

INTERNAL REPORT 52
COMPUTER MODELING OF A
CONIFEROUS FOREST WATERSHED

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BACKGROUND

General Philosophy

A computer model of watershed behavior is a detailed accounting of the inputs, storages, transfer functions, and outputs on a drainage basin basis. The internal processes are modeled as best known within limits of realism and judged importance. As computer programs, they are large and ornate with many branches, checks, and special functions, as are the natural systems they attempt to mimic.

A characteristic of the system and program is a collection of descriptive parameters or coefficients used in modeling the individual processes, functions, storages, and so on. The more detailed the model, the more parameters must be used. A large part of the modeling process, then, is the selection of proper parameter values to match the observed watershed performance with model performance. The generous supply of parameters in a hydrologic model is both a blessing and a curse. On one hand, it allows more opportunity for a genuine description of the operation of the system. On the other hand, in a statistical sense, it consumes degrees of freedom and invites criticism on the grounds of brute force "curve fitting" and the lack of a unique solution.

To be sure, there is an element of curve fitting involved. However, certain parameters can be either measured or surmised, at least partially. Additionally, knowledge of system operation permits placing limits and realistic ranges on other parameters. Also, human judgment and experience are used in parameter selection, thus reducing the danger of blind choices even more. Nonetheless, the process is still something less than pure hard science, and contains elements of art and subjective judgment. Crawford (1971) describes hydrologic modeling as a "gray box," or something between a "white box" (pure deductive science) and a "black box" (pure empirical curve fitting).

Despite these shortcomings, computer-based hydrologic models have been used successfully in a wide variety of operational and research situations. Included are the effects of wildfire on streamflow (Fleming 1971), the effects of channelization on flood peaks (Crawford 1969), re-creation of missing streamflow records, the effects of weather modification on streamflow (Sopper et al. 1969), and online flood control and reservoir management. The attraction is twofold: (1) economy, and (2) the necessity for otherwise unattainable data estimates, or both.

Modeling Strategy

Modeling attempts are approached in a rational order: (1) data assembly, (2) model calibration, and (3) application and check with independent data. The first step is the necessary and tedious task of collecting, augmenting filling, and rationalizing the data needed as model inputs and as

verification in the output. Unglamorous and routine, it can involve considerable work, especially when data are incomplete or must be rectified to the study site.

The second task, calibration, is the heart of the modeling activity. In it, the model is contrived to reproduce the performance of the prototype. For a representative year, input such as precipitation, temperature, and radiation is fed into the model and the parameters are adjusted to match model and prototype output, usually on a daily basis. As the match is seldom exact, a criterion on fit, such as minimum prediction error variance, is established to guide parameter adjustment. In the calibration process, a preliminary choice of important parameters is made; the model is adjusted, restructured if necessary, or both; and finally an optimum choice of selected parameter values is made. Calibration is not an automatic process, as a peculiar situation can highlight shortcomings in the model structure, or the necessity for a different data approach.

When the calibration is complete and parameter values are fixed, the model is further tested by using the input data for noncalibration years and comparing historic against computed output. If the calibration is carried out with care and judgment, and the model is designed to reproduce the essentials of the watershed's function, this independent comparison is usually good. If not, further parameter adjustment, model refinement, or data treatment are necessary.

Model Objectives

In the calibration procedure, a decision is made to judge model performance on the basis of its ability to reproduce some vector of prototype output. It seems natural on a watershed basis to use streamflow for that output comparison and thus assert that exact matching of model to streamflows represents a perfect model. In most engineering contexts, streamflow is indeed the object of attention, because it is used in flood and water supply studies, pollution work, and the like. It is well entrenched in our thought, and instrumented drainages measure streamflow as an absolute prerequisite.

Depending upon the client, however, the internal processes within the program of a watershed may be of greater interest. For example, a plant physiologist may be more interested in the status of soil moisture, a forest hydrologist in vegetative interception, an atmospheric scientist in evapotranspiration or snowmelt. All of these processes are used in calculating streamflow. Unfortunately, continuous field data on them to allow an internal check or calibration are usually absent. Although their status can be computed and displayed, they serve mainly as a means of arriving at the "correct" streamflow. These "spinoffs," nonetheless, can be valuable in providing general pictures of internal process functions, and insight as to their general importance, dimensions, and sensitivity.

The form of the objective function can be influenced by the same consideration of clientele and viewpoint. For example, matching streamflows on an

arithmetic basis minimizes the importance of low flows, and places emphasis on peaks. If the modeling output was of total flows for a fisheries habitat study, however, low flows and droughts both would be of concern. In this case it might be advantageous to work with flow logarithms, giving additional weight to low flows, but less to peaks.

A SPECIFIC EXAMPLE

International Biological Program: H. J. Andrews Experimental Forest

The Coniferous Forest Biome, the "client" in this study, represents much of the northern and western forests, which produce a large part of the nation's wood, water, and recreation. In the use of this forest resource, a number of hydrologic problems such as erosion, floods, and water quality deterioration can and do arise, and are influenced by the vegetative properties of the site. Hence forest managers, and downstream users as well, need information on the relative merits of different harvest methods and land management decisions on flow regimes, sediment production, and on the forest site itself. Customarily this has been done by long, expensive, and often inconclusive field studies.

Hydrologic modeling offers an opportunity to investigate these phenomena by a different, and hopefully more rewarding, approach. The model supplies the basic relationships between and within the processes, i.e., evapotranspiration, snow storage, soil moisture, vegetative and channel interception, interflow, groundwater, surface runoff, and streamflow. Based on the hydrologic model, other models for nutrient and sediment transport, vegetative growth, and site changes might also be built for different study emphasis.

The study area

In the current work, a fundamental hydrologic model is being developed and tested for subwatershed 2 of the H. J. Andrews Experimental Forest in the Cascade Mountains of central Oregon. The watershed has an area of 603 ha, with elevations from 525 to 1005 m. The annual precipitation is heavy (about 2150 mm), with relatively little snow of consequence, and streamflow is about 1450 mm. The climate is mild; freezing temperatures occur only for short periods several times each winter. The vegetation is a heavy stand of old-growth Douglas-fir (100-500 years old) with mixed varying amounts of western hemlock and a thick understory of secondary vegetation. Soils are deep, well developed, and porous, and the average slope is a steep 61%. Streamflow is highly variable, and responsive to precipitation, but never has been zero. The extremes of record are $0.001 \text{ m}^2 \text{ sec}^{-1}$ to $0.680 \text{ m}^3 \text{ sec}^{-1}$. Despite a distinctly seasonal distribution, it is a moist, lush, high water-yielding situation.

The experimental forest has been operated by the USDA Forest Service since 1948, and a number of gaged watersheds (including no. 2) were established in 1952. A climatic station providing temperature, relative humidity, and precipitation data is about 0.4 km from the boundary of the watershed. A concrete trapezoidal measuring flume with a cutoff wall to bedrock measures streamflow. Concurrent records of streamflow, precipitation, and temperature date back to 1957. Occasional records of snow depth and soil moisture are also available for points close to the watershed. The area and the watershed studies are described in detail by Rothacher et al. (1967).

Data adjustment and rectification

Models demand a good deal of data, ideally taken on site and with no missing bits. This situation is seldom found, and thus data from nearby locations must be used and contrived to fit the basin under study. The usual techniques of regression, extrapolation, and estimation, so familiar to most working hydrologists, were used. For example, pan evaporation data from Fern Ridge and Lookout Point Dams, both remote from the study area, were used in arriving at estimates of potential evapotranspiration. Solar radiation data, when used, were extrapolated from Eugene, about 80.5 km to the west in the Willamette Valley. A temperature lapse rate (used to relate station to watershed temperatures) was inferred from general area studies, and found to be 5.03°C per 1000 m. Precipitation throughout the watershed is known to be fairly uniform with elevation, and thus required no extensive correction.

The Utah State University Model

The basic model used in this work was first developed in 1971 in a study of the water budgeting and weather modification for the Weber River basin, Utah, by the senior author (Shih 1971). In the current study, the steep slopes and the well-constructed streamflow measuring station led to the assumption of a "tight" watershed, with no ground-water inflow and outflow. Because of the small area, the model was lumped for initial work, and a time increment of one day is used. The model is constrained by continuity considerations. The sub-process models used within the overall model are discussed in the following paragraphs.

Interception (rain). Interception is the part of precipitation that is caught temporarily by forest canopies and then redistributed either to the atmosphere by evaporation or sublimation or to the forest floor. The amount of interception depends on storm size and intensity, and canopy type and density. In each storm, precipitation must satisfy the interception storage (S_i) of the area before it can reach the ground surface. Hence the amount of interception abstraction of an

individual storm is $S_i - S_i(t)$ where $S_i(t)$ is the interception storage at time t . $S_i(t)$ is decreased by daily evapotranspiration. The value of S_i , estimated to be about 0.5 cm, is checked externally on an annual basis against the earlier work of Rothacher (1963), which showed that about 13% of the annual rainfall is intercepted.

Part of the rain falls directly in the stream channel and its immediate vicinity, and flows rapidly downstream without being subject to interception and infiltration. This mechanism produces a quick response in streamflow even with fairly dry soil moisture conditions.

Snow interception and melt. Two forms of precipitation, rain and snow, are considered in this study, as precipitation gage records indicate only the amount and not the form. A straightline temperature criterion was used to divide total precipitation into the two forms. The expression used was

$$R = P \cdot \frac{T_a - T_g}{T_r - T_g} \quad (1)$$

where R is the amount of the precipitation, P , appearing as rain, T_a is the mean daily air temperature, and T_g and T_r are limiting temperatures below and above which all precipitation appears as snow or rain. Preliminary values of T_g and T_r used were -1.1°C and 3.3°C . This relationship is drawn from earlier work by the U.S. Army Corps of Engineers (1956).

Snowmelt rate depends primarily upon the rate of energy input to the snowpack. Both the complex nature of snowmelt and data limitations prevent a strictly analytical approach to the simulation of this process, however, and air temperatures are frequently applied as an index of available energy. Examples of researchers who have used this approach are Pysklywec et al. (1968), Anderson and Crawford (1964), Amorocho and Espildora (1966), and Eggleston et al. (1971). Because temperature data are the only indicators of energy levels available on watershed 2, a degree-day approach based upon the work of Eggleston et al. (1971) was used to represent the snowmelt process at the surface of the snowpack. This component submodel includes mathematical relationships for various phenomena involved in the snowmelt process. It may be applied to any geographic location by determining appropriate constants through a verification procedure. The expression used is:

$$M_{Tg} = k_m k_v \frac{RI_g}{RI_h} T_a (1 - A) + T_a \frac{P_{rg}}{80} \quad (2)$$

where M_{rg} = snowmelt in centimeters, k_m = a constant of proportionality, k_v = vegetation transmission coefficient for radiation, RI_h = radiation index for a horizontal surface at the same latitude as the particular watershed or zone under study, RI_g = radiation index for a particular watershed zone possessing a known slope aspect and gradient, T_a = surface air temperature in degrees Celsius, A = albedo or reflectivity of the snowpack surface, and P_{rg} = precipitation reaching the snow surface in the form of rain, in centimeters. In the model, the factor $k_m \cdot k_v \cdot (I - A)/RI_h$ was lumped into a single parameter, K , and the expression then reduced to:

$$M_{rg} = T_a (K \cdot RI_g + P_{rg}/80) \quad (3)$$

Infiltration. Rates of water supply to the ground surface, whether in the form of net rainfall or snowmelt, must exceed infiltration rates before any surface runoff can occur. The infiltration rate depends on the physical and moisture characteristics of the soil, as well as the surface organic conditions, and it is often expressed in the form of Horton's exponential equation. The soils of the study area are very porous, however, and no overland flow has been observed. Thus all precipitation reaching the ground surface was assumed to infiltrate into the soil and move to the stream channels as a sub-surface flow.

Soil moisture. Soils on the study watershed are relatively deep and have a high porosity. Data on the physical properties of the watershed soils are available (Rothacher et al. 1967), and this information has been used in estimating the soil moisture holding characteristics.

The model allows infiltrating water first to satisfy the available moisture-holding capacity of the soil within the root zone of the forest canopy. When this storage is filled, additional infiltration is assumed to percolate by gravitation either somewhat laterally within the root zone or downward to deeper soil zones. Water that moves laterally usually reaches a surface channel within a relatively short period of time, whereas deep percolation moves from the watershed more slowly and sustains streamflow during dry seasons. The computer models the part of soil moisture that is subject to yearly change. That is, the soil moisture is computed considering the amount of water depleted from soil profile by interflow, evapotranspiration, and deep percolation.

Evapotranspiration (ET). Factors affecting evapotranspiration include temperature, solar radiation, wind, humidity, and current soil moisture status. Formulas and equations to estimate ET are available from the literature, and use a wide selection of data. In this study, however, only temperature and humidity were available, and thus the choices available were restricted. The Jensen-Haise (Jensen et al. 1969), Blaney-Criddle (1966), modified Hargreaves (1966), and Thornthwaite (Thornthwaite and Mather 1957) methods were all examined for use in the model. As will be shown later, however, it was necessary to resort to extrapolated pan evaporation data as equivalent to potential

evapotranspiration (PET). Evapotranspiration was taken as a fraction of PET depending upon the soil moisture status.

If soil moisture was above field capacity, ET was taken as PET. If soil moisture was below field capacity, ET was taken as a linear fraction of PET, dependent upon soil moisture level above a certain lower critical level. This lower limit is a parameter similar to, but not, wilting point. If soil moisture was below this level, ET was zero.

Interflow. Interflow (N_r) comes from the part of soil moisture detention storage that does not go into deep percolation. The detention storage G_s is soil moisture M_s above its retention capacity M_{es} :

$$G_s = M_s(t) - M_{es} \cdot [M_s(t) > M_{es}] \quad (4)$$

That is, $N_r = K_i K_g K_s(0) \exp -K_g t$, in which gravity storage at time $t = 0$ is represented by $G_s(0)$, and no input to G_s is assumed to occur between $t = 0$ and any other time t . Because a major part of streamflow in this watershed comes from sub-surface flow, K_g becomes an important parameter in the model; K_i is the fraction of the surplus water that contributes to interflow.

Groundwater. Water enters groundwater storage as deep percolation from the overlying plant root zone. The rate of deep percolation G_r is numerically equal to the total rate of gravity water depletion within the root zone less the interflow rate. Thus:

$$G_r = (1 - K_i) \frac{dG_s}{dt} \quad (5)$$

By integrating equation (5) over a specific time period the accumulated inflow to the groundwater basin G_w is estimated for that time period.

$$G_w = \int_0^t (1 - K_i) \frac{dG_s}{dt} dt \quad (6)$$

Considering the groundwater basin to be a linear reservoir, the outflow rate is given by the expression

$$Q_{rg} = K_b G_w \quad (7)$$

where K_b = a coefficient estimated from dry season streamflow hydrographs, and Q_{rg} = the outflow rate from the groundwater reservoir. By combining equations (5) and (7), the net rate of storage change within the groundwater basin is derived as

$$G_r - Q_{rg} = \frac{dG_w}{dt} \quad (8)$$

By substituting equation (7) into equation (8) and rearranging terms, the following relationship is obtained:

$$\frac{dQ_{rg}}{dt} = K_b [G_r(t) - Q_{rg}(t)] \quad (9)$$

The rate of discharge from the groundwater basin as base flow is obtained by solving equation (9) for Q_{rg} by the method of finite differences.

Runoff. The possible sources of streamflow at any reach within a channel are overland flow (surface runoff), interflow, groundwater, and upstream input. Under conditions of watershed 2, however, surface runoff does not occur. There is no upstream input from outside the watershed. Therefore runoff rates at the stream gage are given by summing the channel precipitation, the interflow, and the groundwater discharge rates.

Verification of the model and calibration of the watershed

Model verification includes calibration of the model parameters to a particular area, testing the sufficiency of processes defined in the model, and examination of the prediction performance of the model. At various stages a self-calibrating or optimizing routine may be applied (Hill et al. 1971).

In this study a rough fit was first made, based on parameter values judged, estimated, or guessed, and gross adjustments were made on a subjective basis. Input to the model was precipitation and temperature, and output was streamflow, checked against historic flows. Based on observed persistent aberrations in the output, adjustments were made in the model to account for channel interception, to define base-flow recession, and to account for occasional surface runoff. The latter, previously assumed to be nonexistent, could be inferred at precipitation values over 127 mm per day. This value is in essential harmony with an infiltration threshold of 159 mm per day suggested by Rothacher et al. (1967).

The optimization procedure was then applied to fix remaining slack parameter values, and a continuous record was computed to verify the model. A nagging inconsistency in the computer ET values was then noted, causing a reexamination of the ET subroutines. The techniques used could not account for the historical ET losses: seasonal distributions and annual mass balances did not reasonably match observed performance.

Upon further study of the situation, extrapolated pan evaporation data were used to establish a potential evapotranspiration (PET) distribution, with actual evapotranspiration (ET) as a fraction of it, dependent upon daily soil moisture stress, as described earlier. The mass balance of the watershed was effected by introduction of a "leak" from groundwater storage to an external location. This is compatible with small watershed experiences elsewhere, and with geologic uncertainties of the site. This "leak"

consumed about 200 mm of flow annually. The computed seasonal ET distributions then fell into accord with observations.

Further refinement of the model then followed. The leakage and ET functions were improved, with further parameter optimization and correction of small errors and inconsistencies. The model was subdivided into four areal parts to form a distributed model, with refinement of each subwatershed model. Some of the details of the calibration process are given in Table 1.

Current status; peculiarities of this experience

As of this writing (August 1972), the modeling process continues with additional refinement, examination of the subprocesses, and sensitivity studies. The output matches prototype records well in summer storms, base-flow recession situations, and early winter hydrographs. Many of the middle and late winter storms are of rain, snow, or both, however, and the model division or split of total precipitation into these forms is used often. These storm reactions do not always behave in accord with model prediction: The model snow allocation, storage, and melt routines are the suspected sources of error.

On the other hand, a mass balance in the model is approached, the internal processes of the model perform in accord with realistic assumptions and prior knowledge, and parameter values are within reasonable limits. A certain amount of definition has been made in the contents of the "gray box."

Table 1. Model calibration information, July 1958-June 1959 base period.

Step	Error measures		Evapo-transpiration		Leakage	Comments
	Mass ^a	Var ^b	Poten-tial	Actual		
1	96	3838	1251	843	0	PET by Blaney-Criddle (1966)
2	- 42	1864	2084	864	0	PET by Blaney-Criddle (1966)
3	- 28	1600	1864	869	0	PET by Thornthwaite (Thornthwaite and Mather (1957)
4	137	1522	1124	657	359	PET by pan evaporation
5	106	1477	1124	620	334	PET by pan evaporation
6	100	1522	1132	603	314	PET by pan evaporation, model subdivided

Prototype data: Precipitation = 2145 mm, runoff = 1277 mm.

^aMass = $\Sigma (Q - Q_p)$; ^bvar. = $\Sigma (Q - Q)^2$, where Q is the prototype daily flow, and Q_p is the predicted daily flow from the model. (All data in millimeters and square millimeters.)

This effort pointed up several unusual features peculiar to small forested watersheds. The leak that was introduced is a realistic explanation of inconsistencies experienced in small watershed studies. The concession made to the existence of a flow contribution performing as surface runoff (overland flow) is at variance with the current vogue in forest hydrology (Hewlett and Nutter 1970), but suggests a closer look at the process. The absence of a channel storage and routing procedure is a characteristic of small watersheds. The coniferous forest characteristics of the drainage were manifested in the model through the inclusion of vegetative and channel interception, high infiltration rates, interflow, and generous soil storage. Sensitivity studies to follow will evaluate their relative importance.

Continuing work on this model and watershed will examine and test improvements in the snow distribution and melt process, taking possible account of quick ground melt in the water situations; a variable channel interception function in accordance with the concept of varying source area (Hewlett and Nutter 1970); and further examination of the evapotranspiration subprocess.

DISCUSSION AND CONCLUSIONS

Future Applications, Opportunities, and Uses

A number of openings for applying models in problem solution and research present themselves. While neither complete nor entirely original, the following listing may provide interesting food for thought.

1. In the past (Fleming 1971, Sopper et al. 1969), watershed models have been used for simulation of land management or weather modification responses, or both. The results provide an insight into and suggestion of real responses. A major function of such studies is to raise new questions, both about process functions and about modeling details. For example, if timber cutting is the land management act suggested, the modeler must know which of the model parameters would be affected, in which direction, and to what extent. Thus new information is demanded, leading to more process studies.
2. The effects of perturbations or errors in certain process parameters on the several outputs could be evaluated, with an eye toward their relative importance. For example, the effect of channel precipitation parameters on flood peaks, or vegetative interception on total flow might be considered. An insensitive reaction would suggest that the process is modeled in sufficient detail; a sensitive reaction might suggest that the process should be further investigated, modeled in greater detail, or both.
3. As a basis for estimating the effects of process or input changes on the statistical characteristics of the output, statistical interpretations of hydrologic variables are both popular and necessary,

and are used in all phases of hydrologic engineering. The effects of weather modification on such as the daily mean, variance, skewness, and serial correlation of flows could have profound influences on reservoir design, flow duration curves, and the like. It would be a relatively simple matter to simulate and study these items through the use of models.

4. Application of a model as a research tool in calibrating watersheds in studies of land management effects would be an alternate to the customary paired watershed approach in watershed management research. A drainage basin to be "treated" (e.g., by timber cutting) is modeled so that chosen vectors of output such as daily, seasonal, or annual streamflows can be predicted to a given degree of statistical satisfaction. Then, while the monitoring of the input precipitation, temperature, wind, and the like is continued, the watershed is treated. The difference between the predicted model output and the on-site measured output can then be attributed to the land use change. In experimental situations, with proper data planning beforehand, a high degree of fit can be expected.

Conclusions

While studies are continuing in this specific area, the following conclusions are drawn from the experience thus far:

1. Despite anticipated and unexpected shortcomings and difficulties, the modeling idea seems to work. That is, output from the model matches output from the watershed reasonably well. If not statistically satisfying, it is intuitively pleasing.
2. Data assembly and rectification are both important and time consuming. A great deal of effort must go into this activity before the main act of modeling. Potential modeling efforts should beware of the data requirement.
3. Internal model and data checks should be arranged if at all possible. That is, internal storage data such as soil moisture, snow, or both should be used as checks on the internal operation of the model.
4. Certain infrequently collected information, such as snow water content, albedo, radiation, wind, soil temperature, soil moisture, groundwater levels, and pan evaporation can be important and can be used in hydrologic modeling. The absence of data of this sort restricts further resolution and refinement in modeling. The groundwater item is particularly important because of the large role it can play in water budgeting.
5. Two processes seem to be critical in modeling, (1) evapotranspiration and (2) snowmelt and storage. It is unfortunate that there does not seem to be a suitable ET estimation technique for

wild lands. The existing methods were derived for irrigated flatland situations. The on-land storage characteristics of snow, its thermal properties, and its data similarities to rain act to make it a major factor, when present. Model output seems to be most responsive to these two processes.

6. The role of judgment and subjective interpretation is still prominent. Modeling is still an intellectual activity, and a large part artistic. A "feeling" for the situation and processes is necessary. It requires judgment, knowledge, and familiarity with the details of the hydrologic cycle. Modeling is the finest product of the hydrologist's art.

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