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A SYSTEMS APPROACH TO REAL-TIME RUNOFF ANALYSIS WITH A DETERMINISTIC RAINFALL-RUNOFF MODEL

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California-Nevada River Forecast Office
Sacramento, California
April 1981

UNITED STATES
DEPARTMENT OF COMMERCE

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

National Weather
Service
Richard E. Hallgren, Director

This Technical Memorandum has been reviewed and is approved for publication by Scientific Services Division, Western Region.

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Western Region Headquarters
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A SYSTEMS APPROACH TO REAL-TIME RUNOFF ANALYSIS WITH A DETERMINISTIC RAINFALL-RUNOFF MODEL

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ABSTRACT. The responsibility for providing the United States with warnings of river conditions was assigned to the National Weather Service in 1890. This requirement has led to the development of a systems approach to hydrologic data collection, runoff computation, and forecast production which is being developed and applied in the service area of the California-Nevada River Forecast Center. This system is focused on producing information on the future distribution of water in time and space which affects the safety, welfare, and economic well being of the nation and its inhabitants.

A principal element of any hydrologic warning system is an effective rainfall-runoff model. The authors have constructed such a model, which is now being generally applied by the National Weather Service. It has been our goal to construct a physically realistic and understandable model which, although necessarily parametric, would describe the runoff generation process in a manner which was consistent with the physics of plant, atmosphere, and soil-water interaction. As a basic part of this effort, it was considered necessary to model the percolation process in a manner which retained the desirable infiltration characteristics described by Horton and others and to recognize and improve upon the limitations which such systems possessed.

The formulation of such a system did not, however, solve the rainfall-runoff analysis problem. As the runoff equations were developed to a high level of effectiveness, they led to an ever-increasing appreciation of the deficiencies in available rainfall data. The magnitude of the rainfall data problem, coupled with the authors' responsibilities for real-time river forecasting, led to an additional effort to improve the effectiveness, timeliness, and stability of precipitation measurement in order to provide better data input to the runoff analysis process.

These efforts have recently led to the completion of highly cost-effective computerized techniques for real-time data collection and analysis. The basic measuring device utilized for such data collection is a self-reporting gage which sends each increment of data via an event-activated radio system.

Data storage, analysis, and the forecasting of hydrologic responses may be accomplished instantaneously with such a system. More commonly, however, a hydrometeorologist maintaining close surveillance by interacting with a powerful minicomputer, can incorporate site-specific weather forecasts

into a local hydrologic analysis. This makes it possible for the first time to provide site-specific, quantitative, and reliable rainfall-runoff analysis, i.e., flood forecasts suitable for effective warning, evacuation, or flood fighting in even the smallest basins.

Thus, a systems approach to real-time runoff modeling includes not only an effective deterministic rainfall runoff technique which allows rational analysis of the physical processes— it must also include effectively automated, dimensionally stable inputs, reliable communications, and refined short-term hydrometeorologic forecasts. The development of such an approach provides important feedback mechanisms which provide conjunctive improvements in both the real-time meteorological and hydrological analyses.

I. INTRODUCTION

In 1890 the United States Congress established a new agency, now known as the National Weather Service, to provide public weather and hydrologic warnings. Recognizing the significant interdependence of hydrologic and meteorologic warnings, the National Weather Service has attempted to meet its assigned responsibility throuh the design, testing, and application of equipment and procedures which contributed to the conjunctive success of this dual mission.

At the present time, thirteen National Weather Service River Forecast Centers carry the primary responsibility for those hydrologic warnings which can be quantitatively produced. For those locations where discrete warning techniques have not yet been developed, general warnings are provided by the nation's many Weather Service offices. Such warnings, based upon an interpretation of hydrologic and meteorologic data, lack the specificity which can be obtained from discrete analysis. They do, however, provide important information to locations where more discrete technology is inappropriate or is not yet available.

The process of producing discrete hydrologic warnings affecting the safety, welfare, and economic well being of the nation and its inhabitants is now being advanced through the application of a highly cost-effective technology. Although this automated technology has been applied only over a limited portion of the United States, the potential benefits which can be gained from it are enormous. The analysis of flood threats and the evaluation of potential river flows and surface water availability all stem from the same data collection and analysis techniques. As a consequence, similar systems are being planned for many areas in the United States. The completion of these systems is expected to contribute well over a billion dollars a year in economic benefits to the nation through reduced flood damages and increased effectiveness of water management decisions.

The systems which hold such substantial promise have already produced benefits well in excess of development and operational costs in the limited areas where they have been applied. These benefits will become available to a growing portion of the United States as the resources become available to allow implementation of a systems approach. At the present time, areas of the western United States are enjoying the first fruits of these system concepts (Bartfeld and Taylor, 1980).

II. RAINFALL-RUNOFF MODELING

A key element in the technology of automated hydrologic warnings has been the development and application of an effective rainfall-runoff methodology. After extensive testing nationally and internationally (World Meteorological Organization 1975), the National Weather Service selected the Sacramento Rainfall Runoff Model (Burnash, Ferral, and McGuire, 1973) for this purpose. The Sacramento model is a deterministic generalized hydrologic model which is based upon a parametric conceptualization of percolation, soil moisture storage, drainage and evapotranspiration characteristics. Each variable required in the model is intended to represent a discrete and recognizable characteristic required for effective real-time hydrologic analysis.

The definition of model parameters is achieved by establishing a soil moisture computation which allows the determination of basin streamflow from basin precipitation. Effective moisture storage capacities in the soil profile are estimated not by sampling of the soil profile, but by inference from the rainfall and discharge records. The five basic soil moisture components of the model are upper zone and lower zone tension water storages, which are filled preferentially by infiltrated water, and three free water storages. Upper zone free water storage supplies water for percolation to lower zones and for interflow. The two lower zone free water storages fill simultaneously from percolated water and drain independently at different rates, giving a variable groundwater recession. These storages are diagrammed in Figure 1.

Rainfall occurring over the basin is considered as falling on two basic areas: 1) a permeable portion of the soil mantle, and 2) a portion of the soil mantle covered by streams, lake surfaces, marshes, or other impervious material directly linked to the streamflow network. The first area produces runoff when rainfall rates exceed percolation rates, while the second area produces direct runoff. In the permeable portion of the basin, the model visualizes an initial soil moisture storage identified as Upper Zone Tension which must be totally filled before moisture becomes available for other purposes. This represents that volume of precipitation which would be required under dry conditions to meet all interception requirements and to provide sufficient moisture to the upper soil mantle so that percolation to deeper zones and sometimes horizontal drainage could begin. When the Upper Zone Tension volume has been satisfied, excess moisture above the Upper Zone Tension water capacity is temporarily accumulated in Upper Zone Free Water. Upper Zone Free Water is that volume of moisture in the upper level soil from which lateral drainage, appearing as streamflow, is observable. This form of lateral drainage is identified as interflow. Upper Zone Free Water not only has the horizontal potential to generate interflow, but more significantly has a vertical potential. The rate of vertical drainage is controlled by the contents of the Upper Zone Free Water and the deficiency of lower zone moisture volumes. The preferred path for moisture in Upper Zone Free Water is considered to be vertical. Only when the rate of infiltrated precipitation exceeds the rate at which vertical motion can take place from the upper zone, does horizontal flow in the form of interflow occur. If the precipitation rate exceeds the percolation rate and the maximum interflow drainage capacity, then surface runoff occurs. Under this system, surface runoff is a highly rate-dependent volume with the rate of runoff being determined by the rate of precipitation application and the degree of dryness of the different zones.

The percolation mecahnics have been designed to correspond with observed characteristics of the motion of moisture through the soil mantle and is intended

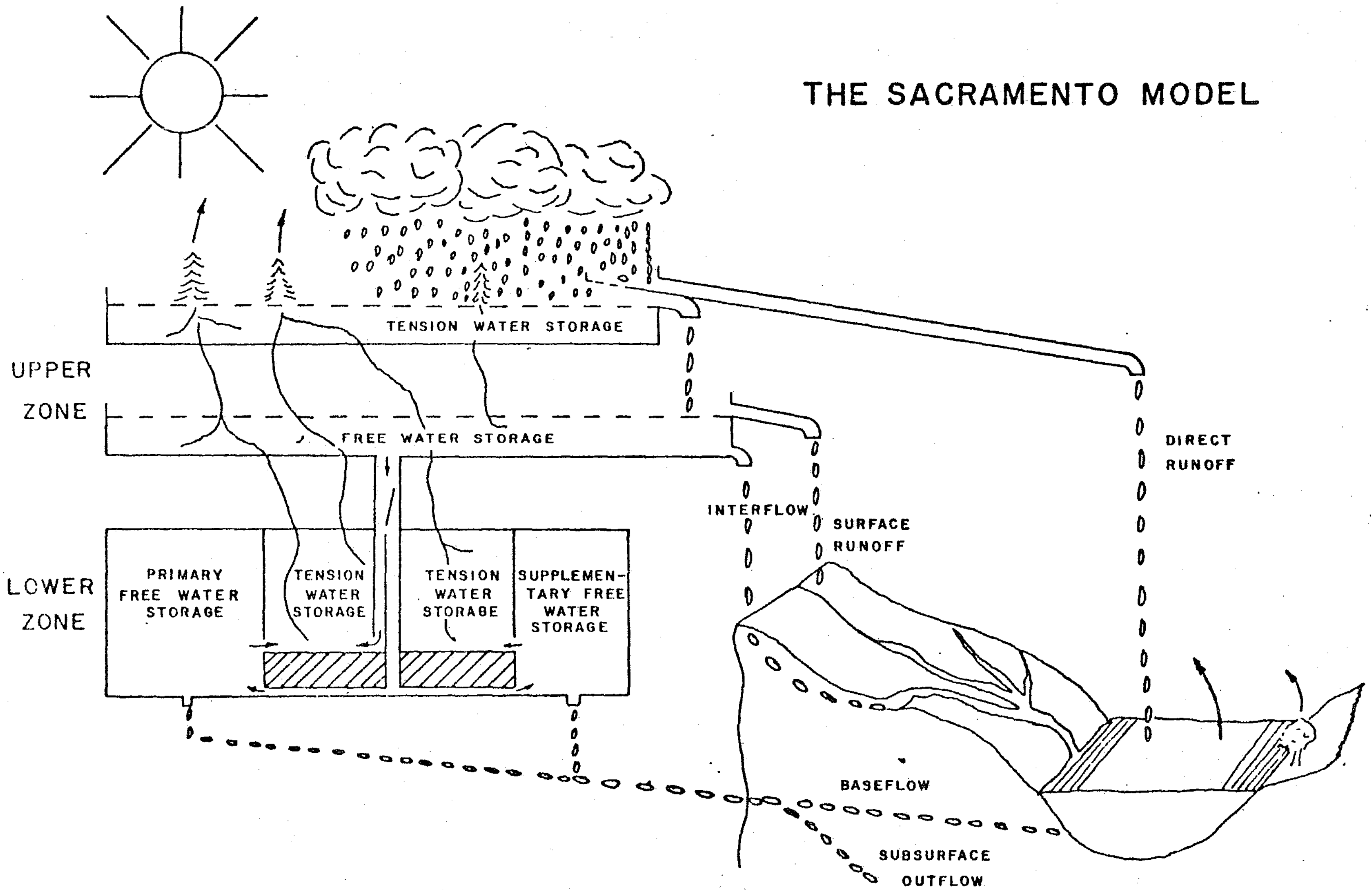

Figure 1. Sacramento model. A conceptual real-time deterministic hydrologic model.

to parallel the formation and transmission characteristics of the wetting front in the soil mantle. Water in excess of Upper Zone Tension requirements can percolate to a deeper portion of the soil mantle through transfer by Upper Zone Free Water. The mechanics of transfer from upper zone to lower zone volumes is based upon the computation of a lower zone percolation demand. When the lower zone is totally saturated, the percolation into the lower zone must be limited to that water which is draining out of the lower zone. This limiting drainage rate is computed as the sum of the products of each of the two lower zone free water storages and its drainage rate. If this limiting rate of drainage is defined as PBASE, then there exists under the driest circumstances a lower zone potential for accepting percolation which is larger than PBASE by a quantity which may be defined as Z*PBASE. Thus, the percolation under all circumstances can be estimated by evaluating the change from PBASE*(1+Z), the driest percolation condition, to PBASE, the saturated percolation condition. An exponential relationship defined by the exponent, REXP, provides a curvilinear percolation form capable of reproducing widely varying percolation characteristics reported in the literature. The resulting equations which reproduce these characteristics are:

Percolation Demand =

$$\text{PBASE}*\left(1+Z\left(\frac{\Sigma(\text{Lower zone capacities less contents})}{\Sigma(\text{Lower zone capacities})}\right)^{\text{REXP}}\right)$$

$$\text{Percolation} = \text{Percolation Demand}*\left(\frac{\text{Upper zone free water content}}{\text{Upper zone free water capacity}}\right)$$

The sums of lower zone capacities and contents include both tension water and free water. Thus, percolation is defined by an interrelationship between soil drainage characteristics and soil moisture conditions. The volume which is percolated to the lower zone is divided among three significant soil moisture storages. The first of these, lower zone tension, represents that volume of moisture in the lower zone soil which will be claimed by dry soil particles when moisture from a wetting front reaches that depth. The tension water capacities defined in this model are capacities for change. In the lower level this is the difference between that water held against gravity after wetting and that remaining after plant roots have extracted all that they are capable of withdrawing. In the upper zone some additional water is lost and the tension water capacity is enlarged by direct evaporation from the soil. Tension water deficiencies would absorb all percolated water until these deficiencies are satisfied. However, variations in soil conditions and rainfall amounts over a drainage basin cause variations from this condition. The effect of these variations is approximated by diverting a fraction of the percolated water into lower zone free water storages before tension water deficiencies are fully satisfied. The free water storages in the lower zone represent those storages which generate horizontal flow generally observable as increase in base flow at the gaging point. As the tension water storage is completely filled, all percolation is diverted to free water storages. At all times the distribution of percolated water between free water storages is a function of their relative ratios of contents to capacity.

If the natural boundary conditions of the basin should allow all applied moisture to leave the basin either at the gaging point or through evapotranspiration, these soil moisture divisions would be adequate. However, subsurface drainage bypasses the gaging site in many basins. In order to approximate this effect within a particular basin, it is assumed that those soils in areas draining in a direction or to a depth away from the stream channel have the same basic drainage characteristics as those soils which drain to the stream channel. Thus, the volume of such subsurface flows can be expressed as a fraction of the volumes integrated from the surface outflow hydrographs. This volume exists within the basin in addition to the volumes which will be observed through the surface outflow hydrograph.

Streamflow is, thus, the result of processing precipitation through an algorithm representing the uppermost soil mantle and lower soils. This algorithm produces runoff in five basic forms: 1) direct runoff from permanent and temporary impervious areas, 2) surface runoff due to precipitation occurring at a rate faster than percolation and interflow can take place when both upper zone storages are full, 3) interflow resulting from the lateral drainage of a temporary free water storage, 4) supplementary base flow, and 5) primary base flow. Runoff forms one and two have similar drainage characteristics while the drainage of each of the remaining components corresponds to observed streamflow features with uniquely different characteristics.

It should be noted that the proportion of impervious runoff, i.e., direct runoff, does not remain a constant with this model. It has been observed in many basins that upon filling the tension water storages, an increasing area assumes impervious characteristics. This, the additional impervious area, provides a useful representation of the filling of small reservoirs, marshes, and temporary seepage outflow areas which achieve impervious characteristics as the soil mantle becomes wetter.

An examination of Figure 1 indicates that water percolating from the upper zone free water to the lower zone may go totally to tension water or some fraction of the percolated water may be made available to the primary and supplementary storages. At any time that the lower zone tension storage becomes filled, continued percolation is divided between the two lower zone free water storages. At all times water made available to primary and supplementary storages is distributed between them in response to their relative deficiencies.

Evaporation from water and phreatophyte surfaces is computed at the potential rate. Over other portions of the soil mantle, evapotranspiration is treated as the only process which depletes tension storage. As the soil mantle dries from evapotranspiration, moisture is withdrawn from the upper zone at the potential rate multiplied by the proportional loading of the upper zone tension water storage. In the lower zone evapotranspiration takes place at a rate determined by the unmet potential evapotranspiration times the ratio of the lower zone tension water content to total tension water capacity. If evapotranspiration should occur at such a rate that the ratio of contents to capacity for available free water exceeds the ratio of contents to capacity of tension water, then water is transferred from free water to tension water and the relative loadings balanced in order to maintain a moisture profile that is logically consistent. Depending upon basin conditions, some fraction of the lower zone free water is considered to be below the root zone and, therefore, available for such tranfers. Various algorithms have been utilized to compute evapotranspiration demand. Hounam (1971) has documented many of the procedures intended for such purposes and indicated many of the problems associated with them. The authors are presently utilizing either daily mean values of evapotranspiration varying with day of the year and defined by model optimization techniques or redimensioned computations of daily evaporation based upon the work of Kohler, Nordenson, and Fox (1955). If computed values are used, they are adjusted by a coefficient that varies with day of the year.

Although the system mechanics of the generalized hydrologic model are simplified approximations of natural processes, the total effect is consistent with observations of the soil moisture profile made by experimental studies such as those by Green et al (1970) and Hanks, Klute, and Brestler (1969).

III. INFILTRATION COMPARISONS

Horton (1939) suggested an infiltration equation which has become quite famous as a technique for computing infiltration. The equation:

$$f = f_c + (f_o - f_c)e^{-kt}$$

is actually a simple decay curve where

f = infiltration rate at time t

f_c = a minimum infiltration rate

f_o = the infiltration rate of $t = \emptyset$

e = the Napierian base

k = a decay constant

t = time

A plot of the log of the derived infiltration versus time is a straight line with a negative slope. Computation of continuous infiltration capacity requires that rainfall be in excess of infiltration throughout the time period. As written, the equation is not applicable for intermittent rainfall, with alternate wetting and drying periods, or for rainfall that does not continuously exceed f. Infiltration capacity almost always exceeds rainfall rates early in a storm, resulting in actual infiltration rates equal to rainfall rates, as described and explained by Mein and Larson (1973). Holtan (1961) and Bauer (1974) proposed modifications and elaborations of Horton's equation for application to intermittent rainfall. They approached this by making infiltration a function of moisture in the soil, not time as such.

The Sacramento model, though not designed as an infiltration model, provides an indication of the vertical distribution of water in the soils. The modeled components of runoff, and by implication net infiltration as the difference between rainfall and runoff, are compared as functions of moisture contained in the soil. Though designed to be applied for real-time hydrologic analysis of runoff conditions with intermittent and variable natural rainfall, system mechanics can be applied to continuing rainfall in excess of infiltration to provide an interesting comparison with Horton's equation. Some similarities and differences can be seen:

1) Observed infiltration curves show very high rates after a short time period, with initial rates at time zero undefined. Examples are seen in Rubin (1966), Mein and Larson (1973), Linsley, Kohler, and Paulhus (1975), and Green et al (1970). The Sacramento model similar to observed conditions provides for very rapid initial infiltration. This takes place as void spaces in the upper soil levels are being filled. Infiltration

then drops to a much lower rate which diminishes slowly with time, as rainfall in excess of infiltration capacity continues. When rainfall stops, infiltration capacity increases very quickly as moisture in upper soil levels drains away, then more slowly as lower soils drain and moisture is removed by evapotranspiration. These features are all compatible with natural conditions and are necessarily included in the model in order to provide an effective real time rainfall runoff transfer function for intermittent as well as continuous rain conditions.

2) Observed infiltration curves in Rubin (1966) p. 746, Green et al (1970) p. 869, Mein and Larson (1973) p. 390, and Linsley et al (1975) p. 263, when replotted in a log f vs t form, are concave upward. A typical plot is shown in Figure 2a. After the rapid initial infiltration rate, the Sacramento model's subsequent infiltration, with some parameter combinations, can give an infiltration-time curve very similar to Horton's, i.e., linear on a log f vs t plot (Figure 2c). More commonly, the Sacramento model gives a log f vs t curve that is concave upward, equivalent to a Horton's k that diminishes with time. A typical plot is shown in Figure 2b. Other parameter combinations, much less common, can give a concave log f vs t curve, equivalent to a Horton's k that increases with time.

Thus, it appears that the Sacramento model has substantially greater flexibility in modeling the diverse observed infiltration curves than is possible with the classical Horton equation. In addition, it provides a reasonable estimate of initial wetting conditions which are not adequately described by Horton's equation.

IV. DATA COLLECTION

This modeling process, in order to be effectively applied for purposes of hydrologic warnings, must necessarily be supported by an effective real-time data-collection system. Manual observations techniques rarely provide sufficiently timely or dimensionally stable data for adequate effectiveness in hydrologic warnings. As a consequence, the application of the Sacramento model with data systems, which in the past were considered acceptable, has led to numerous problems. The model sensitivity, a requirement for more effective analysis, exposed the inadequacy of many existing database systems.

Very few manual observation techniques can maintain a measurement accuracy of five percent over a prolonged period of time. The growth of vegetation, the construction of buildings, slight changes in equipment or exposure all contribute to a lack of consistency.

If such inputs are used in a sensitive model, the impacts upon runoff projections can be quite large. As an example of the sensitivity problem, Figure 3 illustrates the effect of the change in forecast runoff which is produced by a five percent change in the precipitation input. This problem has led to the development and application of fully automated data-collection systems which were more appropriate to the needs of an operational warning system.

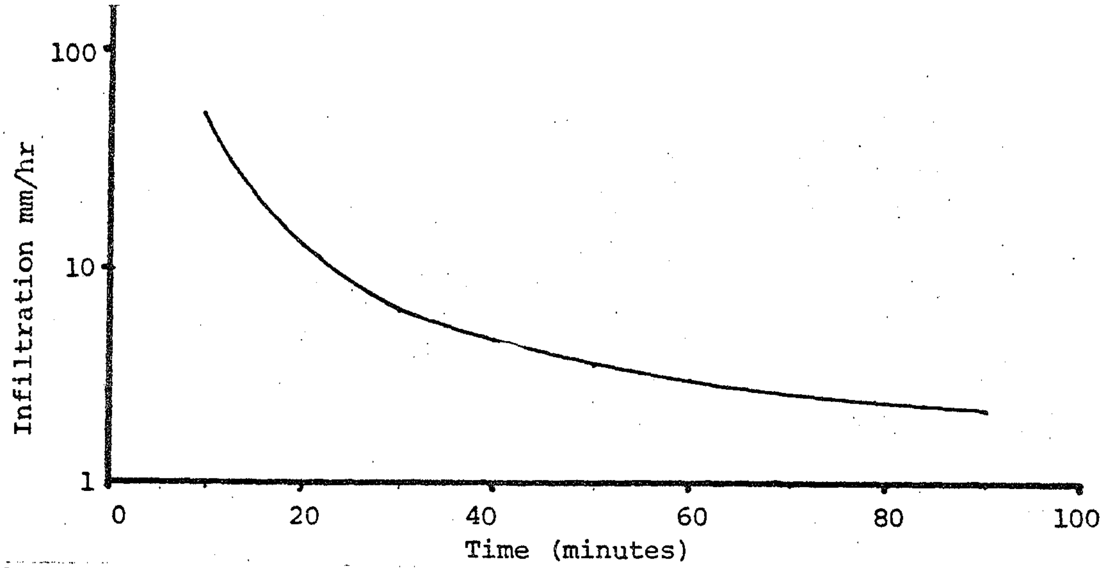

Figure 2a. A typical observed infiltration curve plotted as log f vs time. (Replotted from Linsley, Kohler and Paulhus, Houston black loam.)

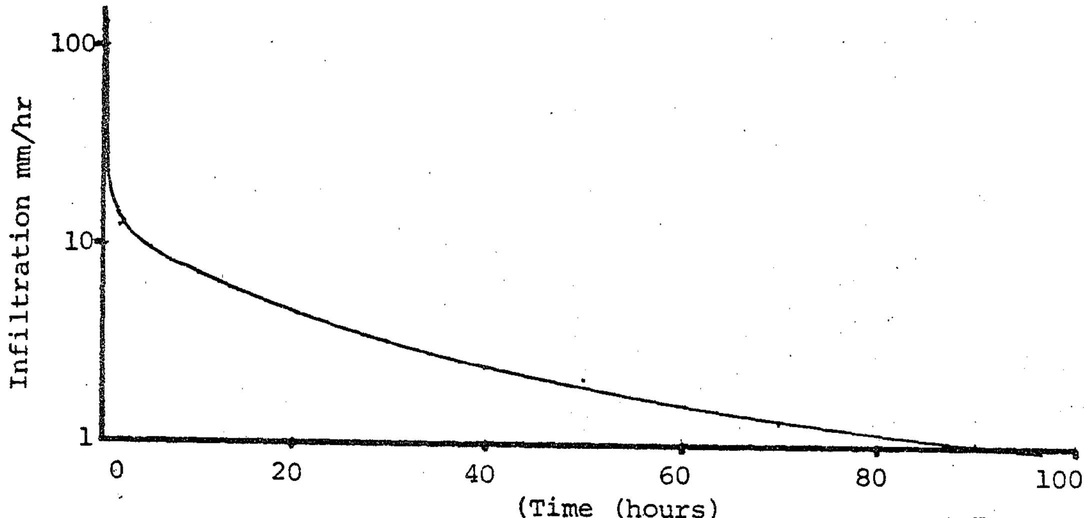

Figure 2b. An infiltration curve generated by the Sacramento model, plotted as log f vs time. (Parameters fitted to Arroyo Seco, California. Excess water applied after wetting and prolonged drying.)

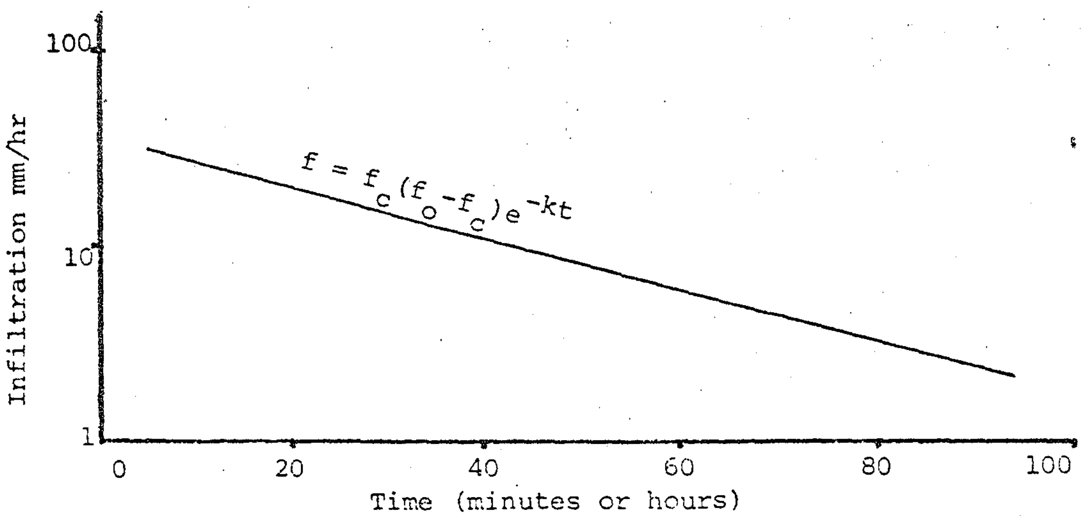

Figure 2c. Horton's equation plotted as log f vs time.

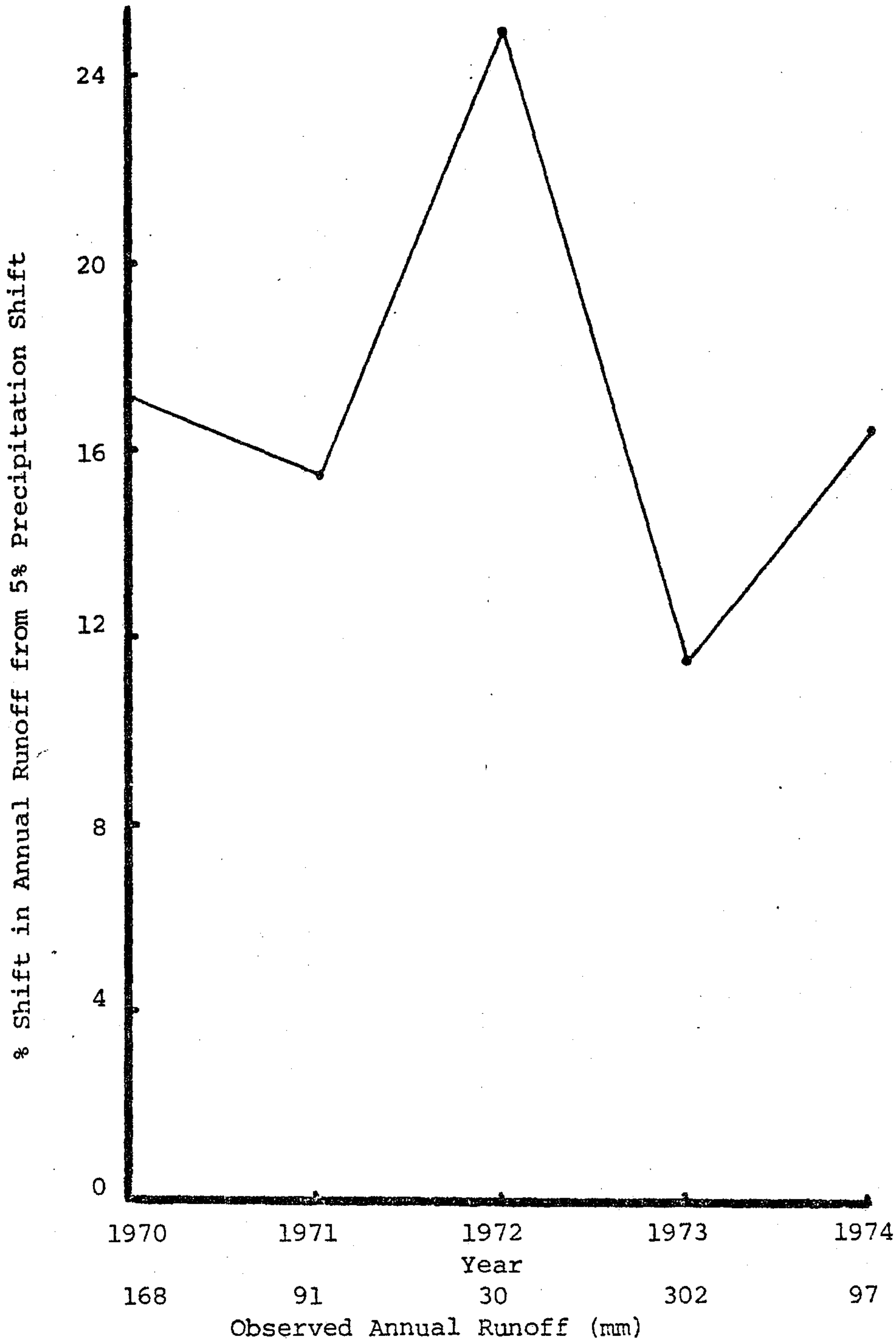

Figure 3. Computed change in runoff produced by a five percent change in precipitation input. Sespe Creek, Ventura County, California (655 sq. km).

That system of automated data which has demonstrated the most effective benefit-cost ratio is based upon installing totally self-contained sensors at those locations where data are required. Such sensors contain their own power supply and communication equipment. Whenever there is a change in the sensor value, the units transmit a self-initiated radio message. Under conditions when the sensors are not producing changes, reports are sent at periodic intervals to verify system operation. To date, this technology has been applied to precipitation, snow pack, temperature, and water levels. A remarkable auxiliary benefit of automated data collection was a reduction in the true cost of collecting data (Burnash and Bartfeld, 1980).

Of primary interest to most hydrologists are the precipitation gages. Three types of precipitation gages are utilized. They are: 1) a simple rain gage for relatively snow-free areas, 2) a modified design for areas where snow occurs but where the winter precipitation does not exceed one hundred centimeters of water content, and 3) the deep snow gage which may be used in areas where the snow depth can reach as much as seven meters, see Figure 4. All sensors send brief radio signals, less than one-quarter second in duration, which place a very small load on the power supply. A single four-kilogram battery has adequate reserves to power a precipitation gage for over a year in the wettest areas of the world. Such gages have been installed utilizing basically line-of-sight radio transmission paths. Data are acquired by a minicomputer which monitors a radio receiver. Where direct radio transmission to a base station is not feasible, radio relays have been utilized. At some locations data are received and interpreted by local microcomputers. These microcomputers meet local requirements for data and site-specific hydrologic warnings. The microcomputers are programmed to allow telephone polling by the River Forecast Center. An example of various communications paths is shown in Figure 5.

Inasmuch as the River Forecast Center computer can be set to interrogate local data collection minicomputers on the basis of satellite imagery or other meteorological data, the telephone polling can be kept at a cost-effective level. The frequency of interrogation is dependent upon the significance of the event. At the River Forecast Center, the data are analyzed by a powerful minicomputer which has in storage the hydrologic characteristics of all areas for which forecast service is provided. The River Forecast Center computer evaluates the precipitation input for the area and through the Sacramento model produces forecasts of runoff and streamflow. Upon completion of the discharge analysis, the computer evaluates significant stage conditions associated with the discharge forecast and prepares an English language statement of river conditions. Based upon the significance of the analysis, the system then determines the appropriate routing of the warning message and the information is routed to the appropriate local office.

At the present time, this developing technology is being applied to a limited but growing number of locations. Although the entire process of data collection, model application, forecast generation and distribution is not yet instantaneous, they can all be completed within minutes. This new dimension in timeliness is not restricted to an arbitrary data collection time, for data are constantly available and always current. Until very recently, the lack of timely data limited site-specific flood warnings to large, relatively slow-rising rivers. This limitation has been eliminated by the continuous collection of real-time data, the use of this data to improve short-term quantitative rainfall forecasts, and the automation of hydrologic data analysis and forecasting. It is now

Figure 4. Self-contained event reporting precipitation gages designed for various site conditions.

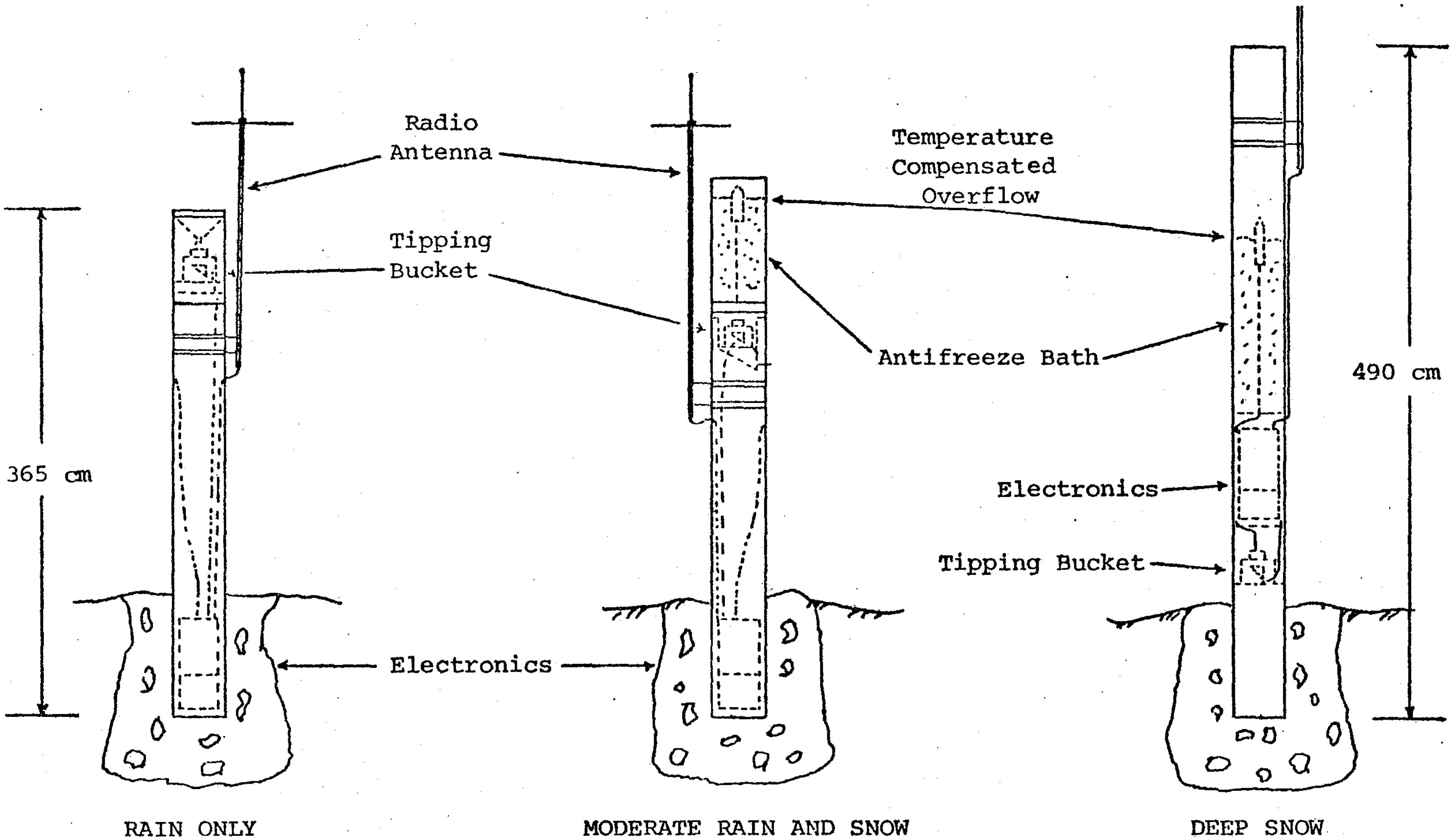

Figure 4. Self-contained event-reporting precipitation gages designed for various site conditions.

Figure 5. Typical data collection and communications system.

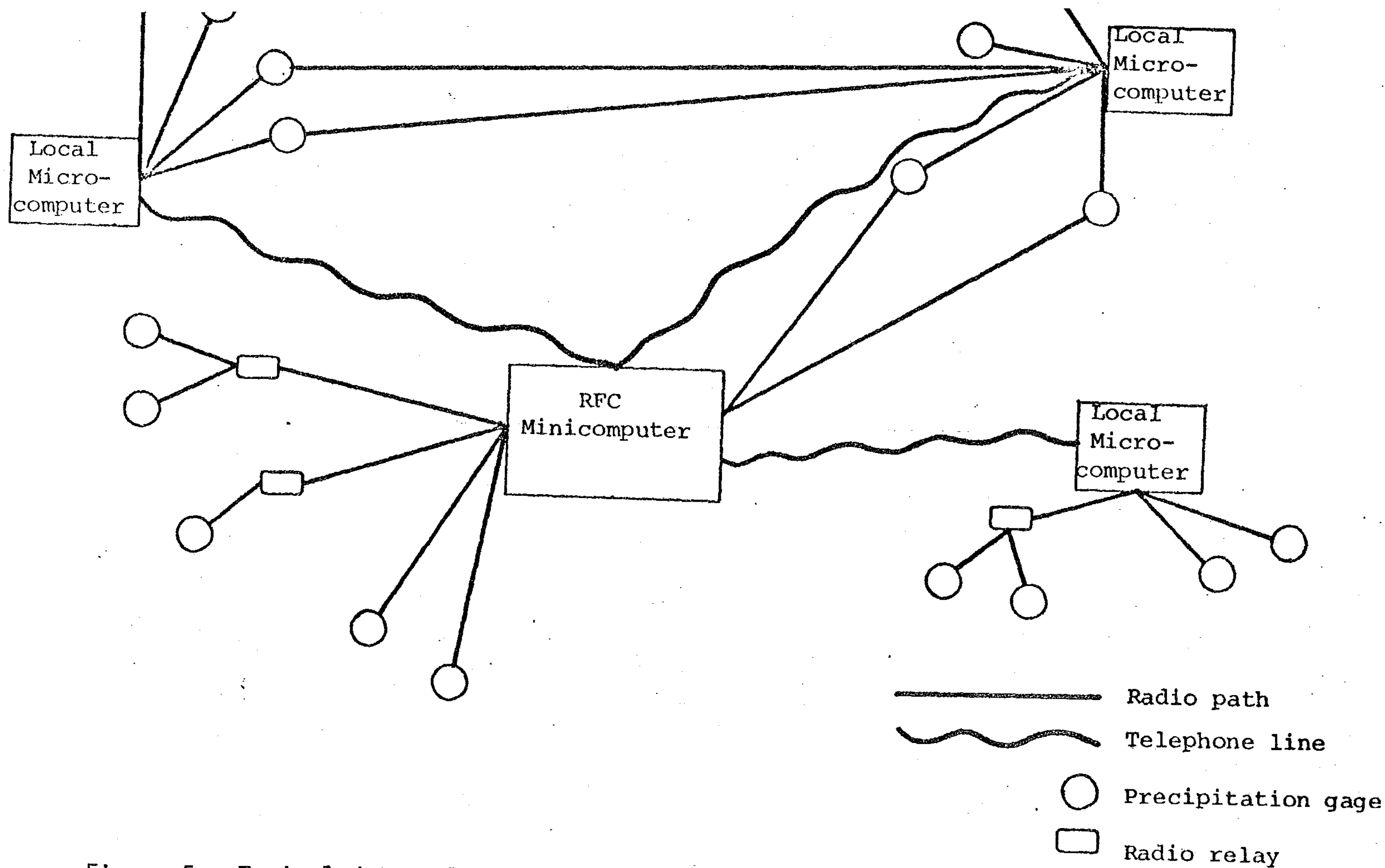

Figure 5. Typical data collection and communications system.

possible to provide effective flood-warning systems where some of the greatest flood hazards exist--along small, fast-rising rivers, creeks, and arroyos.

V. CONCLUSIONS

The combination of the rainfall-runoff model with the other technologies we have discussed has resulted in an information and processing system that not only solves old problems in a more efficient manner, it adds a new dimension to the supporting capability of the meteorologist. The data collected by these systems describe storm movements and intensity changes in a manner which allows a substantial improvement in the ability to evaluate precipitation which is likely to occur during the next few hours. The feedback of such determinations into the hydrologic analysis allows real-time warings to be generated for areas where the time from the slackening of heavy rain to crest conditions is in the scale of minutes.

Thus, real-time automated systems based upon effective data collection, continuous meteorologic and hydrologic analyses, and automated forecast generation and distribution provide the potential for a remarkable improvement in flood-warning programs.

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