the structure of current general watershed models or those that include important parts of the hydrologic cycle and have been used or could be used to describe the transport of pesticides, nutrients, radioactive nuclides or other substances. The objective of most water quality models has been to predict dissolved oxygen concentrations in segments of a stream or an estuary. The more advanced models treat the river as a one- or two-dimensional unsteady system and involve the numerical solution of partial differential equations. Obviously, any model describing the dissolved oxygen content can also describe transport of conservative substances.

The Stanford Watershed Model has been used to describe the hydrologic transport of radioactive aerosols (Strontium 90) with some success and is being modified to handle transport of nutrients. The nutrient transport problem appears to be less suitable for a lumped-system approach because the inputs are not spatially uniform. The transport of nitrogen as an important nutrient seems to be especially difficult because it can exist in six major forms including organic compounds, all of which must be included in the model. Added to the hydrologic complexity which includes transport and storage of liquid water and its transformation into solid or gas are the chemical or biological transformations of the various nitrogen forms. While many of these transformations can be described quantitatively in the laboratory, little can be said regarding the extent to which they take place under field conditions (Stanford et al 1970).

Another problem which appears to be significant is that of estimating initial conditions. In hydrologic modeling, the initial conditions may not be particularly important because the system has a relatively short memory—the state of the system after a few years is not very sensitive to the initial condition. However, nutrients present in soil can be very large compared to those added by fertilizer and will affect the system for a long time.

Considering the urgency of the problems associated with water quality, it is certainly desirable to construct mathematical models describing these phenomena. However, we must give more serious attention to the question of model verification. Can we say in any meaningful way that model A is better than model B? If we cannot do this, we are unable to determine if we are making progress in our research—a very unsatisfactory situation. It appears to me that research into environmental aspects of hydrology should involve two types of modeling: (a) models of relatively complex systems and (b)models of very simple systems. In constructing models of complex systems, we will find out what we need to know and we may develop operationally useful interim models. However, only by carefully constructed, controlled experimentation on a more limited scale can we obtain unambiguous answers to specific research questions.

Empirical, lumped-system models will probably be useful tools in predicting transport of substances which are naturally present in the environment and which are currently being monitored. However, if we must evaluate the environmental impact of new substances before they are released or if the transport system itself may be changed, theoretical models appear to be the only possible approach. This means that we must develop objective techniques of a *priori* estimation of model parameters.

Effective research on transport of environmental contaminants by water will inevitably involve several disciplines because of the variety of problems involved in constructing adequate models.

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