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PACE WATERSHED MODEL (PWM): VOLUME 1, MODEL DEVELOPMENT

by

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INTRODUCTION

The modification of weather to produce greater amounts of precipitation is a subject of interest in the midwestern agricultural community. However, both rainfall and its temporal distribution are uncertain and highly variable processes, and it is not yet well understood whether potential increases in precipitation may come at a time or in amounts that are useful to agriculture. It is possible, for example, that extra rainfall would have greater impacts on areas other than agriculture, such as on the general water resources condition of a region. The Precipitation Augmentation for Crops Experiment (PACE) project was initiated to examine these gaps in the understanding of weather modification, with the specific goal of being able to assess the potential usefulness of summer rainfall increases.

The moisture brought by rainfall eventually contributes to one of four processes: 1) runoff into a stream, 2) seepage into ground water, 3) evaporation into the atmosphere, or 4) abstraction from the soil into plants for eventual transpiration into the atmosphere. Only the last of these processes is of primary benefit to agriculture.

Following precipitation, the distribution of water to the four processes listed above is a complex function of the spatial and temporal distribution of the rainfall and soil moisture, as well as of the general soil and crop conditions and subsequent climatic conditions. To properly quantify the precipitation-crop water situation it is necessary to understand the movement of water within the soil, which stores the water for plants. In addition, in order to evaluate consequent impacts on regional water resources conditions, it becomes necessary to relate the field conditions (at one or several locations) to the total picture on a larger watershed scale. This type of analysis requires a physically based watershed model.

The PACE Watershed Model (PWM) is a quasi-distributed-parameter model which was designed and constructed to simulate the movement of water through the hydrologic system for the purpose of analyzing the effects of precipitation augmentation. The model possesses the flexibility and power to be used for a broad range of hydrologic problems. In particular, the model is well suited for investigations in the area of weather and climatic variability, a field of which weather modification can be considered a component.

Results of this project are presented in two separate reports. The present report (Volume 1) describes the development of the PWM, including a general description of the hydrologic concepts and processes used in the model. Volume 2 presents the results of an application of the PWM to a small watershed in central Illinois and examines the hydrologic impacts of increases in summer precipitation.

Objectives

This research was pursued to increase our ability to assess the impacts on water resources and agricultural products that result from regional climatic changes caused by conscious and beneficial weather modification (such as precipitation augmentation) or by inadvertent weather modification. Since the long-term objective of the PACE project is to learn whether agriculturally useful increases in summer convective rainfall can be produced in the Midwest, the scope of this report will be limited to the study of the effects of rain modification during the critical agricultural water stress period of summer. However, the methods and procedures that have been developed are flexible and comprehensive enough to aid analyses of the impacts of climatic changes on different aspects of water resources.

To assess the potential impact of precipitation augmentation on agricultural productivity and fresh water resources, it is necessary to understand and evaluate the effects of such climatic changes on several components of the hydrologic cycle, such as soil infiltration, soil moisture, baseflow, and runoff.

There is no beginning or end to the hydrologic cycle. Evaporated and transpired water condenses in the atmosphere and returns to earth as precipitation. Some of this water runs off the surface and joins water bodies. Some of it infiltrates into soil and replenishes the soil moisture, and the excess soil moisture percolates further down to recharge the ground-water reservoir, which in turn feeds the lakes and rivers.

Processes like infiltration, soil moisture, baseflow, and runoff are usually studied by investigating watersheds. Watersheds are topographically defined areas which drain through a single outlet; thus applying water budgets to them is simple. The response of a watershed to variations in climatic variables can be analyzed by using watershed (or water-budget) models that can sufficiently describe the movement and distribution of water in the soil-plant-atmosphere interface. Watershed models provide the temporal and spatial resolution, flexibility, level of accuracy, and ease of use necessary for determining the effects of plausible weather modifications on water resources. Therefore the major task of this phase of the PACE project is to develop and employ a watershed model that can simulate variations in soil moisture, infiltration, baseflow, and runoff of a watershed caused by artificially increased summer precipitation, and that can also provide a reliable account of water over a certain period of time. A good watershed model is expected to simulate the temporal and spatial distribution of water within the watershed. The components of the watershed that need to be modeled depend on the area under study.

Water-budget models have several characteristics that make them attractive in hydrological modeling. They have proven to be both flexible and based on understandable physical concepts. They incorporate soil moisture characteristics of regions; permit month-to-month, seasonal, and annual estimates of hydrologic parameters; and use readily available data on meteorological phenomena and soil and crop characteristics. The spatial resolution of water-budget models can range from a few thousand square miles to between 10 and 50 square miles in the case of small watersheds. The temporal resolutions studied can also have a wide range: from annual to sub-hourly.

Desired Attributes for the PACE Watershed Model (PWM)

A model developed for analyzing the effects of weather modification should be able to incorporate the spatial variability of the region to be analyzed, should operate continuously, and should have the capability to use different time intervals for different events. After extensive evaluation it was decided that a model for the PACE project should have the following attributes:

1. It should be a physically based, semi-distributed-parameter model (a combination of lumped- and distributed-parameter models). It should be able to separate the watershed area into smaller segments or sub-watersheds, each segment with relatively similar physical characteristics, to approach the concept of a distributed-parameter model. The most desirable model is a fully distributed model in which all the watershed characteristics are explained by spatially varying, physically based parameters. Such models are expensive in terms of both data requirements and computational costs because an attempt is made to incorporate all the spatial variability of watershed properties (such as land slope and soil type) into model formulations by using large numbers of parameters. The lumped models, on the other hand, are easier to use but usually require extensive calibration for each watershed. This conflict can be relaxed if some of the parameters can be lumped to form physically based, semi-distributed-parameter models. Such models are especially useful for analyzing ungaged, rural watersheds because the need for model calibration for each watershed is partially eliminated.
2. A sequential (continuous) operation model is needed, rather than an event model (single storm or flood model). Sequential models are needed for analyzing the hydrologic conditions over an extended period of several months (e.g., during the crop growth season). The model should also be able to handle storm events, if necessary.
3. The model should have the capability to use small time increments (say, hours) during storm events, and longer intervals (say, days) during sequential operation. This enables better simulation of infiltration and soil moisture during storm events, and requires less computing time during dry periods.
4. Rainfall hydrology is the primary area to be modeled for the purpose of PACE, with submodels to consider infiltration, evapotranspiration, soil moisture, subsurface flow, overland flow, and channel routing.
5. Other climatic parameters to be considered are temperature, potential evaporation, wind velocity, and relative humidity. Physical data

needed include soil and infiltration characteristics, layered-soil profiles for soil moisture accounting, and data on land use, soil cover, topography, and stream network.

6. The modeling capability should extend to a 100- to 1000-square-mile area.
7. The structure and design of the model must be based on considerations regarding the degree of model complexity and the calibration and data requirements that are practical, viewed against the adequacy of the model's representation of the watershed.
8. If there is a need for calibration, the model should have a self-optimizing capability for estimating watershed parameters to avoid numerous trial-and-error solutions.

Two characteristics of the lumped-parameter-type models make them conceptually undesirable for the PACE project. First, when various land-use characteristics are lumped together so the hydrologic response of a total watershed may be estimated, the ability to estimate the effect of precipitation augmentation at the field level is lost. Second, lumped-parameter systems usually require some amount of calibration on the basis of existing streamflow records in order to properly evaluate the massed response of the watershed. On the other hand, distributed-parameter systems generally rely on more physically oriented modeling techniques that require no or minor calibrations, but these systems are more expensive in terms of both computing and data requirements.

Need for a New Model

To develop a watershed model from scratch that has all the desired attributes is an extensive and time-consuming task. To reduce time and effort, a detailed investigation was made of existing watershed models. The investigation showed that none of the existing models was capable of performing all the desired tasks described above. Almost all the available distributed-parameter-type models emphasized a single process; most were designed to simulate events and could not be used in the continuous operation mode. Only a few were capable of modeling soil moisture conditions during the growing season for which precipitation augmentation would be considered desirable. The models that were suitable either required extensive calibration to simulate soil moisture conditions, or were not adequate for describing the effects of precipitation augmentation on water resources. Only a few of the models described baseflow adequately, and these were dedicated and very detailed models which simulated ground-water flow without considering other components of the hydrologic cycle. The models that attempted to simulate all (or most) components of the hydrologic cycle were overwhelmingly detailed in certain aspects, whereas other Darts were modeled crudely.

To adequately simulate the effects of hypothetical precipitation changes on the water balance of an agricultural region, and thereby offer some insight as to how (and where) to measure the effects of actual cloud seeding experiments, it is necessary to model the relevant components of the hydrologic cycle in a physical manner. For this reason it was decided that a new, hybrid watershed model was needed. This model would combine the capabilities of existing models so the impacts of human activities on the hydrologic cycle and therefore on water resources could be analyzed.

The new model was conceptualized as a quasi-distributed-parameter model (a combination of lumped- and distributed-parameter-type models). It required minor calibrations for some benchmark soil groups in Illinois so that further calibrations for other watersheds with the same soil groups would not be needed. It can be operated either as a sequential model by using daily data, or as an event model (if desired) for modeling streamflows during storms by using hourly data. In contrast to the inherent structures of the existing models, which are discussed in the next section, the new model makes extensive use of physically based information such as information on land contours and soils, soil physics, and plant physiology. The PWM has a modular structure in which soil moisture, evapotranspiration, infiltration, ground-water flow, and surface flow are separate components. This modular structure was very useful in importing several sub-models from existing models and fusing them together after the desirable modifications and testings were done.

End Products of the PWM

The PWM should be able to provide information for analyzing the effects of precipitation augmentation on the following:

Agriculture

Soil moisture

Droughts and low flows

Protected and instream flows

Flooding

Water supply

Recreation

Although the purpose of the PWM is to provide information for assessing the effects of precipitation augmentation on agriculture and soil moisture, information about the other factors can readily be obtained as a by-product of the study. This information will be valuable in evaluating the overall impacts of precipitation augmentation on our water resources systems.

Since the PWM uses extensive (but readily available) climatic and physiographic data, it can also be used in real-time operation for predicting future soil moisture deficits, provided that short-term (a month or two) climatic forecasts are available. Such predictions, especially during crop growth periods, are vital in making major long-term decisions regarding precipitation augmentation, supplemental irrigation, or a change to a different crop type to maximize agricultural benefits or minimize damages.

The developed model has undergone extensive testing and some calibration so it can adequately represent changes in soil moisture and streamflows for different precipitation and temperature conditions over a number of years. Its use in the PACE project will also help in answering some of the following questions:

1. How much increase in soil moisture and streamflow occur from different levels of precipitation augmentation for different storms, as determined by the stochastic as well as the deterministic mode?
2. Can an operational procedure be developed for short-term decision making regarding whether to augment precipitation forecast a day or two in advance, on the basis of soil moisture and predicted effect of increased precipitation on soil moisture and streamflow?
3. What is the smallest amount of predicted storm precipitation that should be considered for precipitation augmentation? Models of soil moisture versus crop yield, developed by agricultural economists, may be used for economic analyses.

4. What kinds of field measurements are needed to verify the predicted effects of precipitation augmentation? These measurements will also serve a useful purpose in decision making regarding precipitation augmentation for the next storm. This will lead to a satisfactory monitoring network design.

Acknowledgments

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EVALUATION OF VARIOUS AVAILABLE MODELS

Several authors (Linsley, 1982; Renard et al., 1982; James et al., 1982; Overton and Meadows, 1976) have classified watershed models according to different criteria. For example, watershed models can be classified as physical or mathematical; sequential (continuous) or event (discrete); dynamic or static; deterministic or stochastic; black-box; or lumped-parameter or distributed-parameter. A clear distinction among the classifications cannot always be made because of the variability in the manner in which individual processes are represented. We have attempted to classify models according to the type (lumped or distributed parameter), operation (sequential or event), time and areal scale, general application, and processes represented. Black-box models have not been considered here because their parameters usually do not represent any physical properties of watersheds. Since a large number of models was available, an initial screening was performed on the basis of the desired attributes of the PWM. Only after that were the remaining models classified.

Major Hydrologic Simulation Models

Most of the models that passed the initial screening are major hydrologic simulation models somehow related to the Stanford Watershed Model, SWM (Crawford and Linsley, 1966). The SWM attempts to model most of the hydrologic processes (land phase) in the hydrologic cycle, and it is basically a lumped-parameter model. Several versions of the SWM have evolved following modifications and revisions.

The Kentucky Watershed Model, KWM (Liou, 1970) is an adaptation of the SWM to the climatic and geographic conditions of Kentucky. OPSET is an improved version of KWM that incorporates an optimization technique for estimating some of the watershed parameters (Liou, 1970).

USDAHL-74, a major revision of the SWM that was developed by the U.S. Department of Agriculture (Holtan et al., 1975), incorporates the effects of soil type, vegetation, pavement, and farming practices on infiltration and overland flow. The USDAHL-74 model has relatively extensive data requirements. Continuous records of precipitation, weekly average temperatures and pan-evaporation amounts, and detailed data on soils, vegetation, land use, and cultural practices are required. The model has primarily been used by the Soil Conservation Service for preparing environmental impact statements.

Another version of the SWM, the Streamflow Synthesis and Reservoir Regulation (SSARR) model (U.S. Army Corps of Engineers, 1972), was developed primarily for streamflow and flood forecasting and for reservoir design and operation studies. This model was one of the earliest sequential streamflow simulation models using a lumped-parameter representation.

Yet another version of the SWM (the NWSRFS model) was developed by the Hydrologic Research Laboratory of the National Weather Service (U.S. National Weather Service Office of Hydrology, 1972). The NWSRFS model was developed for use by the National Weather Service in forecasting river flows and stages. Since the NWSRFS model was intended for large basins, it uses larger time increments than the SWM, as well as simpler programming, fewer process computations, and a more rapid procedure for determining optimal watershed parameters.

The most sophisticated version of the SWM was developed by Hydrocomp, Inc., and has been named the Hydrocomp Simulation Program FORTRAN (HSPF) (Crawford, 1971). It incorporates hydraulic reservoir routing and kinematic-wave channel routing techniques. Water-quality simulation capabilities are also included in the model.

A hydrologic simulation model, the European Hydrologic System (SHE), has been developed by the Danish Hydraulic Institute, SOGREAM (France), and the Institute of Hydrology (UK) (Beven et al., 1980). In contrast to the above-mentioned models, this is a physically based distributed-parameter-type model. The SHE model incorporates components for the processes of overland and channel flow and unsaturated and saturated subsurface flow, which have been developed from nonlinear partial differential equations of flow and which are solved by finite-difference methods. SHE is basically an event model. An economically viable and operational version has not yet been implemented.

Rainfall/Runoff-Event Simulation Models

Another group of models (rainfall/runoff-event simulation models) uses a lumped-parameter approach to simulate the hydrologic response of a watershed during or just after a rainfall event. The TR-20 model (U.S. Department of Agriculture, Soil Conservation Service, 1973), which is basically a water surface profile computer program, has primarily been used by the Soil Conservation Service. It is designed to use soil and land-use information to determine the runoff hydrograph. The Storm Water Management Model, SWMM (Lager et al., 1971), developed for the U.S. Environmental Protection Agency, is basically an urban runoff simulation model and cannot be used for large rural watershed simulations. The HEC-1, the flood hydrograph package developed by the U.S. Army Corps of Engineers (U.S. Army Corps of Engineers, 1973), uses unit hydrograph synthesis to generate runoff volumes.

Process Models

In addition to major hydrologic simulation models and rainfall/runoff models, five other models were considered after the initial screening. These models attempt to simulate individual processes with a more-than-average level of sophistication, together with a rough approximation of the related processes. These process models usually require more detailed data than the other types of models.

The CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) model is a lumped-parameter model developed by the USDA (U.S. Department of Agriculture, 1980). Infiltration, evapotranspiration, and percolation processes are well modeled in the CREAMS model. Surface runoff and infiltration are estimated by using the SCS curve number method when only daily precipitation data are available. The Green-Ampt infiltration equation (Green and Ampt, 1911) is used for this purpose when sub-hourly precipitation data are used. Several soil layers have been considered in modeling the distribution of water in the soil matrix. The model is applicable to field-scale sites. A modified version of CREAMS, Simulator for Water Resources in Rural Basins (SWRRB) (Williams et al., 1985), was also considered. This model is designed for application to large complex rural basins.

The SPAW (Soil-Plant-Air-Water) model, developed by the USDA (Saxton et al., 1984), is very similar to the CREAMS model in its approach to the simulated processes. However, the SPAW model uses more sophisticated approaches to 1) simulate water movement in the soil, and 2) represent the relationships between soil moisture and crop characteristics such as rooting depth and crop water stress. The SPAW model uses a Darcian approach for redistribution of water among several layers of soil.

The ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) model (Beasley, 1977) is a distributed-parameter model that uses a grid system to delineate watershed elements. The ANSWERS model basically simulates tils flow, channel and overland flow, soil erosion, and sediment transport in agricultural watersheds. It is an event model, so evapotranspiration is not included in the simulations. The baseflow is very crudely modeled as a function of the ground-water storage volume, released at a uniform rate.

Among the process models investigated, only one model was selected for simulating ground-water and baseflow conditions. The model developed by Prickett and Lonnquist (1971) generates the water-table configuration in an unconfined aquifer by using the finite-difference form of the unsteady-state, partial differential equations of motion and continuity of flow. The P&L model uses the iterative alternating-direction-implicit (IADI) technique to calculate the water-table configuration at all nodes in an aquifer. The model can handle non-homogeneous and anisotropic conditions if the spatial variations of permeability and the storage coefficients are available.

A summary of the characteristics of the above-mentioned models is provided in table 1. In table 2, the processes that are simulated by these models, and the adequacy of their representations, are presented. The processes listed in table 2 are those considered to be important for the PWM.

Model Selection

The most desirable type of model would be a fully distributed-parameter model in which all the physical characteristics of the watershed could be represented by measured or estimated parameters. Designing such a sophisticated model would require excessive human, computer, and data resources. Because of practical limitations, such a goal cannot be easily achieved. Figure 1 illustrates the relative complexity, difficulty of application, and adequacy of watershed representation of different types of watershed models.

Table 1. Watershed Model Characteristics
(After Shafer and Skaggs, 1983)

Model name	Type	Time operation	Period	Areal scale	General application
SWM	Lumped	Sequential	Variable	Large	Rural & urban
KWM & OPSET	Lumped	Sequential	Variable	Large	Rural & urban
USDAHL-74	Lumped	Sequential	Variable	Small	Agricultural
SSARR	Lumped	Sequential	Variable	Large	Mountainous
NWSRFS	Lumped	Sequential	Variable	Large	Rural
HSPF	Lumped	Sequential	Variable	Large	Rural & urban
TR-20	Lumped	Event	Hourly	10 sq mi	Rural
SWMM	Lumped	Event	Sub-hourly	10 sq mi	Rural
HEC-1	Lumped	Event	Variable	Variable	Rural
CREAMS	Lumped	Sequential	Daily & hourly	40 acres	Agriculture
SWRRB	Lumped	Sequential	Daily & hourly	Large	Agriculture
SPAW	Lumped	Sequential	Daily	Small	Agriculture
SHE	Distributed	Event	Sub-hourly	Variable	Variable
ANSWERS	Distributed	Event	Sub-hourly	40 sq mi	Agriculture
P&L	Distributed	Sequential	Variable	Large	Rural & urban

Table 2. Processes Simulated by Watershed Models, and Adequacy of Representation (After Shafer and Skaggs, 1983)

Model name	Rain	PET	ET	Infiltration	Soil moisture zones	Baseflow	Overland flow	Channel flow	Deep percolation
SWM	0	-	0	0	0 (3)	0	0	0	0
KWM & OPSET	0	-	0	0	0 (3)	0	0	0	0
USDAHL-74	0	-	0	+	0 (1)	0	0	0	0
SSARR	+	-	-	-	0 (1)	0	0	0	0
NWSRFS	0	-	0	0	0 (2)	0			0
HSPF	0	-	0	0	0 (2)	0	0	0	0
TR-20	+	-	-	0			-	0	
SWMM	0	0		0			0	0	
HEC-1	0	-		-			0	+	
CREAMS	0	+	+	+	+ (7)		0		+
SWRRB	0	+	+	+	+ (7)		0		+
SPAW	0	+	+	+	+		0		+
SHE	+	+	+	+	+ (2)	0	+	+	0
ANSWERS	+	-		0	0	-	+	+	-
P&L						+			

\+ = above-average representation
0 = average representation
\- = below-average representation
blank = not represented

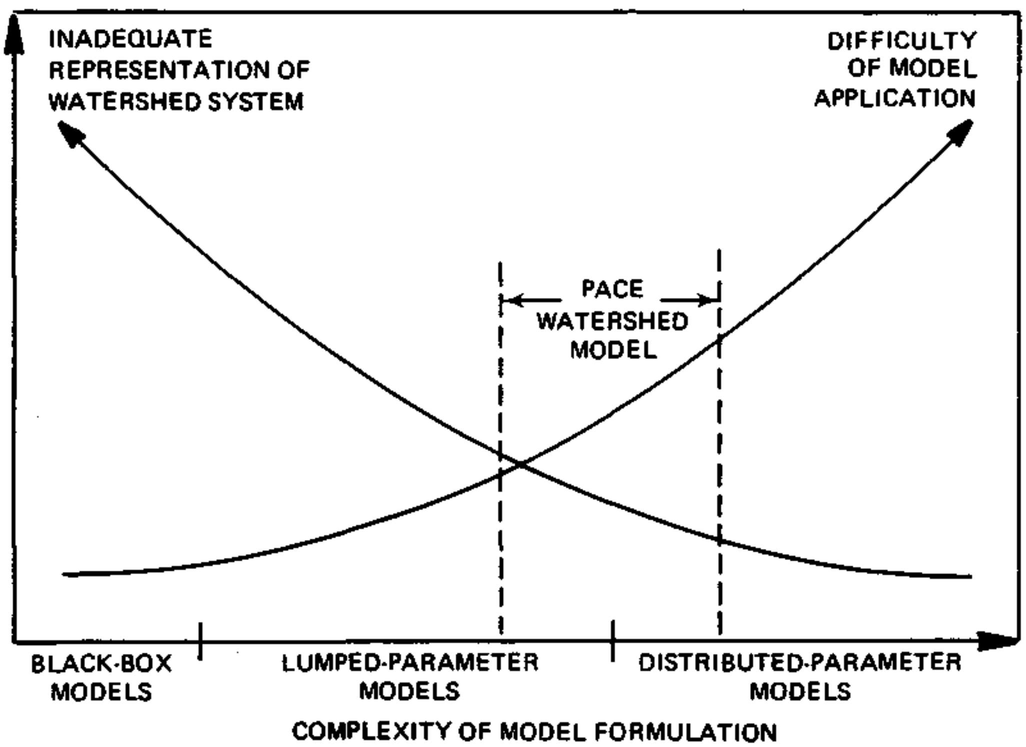

Figure 1. Relative complexity, difficulty of application, and adequacy of watershed representation of different types of watershed models (After Overton and Meadows, 1976)

Our goal was to construct a model that would provide a relatively low risk of not adequately representing the watershed and yet not be very difficult to apply. On the basis of this and the PWM requirements, as well as the attributes mentioned earlier, three models were selected for use as a skeleton in the design of the PWM. These models are the CREAMS, P&L, and ANSWERS models.

These models were selected on the basis of the processes they simulate; their data requirements, operation and model type, flexibility, and modular structure; and the compatibility of each model component with the other components. The selected models, after modifications, are capable of simulating all the processes deemed to be important for the PWM.

The central component of the PWM is its soil moisture component. The CREAMS model is most appropriate for this component since it can use soil, crop, and climatic information and can be modified and pre-calibrated for several soil/hydrologic categories by using existing records of soil moisture for different Illinois soils (or the soils of any other region). The value of relating the hydrologic responses to the soil and crop type is that the model does not need further calibration for any potential study areas beyond the developmental calibration. These calibrations can be associated with each of the benchmark soil types in a large region and thus can easily be implemented with the other distributed-parameter components which require little or no calibration. The CREAMS model can estimate daily deep percolation values that can be used as input to the ground water component, and excess-precipitation values that may be used in overland flow simulations. Another desirable feature of the CREAMS model is that it can use both daily and sub-hourly data, which facilitates the simultaneous use of the model as both a sequential and an event model.

The P&L model has been selected for baseflow simulations because the model is based on theoretical flow motion and continuity equations, which are solved by one of the fastest and most efficient methods (IADI). Its data requirements are highly compatible with those of the selected soil moisture component, and its finite-difference solution technique is very suitable for integration with the grid system of the surface flow component. The P&L model is a dedicated, distributed-parameter model with a highly modular structure. It can handle the variations in soil characteristics in a watershed and can be implemented together with the CREAMS and

ANSWERS models after some adjustments. The time scale can be selected to vary from hours to weeks, depending on the type of process and the size of nodal system used.

Overland flow and channel routing are simulated by using the ANSWERS model. ANSWERS is an event model that should be used only when there is excess precipitation. Since both the CREAMS and P&L models permit the use of variable time scales, the use of ANSWERS with them will not cause any problems. The infiltration, retention, soil moisture, and baseflow components of the ANSWERS model need to be removed, since these processes are better modeled with the CREAMS and P&L models.

MODEL DESCRIPTION

The PWM has three independent major components which can operate simultaneously: the soil moisture, ground water, and surface flow components. Within each of these components one or more of the primary processes of the land phase of the hydrologic cycle considered to be significant in simulating summer crop-growth conditions are modeled. These primary processes are precipitation, infiltration, evapotranspiration, soil moisture, surface (overland and channel) flow, deep percolation, and ground-water (unsaturated and saturated subsurface) flow. The three components and the information exchange among them are illustrated in figure 2.

There are several reasons for deciding on a modular structure for the PWM. One of the reasons, as mentioned previously, is to incorporate and fuse the suitable components of the available existing models, which could be done efficiently only within a modular structure. The modular structure also means that as long as the variables used to exchange information between the components are not changed, the remaining processes and algorithms within each component can be modified without causing repercussions throughout the model. This modular structure enables us to add more features or processes to any component as needed. Consequently, the PWM can easily be updated for new applications and in accordance with advances in prediction technology. For some applications, depending on hydrologic conditions and/or availability of data, some processes or components can be bypassed without affecting the performance of the whole model. A modular model is especially useful when different time intervals are needed for different hydrological processes in order to accommodate variations in time scales.

Hydrologic Processes Modeled in Each Component

Although each component is intended to operate independently, there must be a link for transferring information among the components so the continuity of water in the hydrologic cycle can be simulated. Each component has at least one process that links it to one of the other two components. Basically, the processes involved in the soil moisture component are infiltration, soil moisture retention, vertical movement and redistribution of moisture, evapotranspiration, and deep percolation. The ground water component includes deep percolation, horizontal saturated water flow,

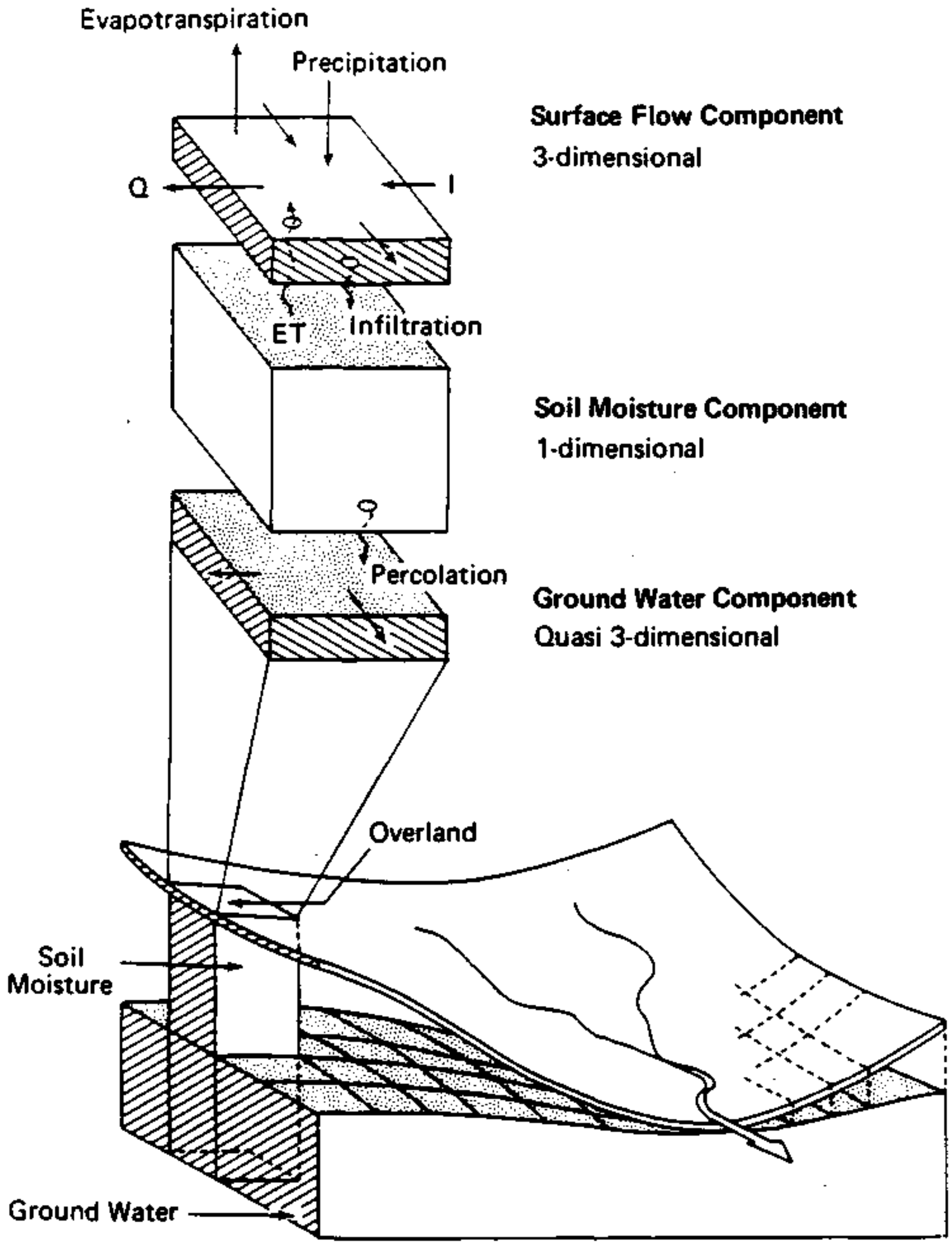

Figure 2. Components of the PACE watershed model (After Beven et al., 1980)

lateral unsaturated flow (interflow), and stream and ground-water interface. The surface flow component simulates overland flow, channel flow (on the basis of excess precipitation amounts), and infiltration.

The soil moisture component acts as a central unit for the redistribution of precipitation input to the system. The precipitation input is divided into excess and infiltrating precipitation. The excess precipitation becomes input to the surface flow component, and infiltrating precipitation becomes input to the soil moisture component. Water is lost from the soil moisture component through evapotranspiration (ET) and deep percolation.

Deep percolating water becomes the main input for the ground water component. The total ground-water flow is treated as two separate processes: interflow (the fast and shallow movement of water) and saturated flow (the deeper and slower water movement in the subsurface). As the total ground-water flow is routed toward lower lands, it eventually encounters a stream and recharges it. During very dry periods, when there is a deficiency in soil moisture along with a lack of deep percolation, ground water can actually replenish soil moisture by capillary movement, which is represented in the model as negative percolation. The movement of water within the components of the model is illustrated in figure 3.

Spatial Distribution and Resolution of Catchment Parameters

The horizontal spatial distribution of watershed parameters is represented by a grid system. This grid system is considered to have a square-element formation with fixed-size elements for the entire watershed area, as shown in figure 4. The size of the elements is chosen on the basis of an economical tradeoff between computational and data-gathering costs, and accuracy in model representation of the watershed characteristics.

Each square watershed element can be viewed as a vertical square column extending from the land surface at the top down to the subsurface impermeable boundary, and consisting of three layers (the three model components). Each model component has a separate grid that represents the spatial variations of the parameters within that component. By superposing these separate grid layers on each other (see figure 2), a three-dimensional grid system is obtained. The combination of the parameters from the

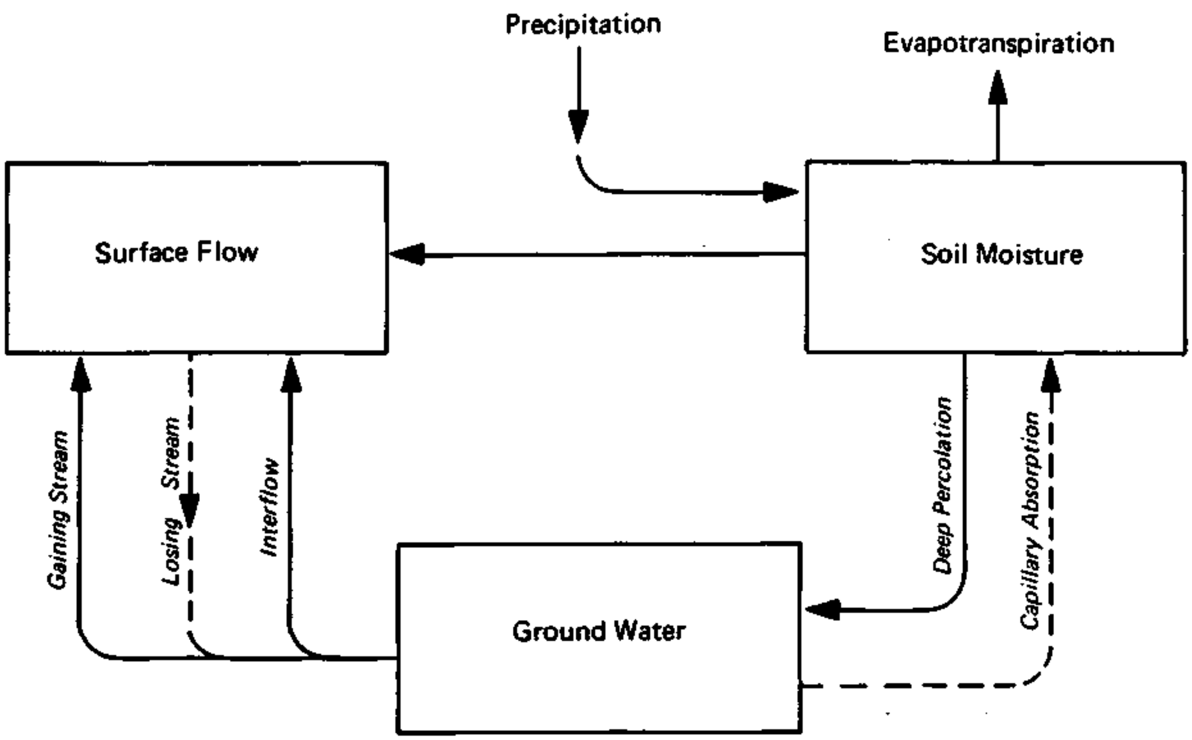

Figure 3. Movement of water within the components of the PWM

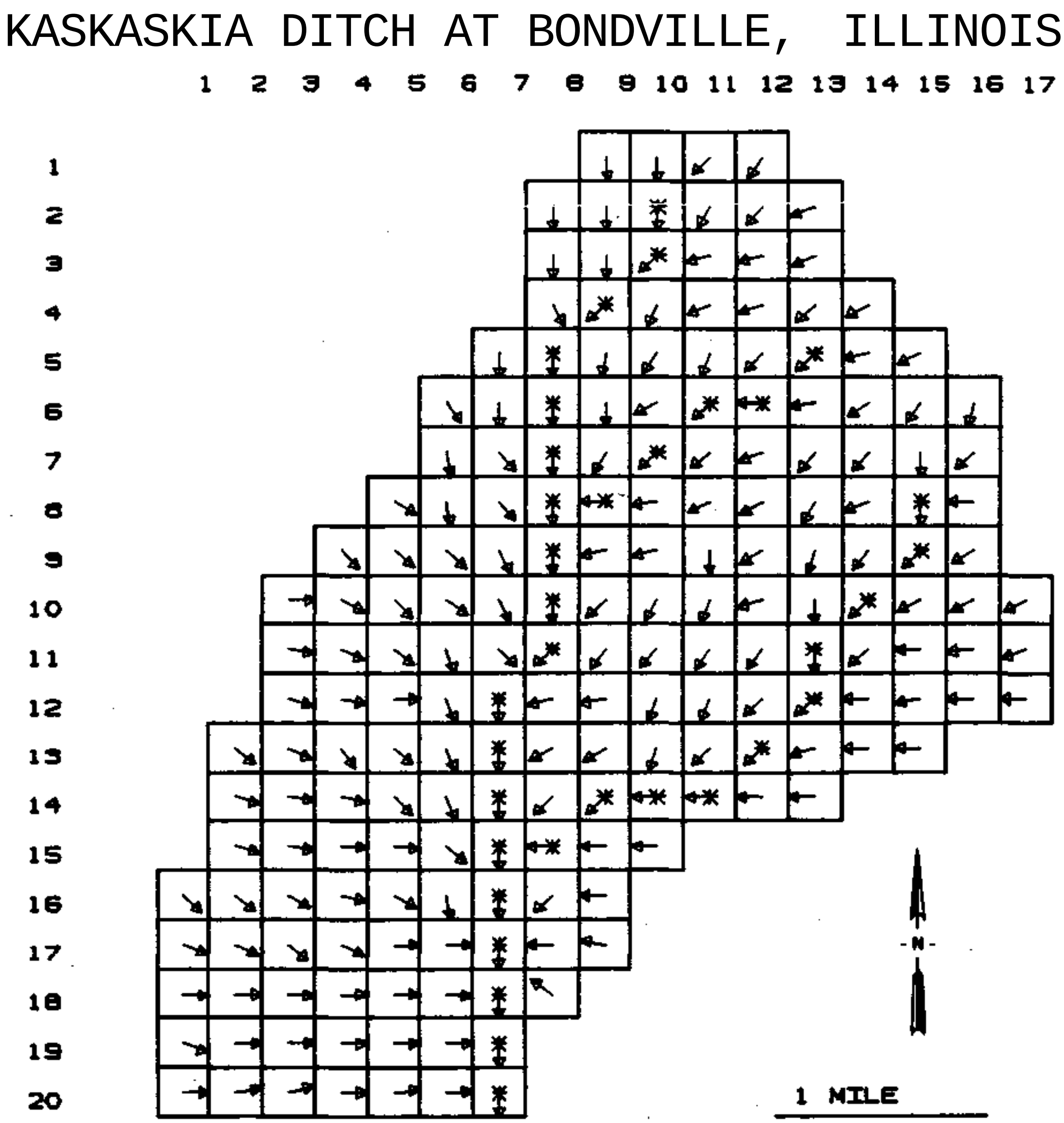

Figure 4. Representation of a watershed area by means of a square-element grid system

three separate layers within the same vertical column constitutes a unique set of parameters for that watershed element.

For each component of the model, different parameters are required to adequately represent the spatial variations of the physiographic and hydrologic features. For example, the surface flow component requires information on the spatial distribution of land slope and slope direction, surface roughness, and stream network. For the soil moisture component, the significant parameters are plant available soil moisture, crop cover, and vertical permeability. The most important parameters for the ground water component are horizontal permeability and the storage coefficient.

The parameters for both the surface flow and ground water components are fully distributed, meaning that for each element the parameters (e.g., land slope and ground-water elevation) are generally unique. Even if two elements have identical properties, the manner in which the hydrologic processes operate on that element, and its relationship to nearby elements, are unique.

The soil moisture component, however, has a discrete number of patterns which are modelled. For every combination of soil type, crop type, and precipitation pattern, a separate soil-crop-precipitation (SCP) association is designated. For example, in a watershed with three soil types, two crop types, and two precipitation gages (located in areas with different precipitation patterns) there will be $3 \cdot 2 \cdot 2 = 12$ SCP associations. The spatial variability of any particular SCP association is assumed to be constant over the entire watershed; therefore many elements throughout the watershed may have identical soil moisture characteristics. If an SCP association is expected to show variation from one location to another (for example, if a different distribution of precipitation is to be used), a separate SCP association will be needed. Thus the soil moisture component contains a discrete number of separate one-dimensional constituents which are selectively placed throughout the elements of the watershed. This manner of parameter distribution within the soil moisture component makes the PWM a quasi-distributed model.

The top two grid layers (surface flow and soil moisture) are formed by square elements as described above. The ground water grid layer, however, is formed by nodes (finite-difference grid). To provide vertical overlapping of all three grid systems, all the grid elements in all the layers must be the same size, and the distance between the nodes in the finite-difference grid must be equal to the length of the square elements, with the nodes located at the centers of the overlapping square elements. In this way each node will represent an area covered by a square element. (The grid system concepts are discussed further in the "Ground Water Component" section and are illustrated in figure 12.) Even though the computational methods used for finite-difference schemes are quite different than the methods used for square-element systems, such approximations provide a strong link and data exchange among the components of the model.

Although a general vertical variability is permitted by using separate grid layers for each component, vertical variation within each layer is highly restricted. The soil moisture component has seven vertical layers with varying thicknesses, which are needed for simulating varying crop water-use by depth. These layers are all aligned vertically within the same grid system.

The channel system is represented as a continuous network, as shown in figure 5. The channel grid system is conceived as a transparent overlay placed on top of the existing overland grid system. Continuity of the channel network is essential and should be confirmed for each model by checking the flow-direction arrows. Each designated channel element can have only one rectangular cross-sectional channel, although an unlimited number of channel widths, roughnesses, and bottom slope combinations can be specified for the whole channel network.

General Assumptions

To obtain a feasible and operational watershed model, some assumptions had to be made. The assumptions and the approximations made in constructing each component are discussed in detail in the following sections. An explanation of some general assumptions is given here.

The biggest assumption is, of course, that the continuous watershed system parameters can be represented by an equivalent set of discrete elements and nodes. Basically, this means that both the spatial and temporal variables are treated as discrete parameters. This assumption affects all three components of the PWM.

Another major assumption relates to the spatial distribution of the soil, crop and precipitation characteristics. For a given soil type and

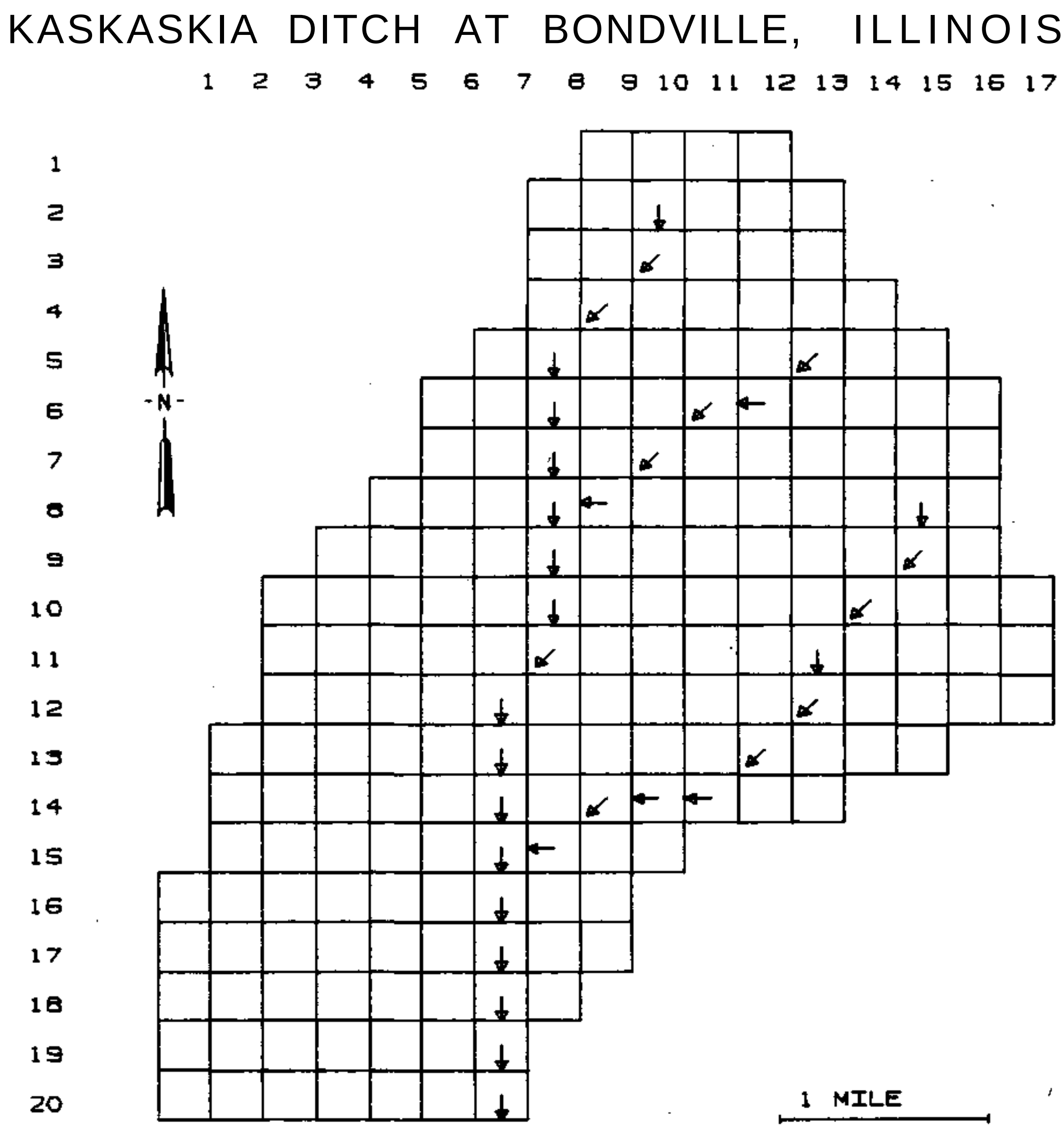

Figure 5. *Representation of the channel network of a watershed as a channel grid system* crop cover, the hydrologic response is assumed to be constant over the watershed. In reality, some neglected horizontal variation of the processes will produce variable responses at different locations. However, the extent of this variability is not known, and the advantages of modeling the locations separately do not justify the costs involved. A similar argument pertains to the assumption of a uniform distribution of precipitation over an area. Usually sufficient information is not available to properly model the spatial variability that could be expected in the rainfall distribution. The number of SCP associations is not limited by the model, but there may be practical restrictions in the implementation stage relating to hardware, computing time, and data preparation.

SOIL MOISTURE COMPONENT

The soil moisture component of the PWM is the central processing portion of the entire model, in that it receives precipitation as input and eventually distributes water among the other components in the model. The soil moisture component has a set of parameters related to soil and crop characteristics. In addition, there are four general processes which operate: 1) infiltration, 2) soil moisture redistribution, 3) percolation, and 4) soil and plant evapotranspiration. These processes are illustrated in figure 6. The soil and crop parameters, along with the status of soil moisture and crop growth, determine the amount of water distributed by each of these processes. The processes are described below in the same order in which they are treated by the model.

Soil and Crop Parameters

Soil Layers. The soil moisture component of the PWM employs a one-dimensional modeling of the distribution of soil moisture within a 78-inch (2-meter) vertical column. The column of soil is divided into seven separate layers, identified by depth as follows:

Layer	Depth of layer
1	0-2 inches (0-5 cm)
2	2-6 inches (5-15 cm)
3	6-12 inches (15-30 cm)
4	12-20 inches (30-50 cm)
5	20-39 inches (50-100 cm)
6	39-59 inches (100-150 cm)
7	59-78 inches (150-200 cm)

Four soil characteristics are considered for each of the soil layers: 1) permeability, 2) the volume of water in the soil at the wilting point, 3) the volume of water in the soil at field capacity, and 4) the upper limit of storage (saturation). Table 3 shows the values assigned to these characteristics and the manner in which they may vary throughout the soil column. For ease in the calibration procedure, the characteristics of some adjacent soil layers were combined.

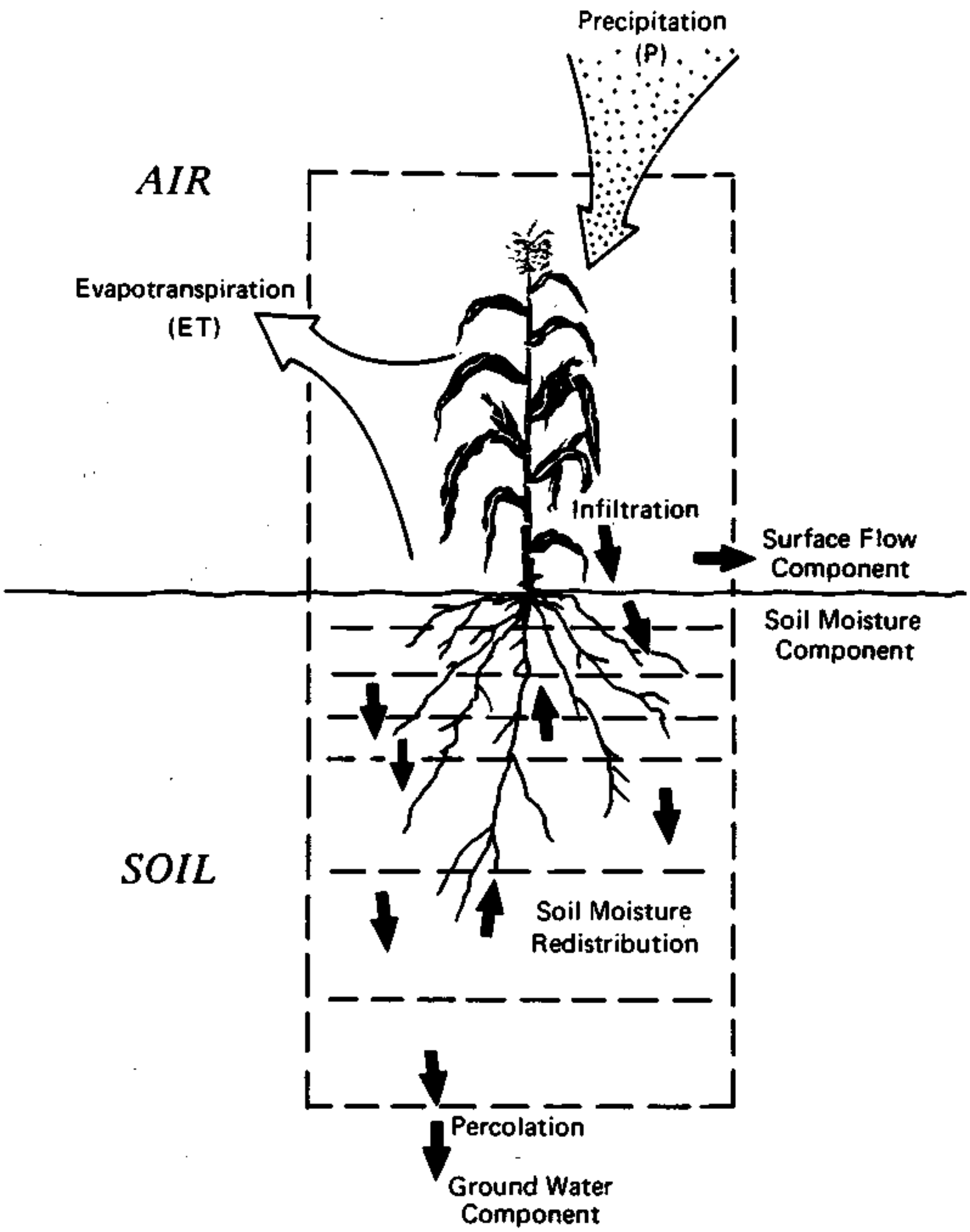

Figure 6. General processes modeled in the soil moisture component of the PWM

Table 3. Soil-Characteristic Values Used in Calibrations
(Flanagan Soil, Bondville, Illinois)

Layers	Permeability (in./hr)	Volume of water* at: Wilting point	Field capacity	Saturation
1 & 2	0.54	0.18	0.42	0.56
3 & 4	0.54	0.17	0.40	0.56
5	0.48	0.16	0.42	0.51
6 & 7	0.48	0.16	0.36	0.51

* Fraction of total soil volume

Wilting point, field capacity, and saturation all refer to volumes of water in the soil and are presented in table 3 as fractions of the total soil volume. The field-capacity and wilting-point volumes are especially important in determining the processes affecting the movement of moisture within the soil. All water volume above the field capacity is subject to gravity flow (described later) and drains from the soil at first opportunity. The wilting point represents the effective minimum amount of water that remains in the soil under the severe pressures of abstraction applied by a plant's root system. The volume of water between the wilting point and the field capacity therefore represents the total amount of "plant available soil moisture."

Crop Development. During any one day of simulation the crop is at a certain stage of growth, not only in the extent of its canopy production, but also in the development of its root system. The canopy of a crop is represented by the leaf-area index (LAI), which is a measure of the surface area of the leaves of the plant divided by the unit area of soil. Figure 7 shows a typical relationship between the LAI of a corn crop and the number of days since emergence of the crop. The LAI is updated each day to describe the dynamic effects of the crop during the growing season. For crops such as corn and soybeans, an LAI value at or near 3.0 represents fully mature crop development.

As the crop continues to mature, its root system grows deeper. The depth to which roots are developed determines the soil layer(s) from which the greatest amount of transpiration will occur. Table 4 shows the distribution of water extraction from the soil, by layers, for different stages

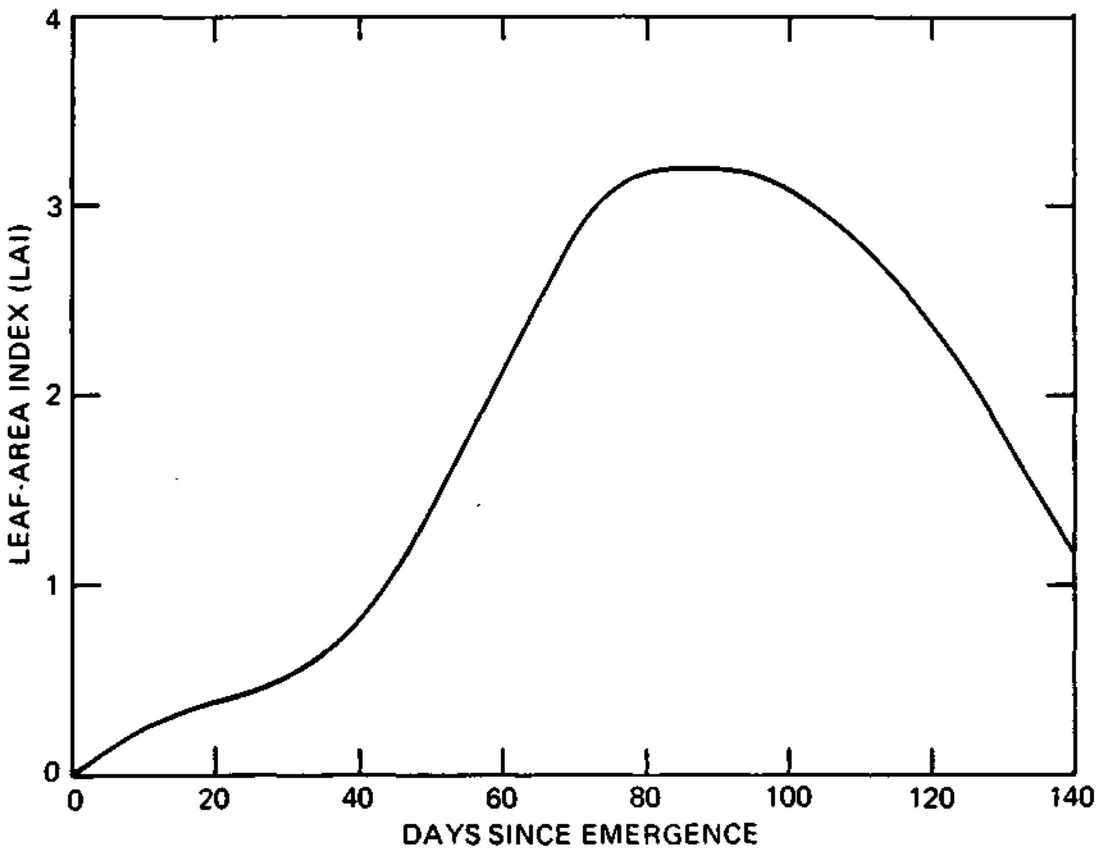

Figure 7. Leaf-area index curve of a corn crop throughout the growing season

of the crop growing season. The root depth (DROOT) on any one date is related to the total plant growth through the leaf-area index:

$$DROOT = DROOT_{max} \quad (LAI/LAI_{max}) \tag{1}$$

in which LAI_{max} and $DROOT_{max}$ are respectively the maximum expected leaf-area index and maximum expected root depth for the given crop. The maximum expected root depth for corn is approximately 60 inches.

Table 4. Percentages of Water Extracted from Different Soil Layers by Developing Corn Plants

	Days since emergence				
Soil layer	20	40	60	80	100
1	100	67	33	24	22
2		33	27	20	18
3			20	15	14
4			20	15	14
5				21	20
6				5	9
7					3

Infiltration

The infiltration process of the soil moisture component is designed to operate on either daily or sub-hourly intervals. The solution at the smaller time increment employs a more physically sound method for determining infiltration, but it is limited by the availability of records describing the temporal distribution of storm rainfall. The model will vary the solution procedure between the daily and sub-hourly methodologies depending on the type of precipitation information available. If the total daily rainfall is less than 0.10 inches, the daily model will be implemented. Both infiltration procedures were obtained from the USDA CREAMS model (U.S. Department of Agriculture, 1980) and were then modified.

Daily Infiltration Procedure. Infiltration is dependent on the minute-by-minute temporal distribution of rainfall input. However, many locations lack the precipitation information needed to evaluate infiltration on this time scale, and therefore infiltration must be approximated from daily rainfall data. All infiltration solution techniques that use daily rainfall information must generalize the rainfall distribution and therefore are empirically based. Of these empirical techniques, the SCS curve number method is most widely used and, in the form used in the PWM, it offers the flexibility to be used under differing soil moisture conditions.

Infiltration is computed by the SCS method as the difference between daily precipitation and estimated daily runoff. Daily runoff is predicted from the equation:

$$Q = (P - 0.2SR)^2 / (P + 0.8SR) \qquad (2)$$

where

Q = daily runoff (inches)

P = daily rainfall (inches)

SR = the retention variable, which changes under differing moisture conditions

The maximum value of SR (SMX) occurs when the soil is completely saturated. For this condition the value of SMX can be determined as a function of the curve numbers provided in the SCS handbook (U.S. Department of Agriculture, Soil Conservation Service, 1972) and numerous other sources.

$$SMX = (1000/CN1 - 10) \qquad (3)$$

where CN1 is the curve number for the appropriate soil type and land use characteristics, assuming the SCS moisture condition I (high antecedent moisture). For its use in the PWM, the value for CN1 is pre-calibrated for each individual soil type. This curve number can also be modified to reflect differences in tillage practices and other local surface conditions.

The day-to-day relationship between the retention variable (SR) and SMX is a function of current soil moisture conditions. A dryer soil will more likely retain a greater portion of the precipitation, and a wet soil will produce greater surface runoff. However, the effect of soil moisture on the retention capability is not uniform throughout the soil column. The top layers of soil will have a greater effect on infiltration than the lower layers. For this reason the relationship between SR and SMX is weighted as a function of the depth of each layer:

$$SR = SMX \{1.0 - \Sigma [W_j(SM_j/UL_j)]\} \tag{4}$$

in which for each soil layer (j) W_j is the weighting factor, SM_j is the soil moisture content, and UL_j is the saturation limit for soil moisture. The weighting factor decreases with depth by a negative exponential function, as illustrated in figure 8.

Infiltration Procedure for Fine Time Increments. When fine time increment precipitation data (for minutes to hours) are available, the infiltration process should be modeled by using physically based techniques . The PWM uses a modification of the Green-Ampt infiltration equation (Green and Ampt, 1911). The Green-Ampt technique, like the daily infiltration method given above, is based on the assumption that infiltration will occur as a piston-type movement downward into the soil.

Infiltration will continue uninhibited until the rate of precipitation exceeds a level somewhere above the maximum rate of percolation (which is generally approximated by the soil permeability, K). After this point, water will start ponding, and the rate of infiltration will decrease with time. The time of ponding, t_p, is a function of the total previous infiltrated amount during the storm, the moisture condition of the soil, and the rate of rainfall, r_p. Since the precipitation rate and moisture conditions are continually changing, the total depth of infiltration needed to produce ponding, F_p, is a dynamic function:

$$F_p = h_c \bullet K \bullet (UL\text{-}SM) / (r_p - K) \tag{5}$$

in which h_c is the effective capillary tension (a calibrated soil parameter). UL and SM are computed for only the top four layers of the soil column (20 inches deep).

Once ponding occurs, infiltration will proceed at a rate defined by:

$$KT = F - h_c (UL\text{-}SM) \ln \{1 + F/[h_c (UL\text{-}SM)]\} \tag{6}$$

where

T = cumulative time since t_p (time of ponding)

F = cumulative depth of infiltration since t_p

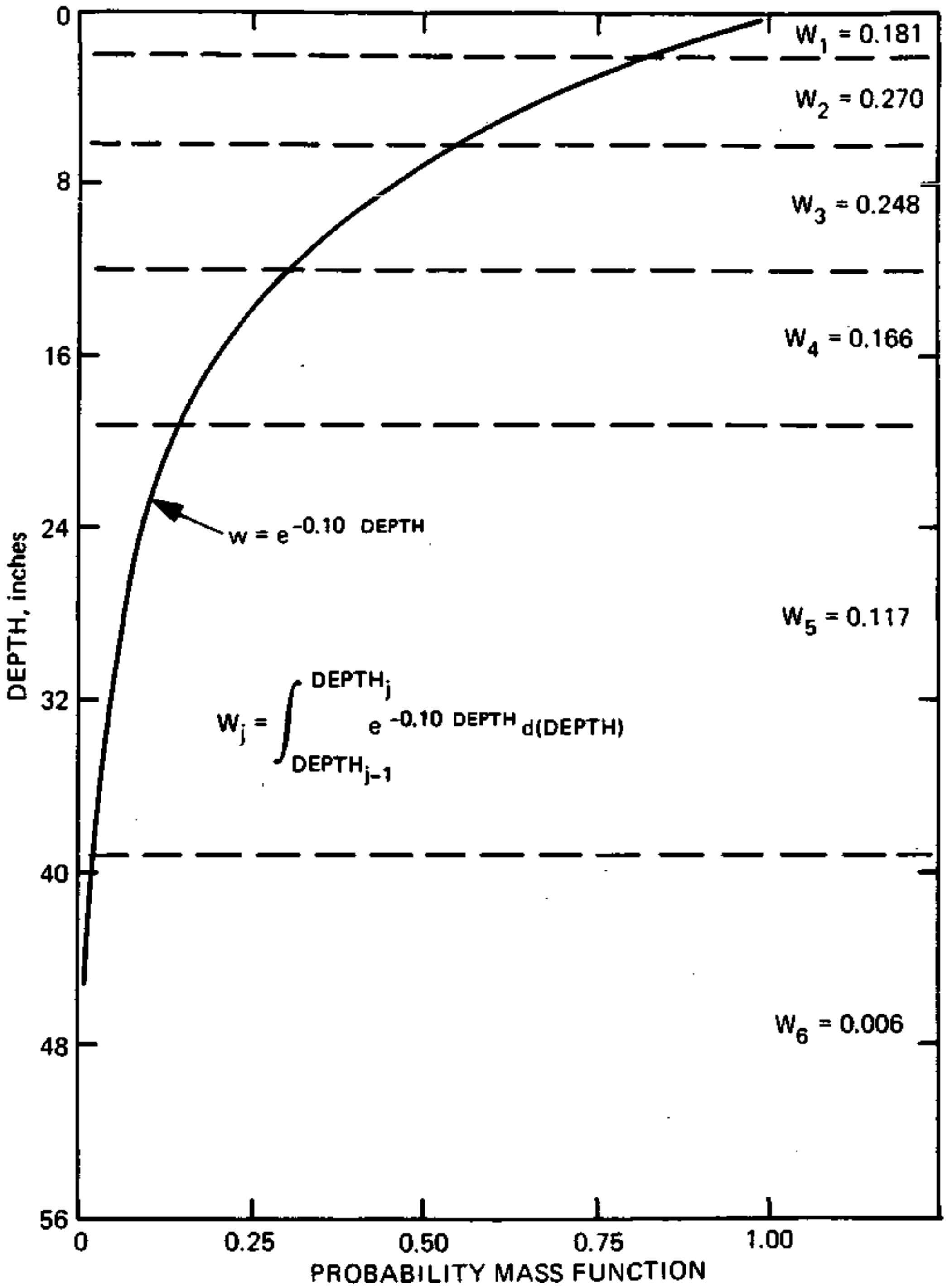

Figure 8. Relationship of the depth of a soil layer to the weighting factor used in the SCS infiltration method

The solution for the amount of infiltration (ΔF) for a time period (Δt) is approximated by the equation:

$$\Delta F = \{4A\ [h_c\ (UL-SM)+F]\ +\ [F-A]^2\ \}^{0.5}\ -\ F\ +\ A \tag{7}$$

in which $A = K \bullet \Delta t/2$. Runoff for the time increment Δt is computed as the remainder between the rainfall and the infiltration (ΔF) for that time period. Retention storage on the ground surface may allow a portion of the estimated runoff to be available for subsequent infiltration.

Distribution of Soil Moisture

In the soil moisture component of the PWM, water can move vertically in one of two fashions: 1) gravity flow, which is the downward flow when the soil is at or near saturation, and 2) unsaturated (Darcian) flow, which is caused by differences in head potential between different layers of the soil.

Gravity Flow. Gravity flow is generally restricted to those periods during and following a rainfall event, when the upper layers of the soil are wetted. As infiltration continues, the zone of wetting moves downward into lower layers of the soil. Figure 9 illustrates how the moisture distribution typically changes within the soil from the start of infiltration (t_0) to successive time periods (t_1 and t_2) under gravity flow conditions. The speed at which the zone of wetting advances is dependent upon the saturated conductivity of the soil, which is approximated by the permeability of the soil. The amount of time it takes for the wetting front to move through a soil layer ($TIME_j$) is the thickness of the soil layer (DZ_j) divided by the permeability of that layer:

$$TIME_j = DZ_j/K_j \tag{8}$$

where $DZ_j = DEPTH_j - DEPTH_{j-1}$.

All water in excess of the soil's field capacity will attempt to move down through gravity flow. If the permeability of a soil decreases with depth, the decreased rate of gravity flow may limit both the gravity flow in upper layers and the infiltration process. In these cases, water will

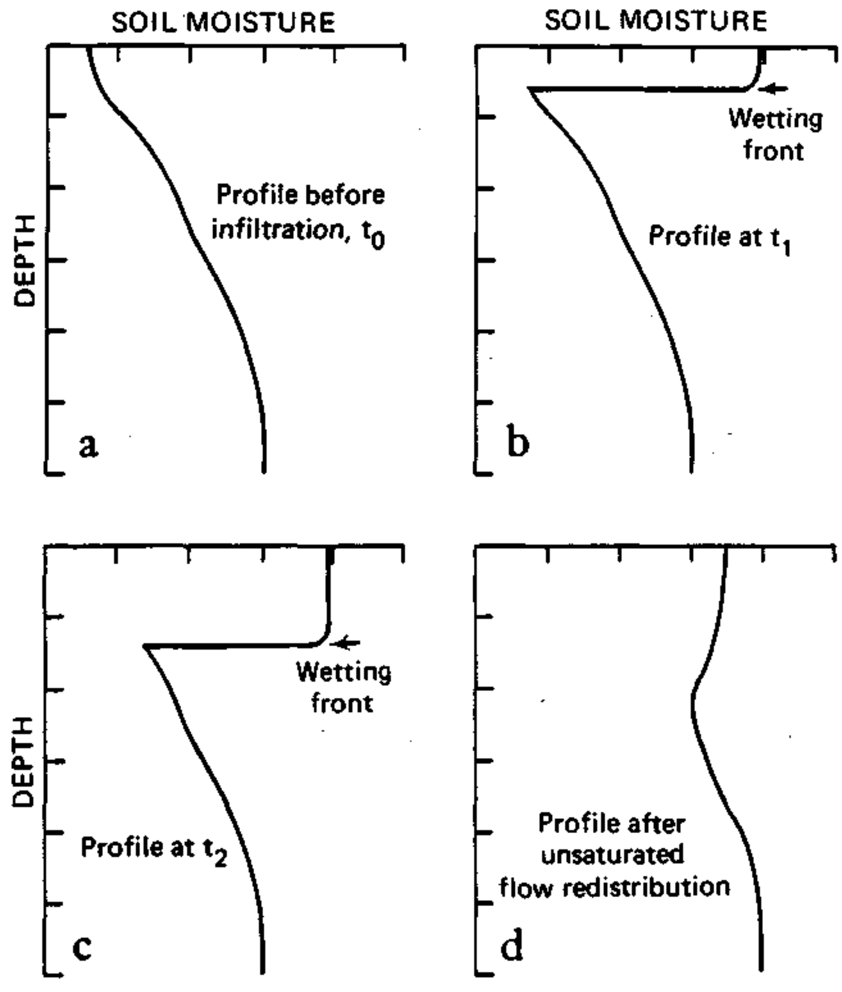

Figure 9. Distribution of moisture through the soil column prior to and following a typical rainfall event

remain in the upper layers of the soil or above the surface of the ground when the soil's saturated level is exceeded. In the latter case this water is then added to the surface flow component of the model.

Unsaturated (Darcian) Flow. Water is continuously moving through the soil, even during periods when the soil is relatively dry. This unsaturated movement of water occurs because of differences in the pressure (head) of the water both vertically and horizontally.

Differences in the head are significant during two situations. First, whenever rainfall occurs over a dry soil, gravity flow restricts the downward movement of this water to the top layers of the soil, creating a situation where the upper layers are saturated and the lower layers remain dry. Unsaturated flow is the process that allows the lower layers of the soil to receive some of this moisture. The effect of unsaturated flow on the moisture distribution of a soil column following infiltration can be seen by comparing figures 9c and 9d. Unsaturated flow is also of significance during dry periods in the growing season. In these situations water will move from the lower layers of the soil upward to the root zone through capillary action to help satisfy the crop's water requirement.

The pressure gradient in the horizontal direction is usually much smaller than the gradient in the vertical direction, and therefore horizontal movement of water is not simulated in the soil moisture component of the PWM.

The unsaturated vertical movement of water (q) from one soil layer to an adjacent layer during a given time period, t, can be described by a form of Darcy's flow equation:

$$q_t = k \bullet (h_j - h_{j-1} + DZ_j)/DZ_j \tag{9}$$

in which q is the vertical flow of water, k is the unsaturated hydraulic conductivity, and h is the head for each respective soil level.

The potential head for a given soil level is a function of the soil moisture content of that layer. The head increases with a decrease in soil moisture; the change is represented by the empirical function:

$$h_j = 407 \bullet 2^4 \,[(FC_j - SM_j)/(FC_j - WP_j)] \tag{10}$$

in which FC_j, WP_j, and SM_j are the field capacity, wilting point, and soil moisture content for level j, and h_j is given in units of inches.

The unsaturated hydraulic conductivity, k, is a function of the soil moisture content, and for a given soil layer it is approximated by an exponential function:

$$k_j = k_0 \bullet 10^{\{1.5 - 2[(FC_j - WP_j)/(SM_j - WP_j + FC_j/3)]\}} \tag{11}$$

The parameter k_0 is the unsaturated hydraulic conductivity at field capacity and is a calibrated soil property. In the application of equation 9, the value of k is chosen as the minimum of k_j and k_{j-i}.

Equation 9 is solved by a forward implicit solution technique using constant time periods. The time interval, t, will vary depending on the magnitude of the head difference between levels. For dynamic soil moisture situations, t must remain fairly small (between 3 and 6 hours) to keep the solution steady.

Percolation

Percolation in the PWM is defined as the exchange of water between the bottom layers of the soil and the ground water component of the model. Ground-water storage is viewed as an additional (eighth) layer of the soil, although it possesses the additional quality of horizontal variability. The exchange of water between the soil column and the ground water component occurs by either gravity flow or unsaturated flow. Most of the movement occurs in the downward direction as a result of gravity flow, in which the soil column is drained. The movement of unsaturated flow between components is limited to the upward direction, allowing uptake of water from the ground-water table during conditions when the soil is especially dry. This upward movement of water out of the ground water is termed capillary absorption. The potential capillary absorption rate is a function of the gradient in head within the lower layers of the soil (equation 10). If the water table is especially deep, the soil will not be able to absorb moisture from ground water at the potential rate. The relationship between depth of the water table and actual capillary absorption is explained in a later section of this report.

Reference (Potential) Evapotranspiration

An estimation of the daily potential evapotranspiration that can occur from the combination of soil evaporation and plant transpiration is provided by using the FAO Blaney-Criddle equation (Doorenbos and Pruitt, 1977) as modified by Frevert et al. (1983):

$$PET = a + b \cdot PDAY \cdot TF/100 \qquad (12)$$

where

PET = potential evapotranspiration (inches/day)

PDAY = total length of possible sunshine per day (minutes)

TF = average daily air temperature (degrees Fahrenheit)

$a = (0.0043\ RH - 0.01\ PSUN - 1.41)/25.4$

$b = 0.81917 - 0.0040922\ RH + 0.010705\ PSUN + 0.0338\ WIND - 0.00005968\ RH \cdot PSUN - 0.0003072\ RH \cdot WIND$

where

RH = minimum afternoon relative humidity

PSUN = percent of possible daily sunshine

WIND = wind speed at time of minimum humidity (miles per hour)

The PET value is an estimate of the amount of incoming solar radiation that is available for the evapotranspiration process. Depending on the development of the vegetative cover, this energy can be used for either plant transpiration or direct evaporation from the soil. The distribution of energy to these two processes is determined as a function of the leaf-area index (LAI). A leaf-area index in excess of 3.0 represents a situation where all of the incoming solar radiation will be intercepted by the plant and thus will be available for use in the transpiration process. Thus the potential plant transpiration (PTR) is estimated by the equation:

$$PTR = PET \cdot LAI/3 \qquad (13)$$

The potential soil evaporation (PSE) is the difference between the potential evapotranspiration and potential plant transpiration:

$$PSE = PET - PTR \qquad \text{when } 0 < 1AI < 3 \tag{14a}$$

$$PSE = 0 \qquad \text{when } LAI > 3 \tag{14b}$$

<u>Actual Transpiration</u>. The actual amount of transpiration that occurs from plants is not only a function of the total available energy (as indicated by the PTR), but also may be limited by the available soil moisture, which is the source of water supply for the plant. The soil depth from which water is obtained depends on the stage of growth of the plant and the resulting development of the plant's root system. Young emerging plants may have roots that extend to only several inches in depth. Any possible transpiration from these plants must therefore originate in the top layers of the soil. Mature corn plants usually have roots that extend as much as 60 inches into the soil, and therefore they have a much greater potential source to supply their water needs.

The soil levels from which transpiration occurs are determined by the root depth value (DROOT) described previously. When the upper layers of soil are dry, additional moisture can be taken from lower layers of the soil up to but not exceeding the total root depth.

The physics of water movement within the soil may also limit the transpiration rate. As the transpiration rate increases, greater stress is put on the crop's root system to abstract water from the soil. Transpiration ordinarily occurs uninhibited as long as the soil moisture remains high. However, if the transpirative rate is great enough, the roots may have difficulty abstracting water even under moist soil conditions. The potential daily transpirative uptake by the roots, EPMAX, is a calibrated property of the soil type.

The effect of the soil moisture, transpiration rate, and soil physics (as represented by EPMAX) on the transpirative uptake of water from a layer of soil (UP_j) is given by the function:

$$UP_j = PUP_j \; [(SM_j - WP_j)/(FC_j - WP_j)] \; (EPMAX/PTR) \tag{15}$$

in which PUP is that portion of the potential plant transpiration (PTR) that applies to soil layer j. A simplified version of equation 15, representing the cumulative transpiration over all seven layers of the soil, is presented in figure 10. As the transpirative rate increases or the amount of plant available soil moisture decreases, the ability of the plant to withdraw the full amount of water from the soil is inhibited. In both cases (equation 15 and figure 10), the value of PTR cannot exceed the maximum rate as designated by EPMAX. If the value of EPMAX were reduced (which could be expected with a tight clayey soil), a proportional reduction in the actual transpiration under limiting conditions would result.

Effect of Water Stress on Crop Growth. When the ratio between the actual and potential transpiration is less than 0.8, plants are considered to be under partial stress. Under these conditions the crop water stress causes a reduction in the development of the plant, and the leaf-area index for the following day reflects this reduced rate of growth. When the ratio between actual and potential transpiration is less than 0.5, the plants are under acute stress and no plant growth will occur. The amount of crop growth is a linear function, ranging from 0% at a ratio of 0.5 to 100% at a ratio of 0.8.

Actual Soil Evaporation. Soil evaporation occurs within the top two layers of the soil column (to a depth of 6 inches) and is computed as a two-stage drying process (Ritchie, 1972). Initially, following a rainfall period in which the soil is wetted, evaporation is limited only by the energy available at the surface and thus occurs at the potential rate. After a certain amount of drying of the upper layers of the soil, the second phase of reduced evaporation begins.

The amount of water, ES1, which can evaporate during the first stage (at the potential level) is a function of the soil properties. For most silty-clay soils in Illinois a value of ES1 = 0.25 inches is appropriate.

The maximum evaporation that can occur during the second stage of drying is a function of time:

$$ES2_t = SEP\ [t^{0.5} - (t-1)^{0.5}] \qquad (16)$$

in which the evaporation (ES2) on day t is a function of SEP, a soil evaporation parameter, and t, the number of days since the second stage of evaporation began. The soil evaporation parameter generally ranges from 0.13 inches for soils with low available moisture, up to 0.18 inches (Ritchie, 1972).

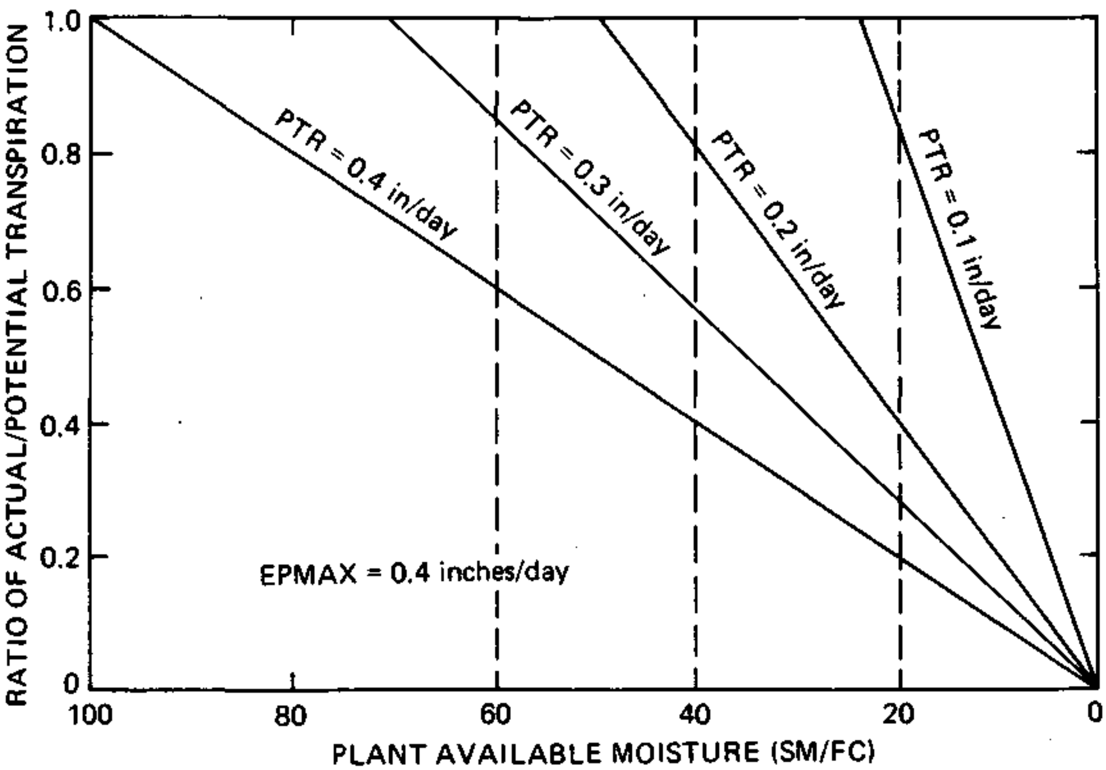

Figure 10. Effect of soil moisture and potential transpiration rate on the reduction of actual transpiration

GROUND WATER COMPONENT

The basic function of the ground water component of the PWM is to keep track of ground-water storage over an extended period of time and to estimate the baseflow contribution of ground water to streams. Basically, shallow water-table flow conditions and the resulting baseflow conditions are simulated for watersheds which are predominantly covered with glacial tills. The ground water component receives water that has percolated from the soil moisture component and routes it along the watershed from the highlands toward the lower areas. Stream and aquifer interactions and tile drainage are extensively simulated in the PWM to calculate the ground-water contribution to the stream network.

The nucleus of the ground water component of the PWM is an adaptation of the ground-water resource evaluation techniques developed by Prickett and Lonnquist (1971). The main rationale for using these techniques is that all the special cases of ground-water movement studied by Prickett and Lonnquist were based on a basic aquifer program intended for studying cause-and-effect relationships in heterogeneous aquifer systems, with constant pumpage taking place from wells simulated at any nodal point of the digital model.

The basic aquifer simulation program is intended for analyzing cause-and-effect relationships involving drawdowns or heads in a nonsteady-state, nonhomogeneous, isotropic aquifer system under nonleaky, confined-aquifer conditions. It is possible to make modifications to simulate anisotropic, unconfined (water-table) aquifer systems with time-varying recharge or withdrawals, stream and ground-water interface, capillary movement, and tile drainage. It is also possible to include special conditions such as barrier and recharge boundary conditions, as well as point withdrawal and recharge rates.

Mathematical Derivation of Finite-Difference Equations

Continuity equations, equations of motion, and energy equations are particularly useful in ground-water modeling. Continuity equations are mathematical expressions of the principle of conservation of mass. In ground-water applications, continuity equations are usually combined with Darcy's law of motion for a porous medium to yield a ground-water equation.

Energy equations such as Bernoulli's equation can be used effectively in treating constant-head boundary conditions.

The time-varying conditions of the confined ground-water flow in a two-dimensional, nonhomogeneous, anisotropic aquifer can be obtained by combining Darcy's law and the mass conservation principle as:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) = S \frac{\partial h}{\partial t} + Q \qquad (17)$$

where

T_X and T_y = aquifer transmissivity in the x and y directions

h = head

t = time

S = aquifer storage coefficient

Q = net ground-water withdrawal rate per unit area

In the case of a confined aquifer, $T = K \cdot b$, where K is the permeability coefficient and b is the thickness of the aquifer as shown in figure 11a. Since the temporal variation of aquifer thickness b is constant, the transmissivity of a particular location will remain constant unless the head levels h remain within the aquiclude overlying the aquifer. If the aquifer is unconfined at the top as shown in figure 11b, water is released from storage by gravity drainage of the pores. Because of this drainage, the saturated thickness b of the aquifer and therefore its transmissivity change with time. Therefore water-table conditions (unconfined aquifers) are more difficult to model than confined aquifers because of the additional free boundary of the water surface. Because the PWM was designed for shallow water-table conditions, only the derivations related to unconfined (water-table) aquifers are discussed in the following sections.

There is no general solution to equation 17; however, a numerical solution can be obtained through a finite-difference approach. The finite-difference approach involves first replacing the continuous aquifer parameters by a set of discrete system parameters. Secondly, the equations governing the flow of ground water in the discretized model are written in the finite-difference form. Finally, the resulting set of finite-difference equations is solved numerically with the aid of digital computers.

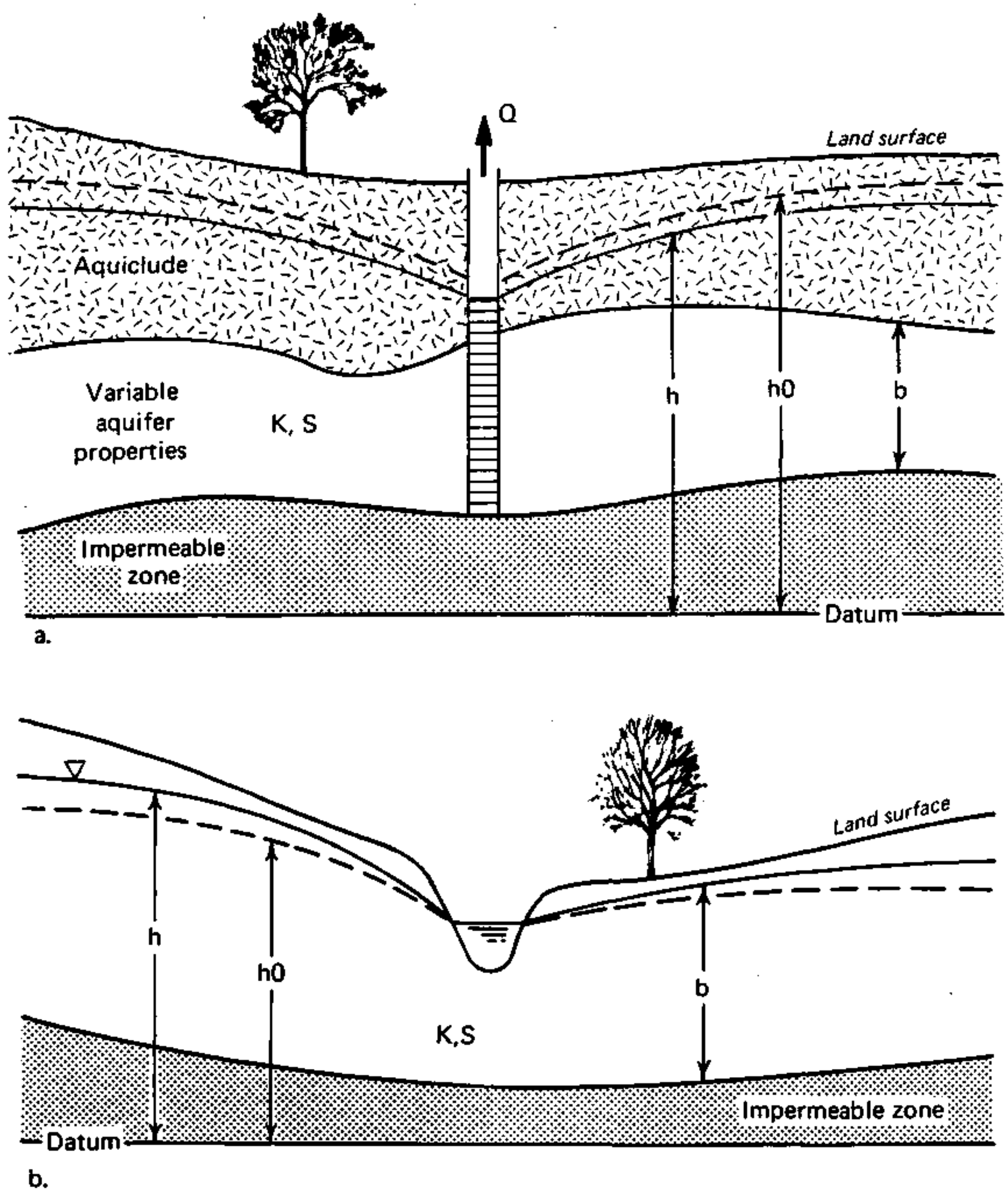

Figure 11. Generalized cross sections of a) confined aquifer and b) unconfined aquifer, for ground-water flow modeling

The finite-difference grid is superimposed over a grid map of the watershed, as illustrated in figure 12. The intersections (also called nodes) of the finite-difference grid lines of the aquifer system are located at the centers of the square elements of the discretized watershed map. The nodes are referenced with column (i) and row (j) coordinates, as shown in figure 12, which correspond to the x and y directions, respectively. Thus the aquifer is subdivided into volumes having dimensions $b \cdot \Delta x \cdot \Delta y$, where b is the depth of the saturated ground-water flow. If Δx and Δy are sufficiently small, they can replace ∂x and ∂y of equation 17. For practical reasons, Δx and Δy are considered to be equal in this model. The accuracy of the model representation of the actual system is highly correlated with the magnitude of Δx and Δy.

The flow rate terms Q_1 through Q_4, as illustrated in figure 12, represent the node-to-node water transfer rates. Q_5 is the flow rate associated with the rate at which water is taken into or released from storage during time interval Δt. Q_6 is the net constant withdrawal or recharge rate at a particular node. The generalized flow rate term Q_n accounts for all other special conditions such as tile drainage and stream interface, which are explained later in this section.

The continuity condition relating the flow rates entering and leaving the node i,j of figure 12 can be expressed as:

$$Q_1 + Q_3 + Q_n = Q_2 + Q_4 + Q_5 + Q_6 \tag{18}$$

where the flow directions are assigned arbitrarily. Although actual ground-water flow in an aquifer can take place in any direction, flow in the model is restricted to the x and y directions.

Each individual flow term in equation 18 represents a different portion of the aquifer around a node. The portions of the aquifer included in the flow-rate terms will be referred to as "vector volumes" to emphasize that they are not only volumes but also show the direction of the flow being considered.

Horizontal projections of vector volumes Q_1, Q_2, Q_3, and Q_4 are illustrated in figure 13. All the vector volumes in figure 13 extend the full depth of the aquifer, b. Furthermore, each vector volume extends to one-half of the grid interval on either side of a node. The horizontal

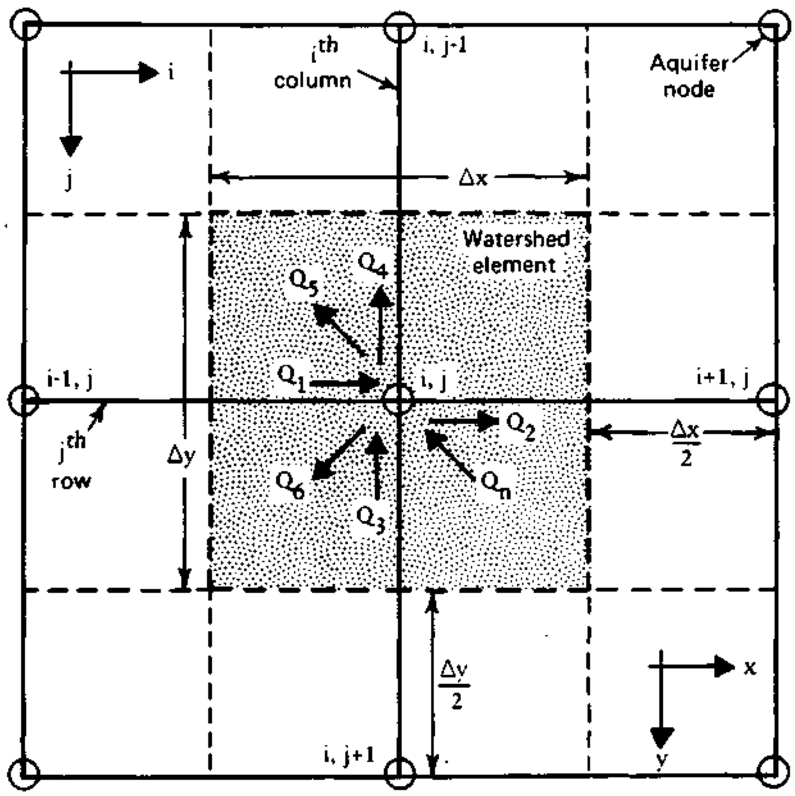

Figure 12. Superimposition of a watershed element on a finite-difference grid (After Prickett and Lonnquist, 1971)

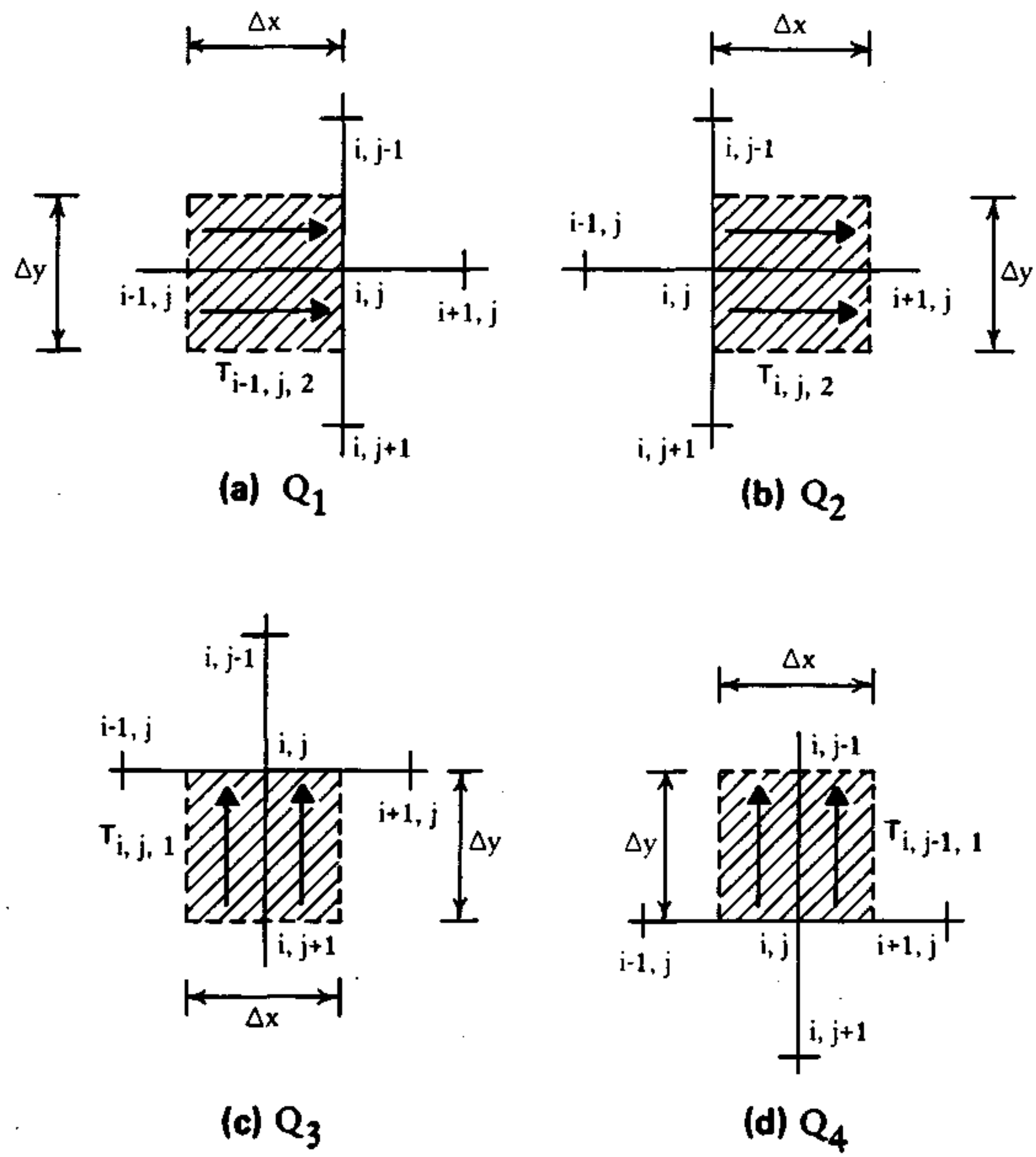

Figure 13. Horizontal projections of vector volumes for node-to-node flow rate terms (From Prickett and Lonnquist, 1971)

projections of the vector volumes Q_5, Q_6, and Q_n cover the area centered around a node, as indicated by the dashed lines in figure 12, and they too extend the full depth of the aquifer.

If Darcy's law is applied to flow rate terms Q_1 through Q_4, we get

$$Q_1 = T_{i-1,j,2} (h_{i-1,j} - h_{i,j}) \Delta y/\Delta x \qquad (19a)$$
$$Q_2 = T_{i,j,2} (h_{i,j} - h_{i+1,j}) \Delta y/\Delta x \qquad (19b)$$
$$Q_3 = T_{i,j,1} (h_{i,j+1} - h_{i,j}) \Delta x/\Delta y \qquad (19c)$$
$$Q_4 = T_{i,j-1,1} (h_{i,j} - h_{i,j-1}) \Delta x/\Delta y \qquad (19d)$$

where

$T_{i,j,1}$ = aquifer transmissivity within the vector volume between nodes i,j and i,j+1

$T_{i,j,2}$ = aquifer transmissivity within the vector volume between nodes i,j and i+1,j

$h_{i,j}$ = calculated heads at the end of a time increment, measured from an arbitrary datum at node i,j

In the above expressions, i=1,...,NC and j=1,.....,NR, where NC and NR are the number of columns and rows in the discretized model, respectively.

The flow rate term Q_5, representing the rate at which water is taken into or released from storage, is given by

$$Q_5 = S_{i,j} \Delta x \Delta y (h_{i,j} - h0_{i,j})/\Delta t \qquad (20)$$

where

$h0_{i,j}$ = calculated head at node i,j, at the end of the previous time increment Δt

Δt = time increment elapsed between calculations

$S_{i,j}$ = storage coefficient of the vector volume centered around node i,j

The flow rate term Q_6 represents a constant net withdrawal rate (positive) or recharge rate (negative) during Δt, for the vector volume of node i,j, as follows:

$$Q_6 = QP_{i,j} \tag{21}$$

Flow rates due to pumpage, percolation, and evapotranspiration are all consolidated in QP. Evapotranspiration rate is discussed later in this section.

A special sink or source term Q_n is added to represent tile drainage and stream infiltration at a node. If such conditions do not exist; Q_n can be set to zero. Therefore

$$Q_n = QC_{i,j} - QT_{i,j} \tag{22}$$

where

$QC_{i,j}$ = stream infiltration rate at node i,j (positive for losing stream conditions, and negative for gaining stream conditions)

$QT_{i,j}$ = flow rate at which water is taken from storage due to tile drainage from node i,j

Methods for calculating the stream infiltration rate $QC_{i,j}$ and the tile drainage rate $QT_{i,j}$ are explained later.

Substituting equations 19, 20, 21, and 22 into equation 18; dividing both sides by the product of $\Delta x \Delta y = \Delta x^2$ (since, for practical purposes, we assumed $\Delta x = \Delta y$); and rearranging terms yields

$$\begin{aligned} &T_{i-1,j,2} (h_{i-1,j} - h_{i,j}) + T_{i,j,2} (h_{i+1,j} - h_{i,j}) + \\ &T_{i,j,1} (h_{i,j+1} - h_{i,j}) + T_{i,j-1,1} (h_{i,j-1} - h_{i,j}) \\ &= S_{i,j} (h_{i,j} - h0_{i,j}) \Delta x^2/\Delta t + QP_{i,j} - QC_{i,j} + QT_{i,j} \end{aligned} \tag{23}$$

Regrouping equation 23 to leave the principal unknown $h_{i,j}$'s alone yields

$$\begin{aligned} &h_{i,j} (T_{i-1,j,2} + T_{i,j,2} + T_{i,j,1} + T_{i,j-1,1} + S_{i,j}\Delta x^2/\Delta t) - \\ &h_{i-1,j} T_{i-1,j,2} - h_{i+1,j} T_{i,j,2} - h_{i,j+1} T_{i,j,1} - \\ &h_{i,j-1} T_{i,j-1,1} = (S_{i,j}\Delta x^2/\Delta t) h0_{i,j} - QP_{i,j} + QC_{i,j} - QT_{i,j} \end{aligned} \tag{24}$$

Equation 24 is the finite-difference form of the partial differential equation (see equation 17) for nonsteady-state, two-dimensional flow of ground water in a nonhomogeneous, confined aquifer. Equation 24 can be modified for water-table conditions by replacing the transmissivity values with the equivalent aquifer transmissivities of the wedge-shaped vector volume (as illustrated in figure 14) by using the following formula:

$$T_{i,j,2} = PERM_{i,j,2} \sqrt{(h_{i,j} - Z_{i,j}) \cdot (h_{i+1,j} - Z_{i+1,j})} \qquad (25)$$

where $PERM_{i,j,2}$ is the hydraulic conductivity of the aquifer within the vector volume between node points i,j and i+1,j, and $Z_{i,j}$ is the elevation of the top of the impermeable zone at node point i,j.

Similarly, the equivalent aquifer transmissivity of the vector volume between node points i,j and i,j+1 is given as:

$$T_{i,j,1} = PERM_{i,j,1} \sqrt{(h_{i,j} - Z_{i,j}) \cdot (h_{i,j+1} - Z_{i,j+1})} \qquad (26)$$

For water-table conditions, new transmissivity values for each node should be calculated at the end of a time increment, and those values should be used for the subsequent time increment. Transmissivities calculated by equations 25 and 26 represent geometric means and are more accurate than the values computed as an average between nodes, especially when the gradients are steep.

Solution of Finite-Difference Equations

Equation 24 can be applied to every node of the discretized model, and therefore a large set of simultaneous equations must be solved to obtain the water-table configuration (i.e., $h_{i,j}$ values). A modified form of the alternating-direction-implicit (ADI) method of Peaceman and Rachford (1955) is used to solve the set of simultaneous equations. The details of the ADI method are beyond the scope of this report, but the solution technique will be explained briefly. For a more detailed discussion of the ADI method, readers should refer to Peaceman and Rachford (1955) and Prickett and Lonnquist (1971).

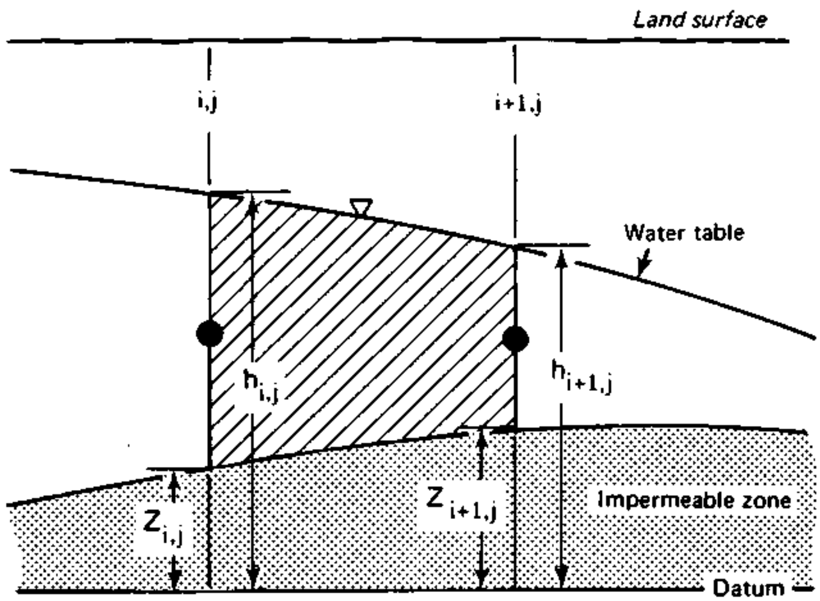

Figure 14. Typical vector volume of an element in the ground water component for water-table conditions (After Prickett and Lonnquist, 1971)

Briefly, the iterative ADI (IADI) method involves first, for a given time increment, reducing a large set of simultaneous equations to a number of small sets. This is done by solving the node equations of an individual column by the Gauss elimination method while keeping all the related terms in the adjacent columns constant. Since the set of column equations is then implicit in the direction along the column and explicit in the direction orthogonal to the column, the solution of the set of column equations is a straightforward process.

After all the column equations have been processed column-by-column, the same procedure is applied to row calculations. After all equations are solved row-by-row, an "iteration" has been completed. This process of solving column and row equations is repeated a sufficient number of times for a convergence criterion to be achieved, and this completes the computations for the given time increment. Peaceman and Rachford (1955) point out that this technique is unconditionally stable regardless of the size of the time increment.

Stream/Aquifer Interface Simulation

As the subsurface water, originating as deep percolation from the overlying soil moisture column, moves from the uplands to the lowlands and the stream valley, it eventually intersects one or more stream channels and seeps into the stream. This slow but continuous feeding of the stream is referred to as the baseflow contribution of the ground water. Although the process may seem very trivial, it is an important phenomenon, keeping streams flowing and providing water resources for our water supplies during dry periods lasting days or even weeks. As mentioned previously, one of the objectives of the PACE project was to simulate the variation in the baseflow caused by artificially increased summer precipitation. Therefore a comprehensive stream/aquifer interface algorithm was incorporated into the PWM to simulate baseflow, especially during dry summer periods.

The stream/aquifer interface algorithm was developed in such a way that each discrete element on the watershed grid map designated as having a channel segment could independently receive different amounts of water from the subsurface storage during a specified time increment. Such a spatial distribution of baseflow contribution from the subsurface flow to the stream network was contemplated for the future use of these inflows in the channel routing, if deemed necessary.

A typical discretized representation of a channel network in the element/node grid system is illustrated in figure 15. The natural stream network is replaced by contiguous straight line segments extending from one node to another. It is essential that continuity of streamflow be maintained in the discretized scream model because the streamflow/aquifer interface algorithm and the surface flow routing component are based on the assumption that continuity of flow is maintained in the channel network. It is strongly recommended that some of the utility software prepared to verify the acceptability of the selected streamflow directions in the surface flow routing component be used along with the stream/aquifer interface algorithm.

Each element designated as a channel element, indicated by the shaded areas in figure 15b, is assigned certain parameters which explain the physical characteristics of that particular channel segment that are essential in estimating subsurface water infiltration into the stream. These parameters and their impact on the rate of stream infiltration are discussed later in this subsection.

According to Walton and Ackroyd (1966) the stream infiltration rate is directly proportional to the streambed area, the permeability of the streambed, and the head difference between the water levels of the aquifer and the stream. It is inversely proportional to the streambed thickness. In equation form, the rate of infiltration through the streambed can be expressed by the following modified form of Darcy's law:

$$QC_{i,j} = PERM_{i,j} \cdot \Delta h_{i,j} \cdot AC_{i,j}/TC_{i,j} \tag{27}$$

where

$QC_{i,j}$ = infiltration rate through the streambed for channel element i.j

$PERM_{i,j}$ = hydraulic conductivity of the streambed for channel element i.j

$\Delta h_{i,j}$ = head difference between the water level in the aquifer and that in the stream in the channel element i,j

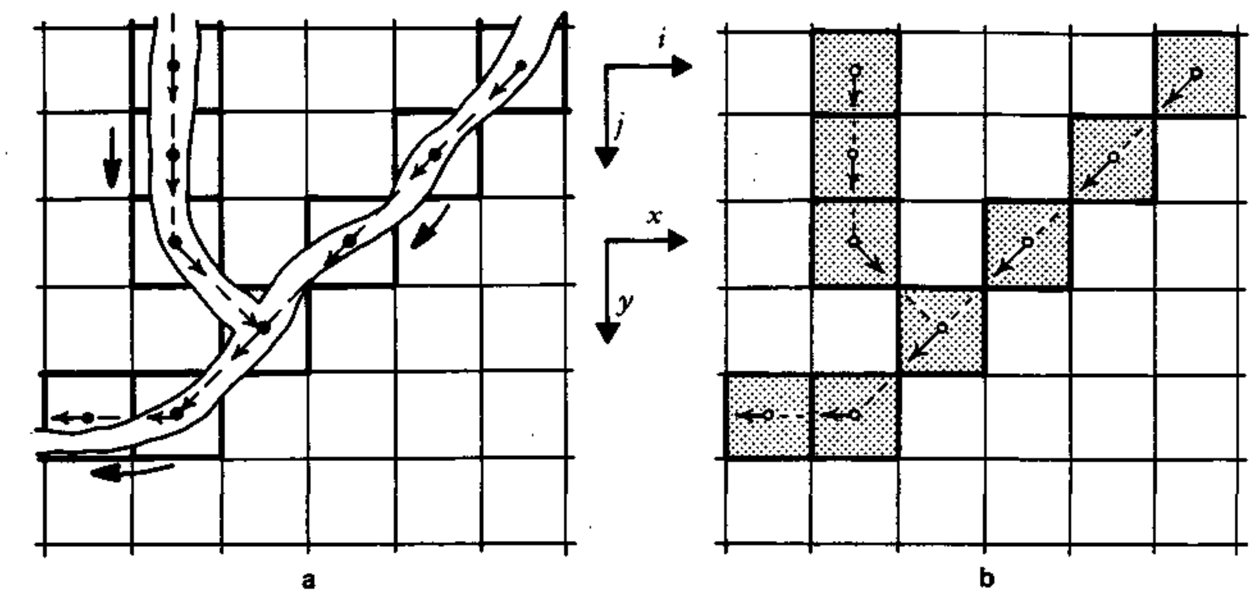

Figure 15. Grid-system representations of a) a natural stream network, and b) a typical discretized channel network

$AC_{i,j}$ = streambed area through which infiltration can occur

$TC_{i,j}$ = thickness of the streambed

Actual and approximate representations of a channel element are illustrated in figure 16. All the parameters used in equation 27 either are measurable or can be calculated from the measured watershed parameters and the calculated water-table conditions. Different values are used for the hydraulic conductivity of the streambed than for the hydraulic conductivity of the aquifer because the streambed material usually has different origins than the aquifer material. The hydraulic conductivity and the thickness of the streambed can usually be measured by a few field and laboratory tests. The streambed area, AC, through which infiltration can occur is calculated as follows:

$$AC_{i,j} = WC_{i,j} \cdot LC_{i,j} \tag{28}$$

where $WC_{i,j}$ and $LC_{i,j}$ are the width and the length of the stream segment, respectively. The length $LC_{i,j}$ of the stream segment in an element is either ΔX or $\sqrt{2}\cdot\Delta X$, depending on the direction of the streamflow within the element. As shown in figure 15b, the direction of streamflow in an element is indicated by an arrow originating at the node point of that element. If the flow direction is in the X or Y direction then $LC = \Delta X$; if the flow direction is diagonal then $LC = \sqrt{2}\cdot\Delta X$.

The head differential Δh is actually the difference between the computed head in the channel element and the surface elevation of the streamflow (see figure 16). However, this computation of Δh involves incorporating a variable boundary condition (the stream surface elevation) in the computations. To avoid the complex modeling of that variable boundary condition, Δh is approximated as the difference between the computed head in the channel element and the elevation of the streambed Z, which can be obtained easily from maps. This approximation is quite acceptable for small watersheds where the streamflow depth is small, especially during dry summer months. However, for large rivers, a stage-discharge curve is needed for estimating the depth of the flow, d, and determining Δh.

If the streambed elevations are used for determining Δh, then only the gaining stream conditions can be simulated. As soon as the water head in a channel element falls below the bottom of the streambed, Δh is set to

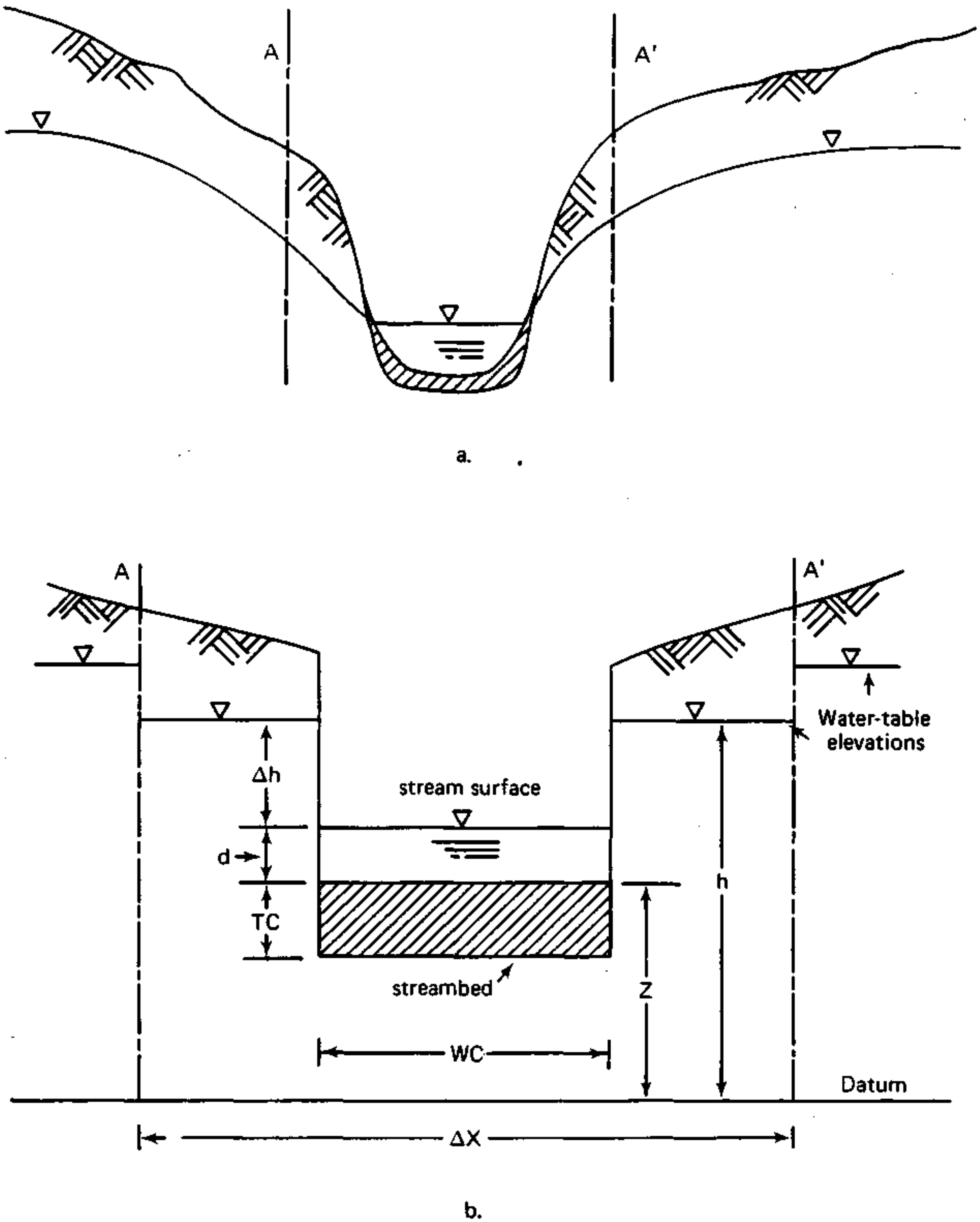

Figure 16. Actual and approximate representations of a channel element: a) actual cross section of an aquifer containing a stream, and b) approximation of channel section A-A' for modeling purposes

zero and the streambed infiltration stops for that element. Streambed infiltration starts again when the water-table levels in that element rise above the streambed elevations. This situation can be formulated as follows:

$$\Delta h_{i,j} = h_{i,j} - Z_{i,j} \qquad \text{if } h_{i,j} > Z_{i,j} \tag{29a}$$
$$\Delta h_{i,j} = 0 \qquad \text{otherwise} \tag{29b}$$

Combining equations 27 and 29 gives

$$QC_{i,j} = PERM_{i,j} \cdot AC_{i,j} \, (Z_{i,j} - h_{i,j})/TC_{i,j} \qquad \text{if } h_{i,j} > Z_{i,j} \tag{30a}$$
$$QC_{i,j} = 0 \qquad \text{otherwise} \tag{30b}$$

The characteristics of a channel element needed for modeling the stream/aquifer interface and streamflow routing are represented by a number of spatially varying parameters. In the PWM, the channel elements with similar features are grouped together so the number of parameter combinations can be reduced. This is done entirely on the basis of storage savings in the computer and is by no means a limitation of the model. Instead of grouping the channel parameters, individual sets of parameters can be used if detailed data are available. The Z values, which indicate the ground elevation for regular elements (or nodes), are used to indicate the streambed elevation of the channels for the channel elements.

The stream infiltration rates for the channel elements can not be calculated directly since this calculation relies on knowledge of the $h_{i,j}$'s, which need to be obtained from the implicit solution of equation 24. The head elevation for a new time increment is calculated by inserting equation 30 into equation 24 and solving it by the IADI method. Following that, the $QC_{i,j}$ values are estimated by equation 30, by using the new $h_{i,j}$ values and assuming that the water-table configuration does not change during the specified time increment as a result of channel infiltration. The total baseflow from the watershed is then calculated by adding the stream infiltration rates for all channel elements for the specified time increment.

Tile/Interflow Simulation

As described earlier, subsurface flow has been conceptualized in two parts. The first part is the slower horizontal movement of the ground water which takes place in the deeper layers of the saturated zone. This water provides the continuous baseflow for the streams. The second part is the tile drainage flow (or interflow) which takes place in the top portion of the subsurface flow, moves much faster than the deeper ground water, and usually occurs immediately following a precipitation event. This flow contributes to the fast rising of the streamflow hydrograph even if there is not observed runoff in the watershed.

The tile-drainage/interflow is definitely not a Darcian flow. It takes place through the man-made tile-drainage system or the cracks and fissures within the soil. Therefore it is not so easy to incorporate this flow into the governing equation of subsurface flow given by equation 24. This is why the discharge (loss) term $QT_{i,j}$ has been added in equation 24. QT actually accounts for the amount of water drained from element i,j due to tile drainage or interflow during the given time interval.

Tile drainage or interflow is assumed to be directly withdrawn from ground-water storage and conveyed to the stream. This assumption is made because most of the interflow travels through tiles and/or highly permeable paths in the subsurface. Currently, no routing of the tile drainage or interflow has been modeled, since all the water from this source is expected to reach the watershed outlet at the end of the time increment. However, tile-drainage or interflow withdrawals are calculated and stored for each element in the watershed and can easily be used for routing purposes by superimposing a tile-drainage grid map on the watershed map. This was not done since detailed maps of the locations of drainage tiles in the watershed were not readily available.

A cross section of an element, illustrating tile-drainage conditions and the parameters involved, is shown in figure 17. To have a tile-drainage or interflow withdrawal from a given element, the element should be designated as a tiled element, and the water-table level at the end of the previous time increment should be above the tiles. The rate of tile drainage from the element is assumed to vary with the head of water above the tile. The tile-drainage/interflow volume is simulated by using the following equation for the elements designated as having tiles:

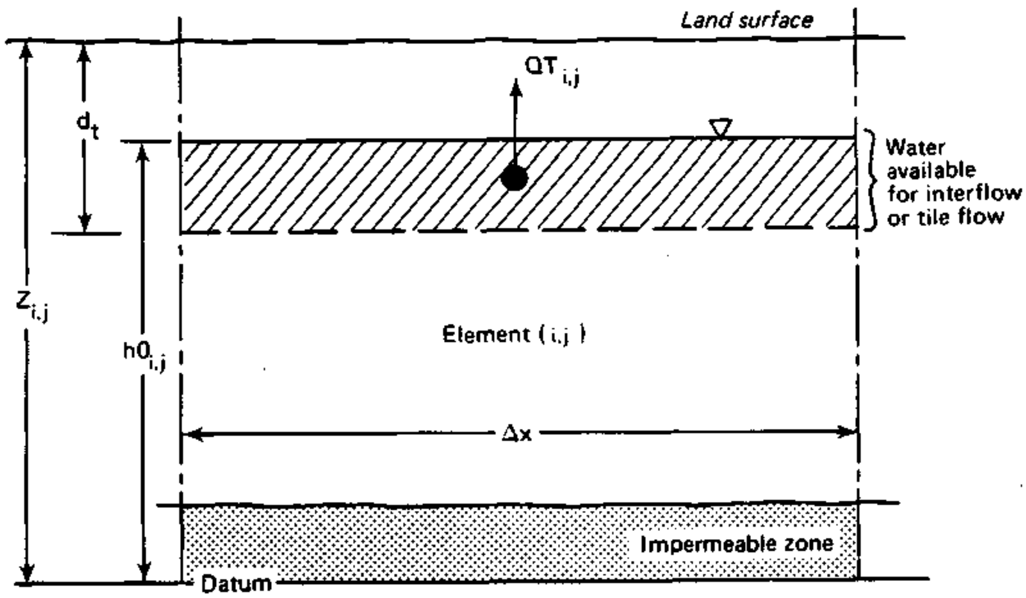

Figure 17. Typical cross section of an element, illustrating tile-drainage conditions

$$QT_{i,j} = c_t \cdot \left(1 - \frac{Z_{i,j} - h0_{i,j}}{d_t}\right) \qquad \text{if } (Z_{i,j} - h0_{i,j}) \leq d_t \qquad (31a)$$

$$QT_{i,j} = 0 \qquad \text{otherwise} \qquad (31b)$$

where

c_t = potential rate of tile drainage in element

d_t = depth of tiles from the ground

Equation 31 applies only to non-channel elements since channel elements are assumed not to have tiles.

The maximum tile drainage rate is equal to c_t and can occur only when the water-table level rises to land surface. The $QT_{i,j}$ values for each element are calculated by using the water-table elevations obtained during the previous time increment. These values are then inserted in equation 24, and new water-table levels are obtained for the current time increment, assuming that QT values will not change during that time increment.

The values of c_t and d_t can be obtained for watersheds which were tiled in the past. Even then, obtaining current values for the potential drainage rate of the tile system may be difficult because of breaking, clogging, and other defects of the tile system caused by aging. In such cases an appropriate design value may be obtained from handbooks on the basis of soil type, kind of agriculture in use, and topography. This design value can then be reduced in accordance with the age of the system. If no reliable value is available for d_t, a value close to plant root depth may be used since for most practical applications tiles are laid to dewater the root zone of plants. If there is no reliable information on c_t and/or d_t, or if there is no tiling in the watershed but there is some interflow, then these parameters need to be calibrated by using past streamflow records.

Ground-Water Contribution to Soil Moisture

The simulation of soil moisture replenishment from ground-water storage has been adapted from the ground-water evapotranspiration formulation of Prickett and Lonnquist's (1971) ground-water simulation techniques. In the PWM no direct evapotranspiration from ground-water storage has been contemplated since no direct path between ground-water storage and the atmosphere has been included in the model. Therefore if any water is to evapotranspirate from ground-water storage, it first has to be processed through the soil moisture component.

In reality, ground-water evapotranspiration can occur concurrently with deep percolation. That is, while the excess water within the soil moisture component is being percolated down and is recharging ground-water storage, water can also be withdrawn from ground-water storage by evapotranspiration through deep plant roots. In the PWM this complicated process was considered to be two separate processes and was modeled accordingly.

In simple terms, the available soil moisture within the root zone, the magnitude of evapotranspiration, and the deep percolation (if any) are estimated by using the soil moisture component. If there is sufficient water for deep percolation, the ground-water storage is recharged. If, however, the soil has a moisture deficit, the soil moisture component determines the amount of water that can potentially be absorbed from ground-water storage under existing conditions. This amount is called the potential capillary absorption (PCA). This process is indicated by the dashed-line link between the soil moisture and ground-water components in figure 3, whereas the deep percolation is indicated by a solid line. The method for estimating the potential capillary absorption rate was explained in the section on the soil moisture component.

The potential capillary absorption rate is not the actual withdrawal rate from ground-water storage, but the maximum rate that can be provided under ideal conditions. The potential capillary absorption rate cannot always be achieved because it is calculated by assuming that the soil just below the root zone will be saturated. Therefore the ideal conditions are such that the water-table level is near the land surface or just below the lowest zone of the soil moisture component, which is usually considered as the end of the root zone. If the water table is lower than the root zone, the actual capillary absorption rate (ACA) should be calculated according to the current depth of the water table. All capillary absorption is assumed to cease below a certain depth, which is determined empirically. The capillary absorption process and its variation with depth are illustrated in figure 18. The actual capillary absorption rate is estimated by using the following equation:

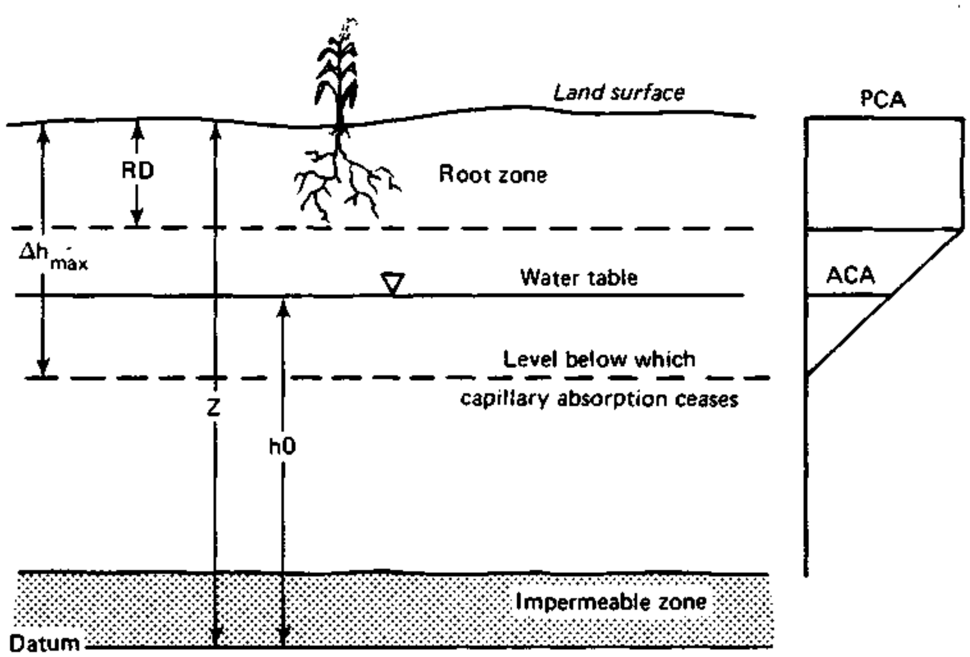

Figure 18. Construction of the actual capillary absorption (ACA) function

$$ACA_{i,j} = PCA_{i,j} \qquad \text{if} \quad Z_{i,j} \geq h0_{i,j} \geq Z_{i,j} - RD \tag{32a}$$

$$ACA_{i,j} = PCA_{i,j} \left(1 - \frac{Z_{i,j} - h0_{i,j} - RD}{\Delta h_{max} - RD}\right) \qquad \text{if} \quad Z_{i,j} - RD > h0_{i,j} \geq Z_{i,j} - \Delta h_{max} \tag{32b}$$

$$ACA_{i,j} = 0 \qquad \text{if} \quad h0_{i,j} < Z_{i,j} - \Delta h_{max} \tag{32c}$$

where

ACA = actual capillary absorption rate

PCA = potential capillary absorption rate

Δh_{max} = depth from the land surface below which all capillary absorption ceases

RD = thickness of the root zone, which is taken as the total depth of the soil column used in the soil moisture component

During each time increment, the model checks the output from the soil moisture component. If there is deep percolation, the $QP_{i,j}$ term in equation 23 (or 24) is set to the negative value of the deep percolation, since recharge rates have to be negative in the model. On the other hand, if the output from the soil moisture component indicates a moisture deficit, the actual capillary absorption rate is calculated by using equation 32 and is assigned to the $QP_{i,j}$ term in equation 24 without its sign being changed.

The ACA value calculation is done by using the head elevations calculated at the end of the previous time increment. The depth from the land surface below which all capillary absorption ceases usually varies with the subsurface soil type and the depth of the root zone. In the model, Δh_{max} is set to 25 feet but can be changed if more detailed information is available.

Variable Time Increments

Subsurface flow of water is, by and large, much slower than surface flow. Even the faster movement of water due to interflow and/or tile drainage is slower than surface flow rates by several orders of magnitude. Therefore it is quite common to use daily time intervals for analyzing ground-water movement since hydraulic conditions change so slowly.

However, because of conditions that have been included in the nucleus of the ground water component, some provisions were needed for handling shorter time increments. The conditions that may require shorter time increments are the rapid swelling of the water table due to precipitation (large percolation values); the rise of the water table above the land surface, causing complete inundation of the land; and finally, tile drainage or interflow.

wherever the deep percolation rates are high (for a particular soil type), the time increments used in the ground-water simulations are reduced in proportion to the magnitude of the deep percolation rate. If the initial time increment was Δt, then new time increments such as $\Delta t' = \Delta t/2$ or $\Delta t/4$ would be used for simulating water-table elevations and tile-drainage rates, by keeping the deep percolation rate the same until the end of Δt is reached. The results can be used as they were simulated by using finer time increments ($\Delta t'$), or average values can be obtained by the model for Δt.

This method of time increment reduction is very effective in simulating wet conditions where land surface inundation and heavy tile-drainage conditions exist. In cases where most of the root-zone saturation is eliminated due to interflow within less than one Δt period, the results would be in error without using shorter time increments.

Initial and Boundary Conditions

The solution of equation 24 by the IADI method requires specification of the initial and boundary conditions for the watershed. The initial conditions required for the solution are the water-table elevations at every node. Such detailed information is usually unavailable for the whole watershed. In rural areas there frequently are no wells for tens of square miles. If any observation or pumping wells exist, the data from these wells can be used to estimate the water-table conditions at certain seasons. Lakes and streams can also be helpful in estimating the initial water-table conditions since they already represent some measurable boundary conditions. What is suggested, in case no reliable initial condition values exist, is to use whatever information is available, perform the simulations starting at a low-flow period, and continue a full cycle until the next low-flow period is reached. In most cases the ground-water conditions approach a steady-state condition if the simulations are performed over a few cycles with the same data and with the results of one cycle used as the initial condition of the next cycle.

A watershed can be defined as an area from which all the water drains through a single outlet. Although this definition is usually intended for surface flow, in the PWM it is used for a vertical column extending to an impermeable layer below the land surface, thus including the ground water. The physical surface boundaries of a watershed are clearly defined by the topography. However, such distinct separation of the watersheds underground is usually not possible. For all modeling and computational purposes it has been assumed that the watershed is strictly bounded in three dimensions.

The ground water component of the PWM is intended to be used for unconfined aquifer (water table) conditions. The ground-water flow that affects the baseflow is assumed to occur within the top, most recent glacial drifts. In most cases this glacial drift is not bounded by a bedrock, but overlies an earlier drift. In either case, the boundary between the top and lower drifts is assumed to be an impermeable boundary with no leakage and is referred to as the "bedrock."

The parameters of the watershed defined by the edges of the elements centered around the nodes (1/2 of a grid interval beyond the end node points) are considered to be barrier boundaries. A barrier boundary is defined as a boundary across which there is no flow of water. It should be realized that the edges of the elements defined by i = NC and j = NR also represent barrier boundaries. This type of boundary can be formed in the model by assigning zero transmissivities outside the boundary of interest. The storage coefficients should not be set to zero; if this is done, a zero divide error will be generated by the computer program.

The use of barrier boundaries is based on the assumption that there is no inter-watershed movement of water. This is simply an assumption that the hydraulic head gradients at the watershed boundary are zero. In most cases the natural water table more-or-less follows the land topography and therefore forms a ridge at the highland watershed boundary, creating no or negligible gradients. In the lowlands the water table is assumed to be rather flat with the only significant gradient existing towards the streams. Thus no water exchange occurs at the boundary.

Large bodies of water within the watershed can be simulated as recharge boundaries. A recharge boundary is defined as a boundary along which there is no drawdown or change in water level. This boundary is further assumed to fully penetrate the aquifer. This type of boundary condition is most easily handled in the model by assigning very large storage coefficients to the nodes inside the boundaries.

A subroutine program is specifically prepared to handle variable boundary conditions. Different combinations of boundary conditions can be specified in this program, independent of the ground-water simulation package. If the user wishes, each of the parameter grid elements can be assigned a special boundary condition within the data set.

SURFACE FLOW COMPONENT

The surface flow component of the PWM can be used for modeling the impacts of precipitation augmentation on surface flow conditions such as stream peaks and duration. Unlike the soil moisture and ground water components, the surface flow component is an event model and consequently is meant to operate on a different time scale than the other two components. The appropriate time increments that should be used with the surface flow component are usually minutes or hours, whereas for the soil moisture and ground water components the appropriate time increments are hours or days. Because of these differences, simultaneous and continuous operation of all three models would be very inefficient and time-consuming, since the speed of computer execution would be highly controlled by the shorter time increments of the surface flow component.

To avoid possible complications due to simultaneous operation of all three components, the surface flow component has been contemplated as an auxiliary component which would be implemented only if hydrologic conditions required it. This approach is also supported by the extensive physiographic and hydrologic data requirements of the surface flow component. Therefore the surface flow component remains idle during dry periods and can be activated during storms if sub-hourly precipitation data are available. Due to these restrictions, testing and sensitivity analysis of the surface flow component were not done. However, the computer codes have been prepared, with the proper modifications, and can be implemented in the PWM when desired.

The general idea of the surface flow component is adapted from the ANSWERS model (Beasley, 1977). ANSWERS is a distributed-parameter, event model that is intended to simulate the behavior of watersheds immediately following a rainfall event. Within its topographic boundary the catchment is divided into a matrix of square overland elements as shown in figure 19. Each element acts as an overland flow plane having a fixed slope and slope direction. Channel flow occurs through a continuous link of channel elements superposed over the overland flow elements. The channel elements are shown by asterisks in figure 19. Flow from one overland element can go to an adjacent overland or channel element, whereas all the overland flow within a channel element must flow into the channel segment in that element. Flow out of a channel element goes into the next downslope channel

KASKASKIA DITCH AT BONDVILLE, ILLINOIS

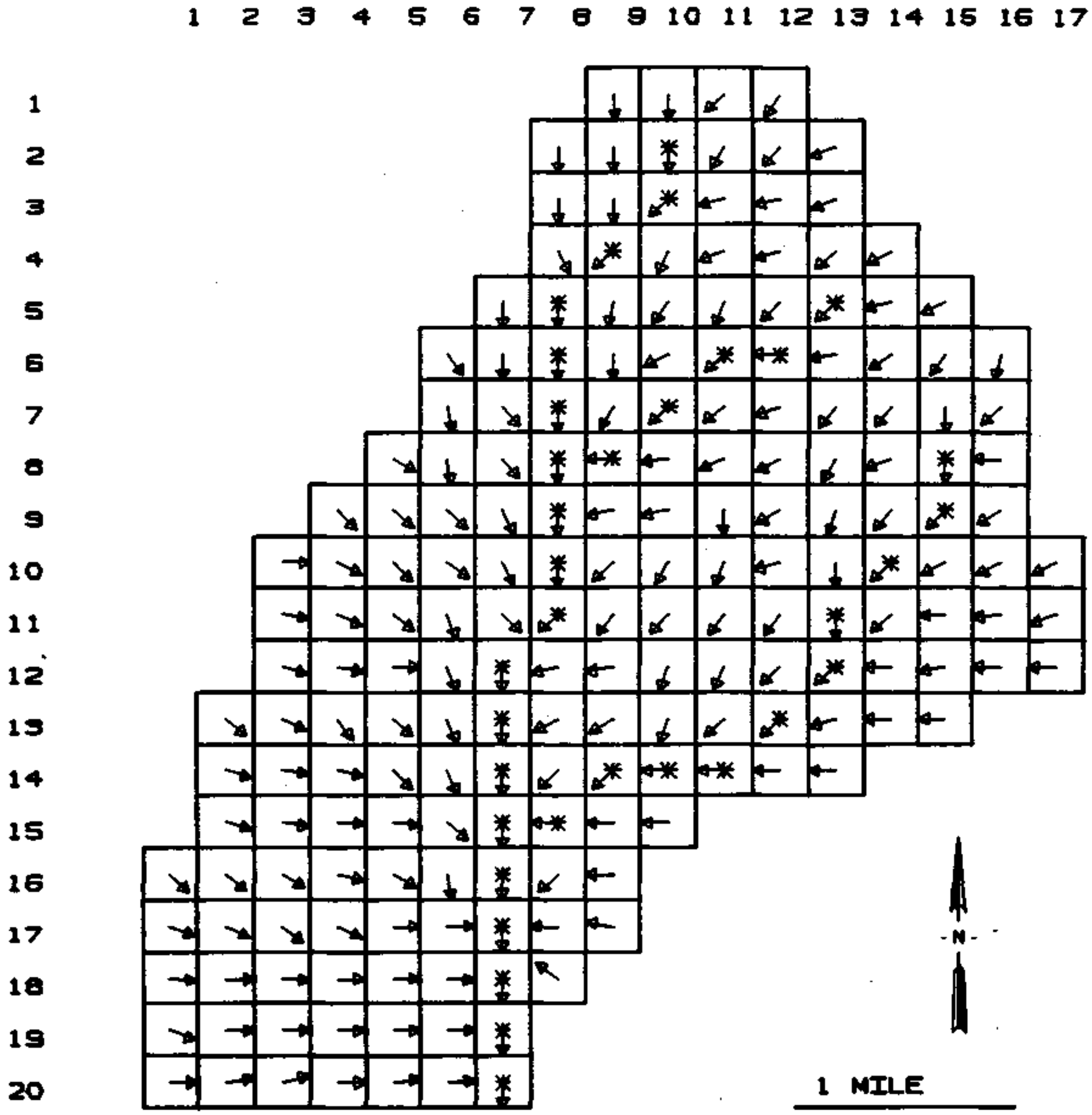

Figure 19. Representation of a catchment as a matrix of square overland and channel elements (See figure 4)

element. Channel elements also can receive flow from tile drainage and ground-water infiltration. Each overland and channel element must have a drainage outlet. In other words, ponding is not permitted by the model.

The parts of the ANSWERS model that have been used in the PWM are the square-grid-element structure with fixed slope and slope directions, and the flow routing scheme used for overland and channel flow routing. Most of the other features of the ANSWERS model such as infiltration, interception, baseflow, and tile flow have either been modified or are handled more efficiently by the other two components of the PWM. As used in the PWM, the surface flow component is a pure surface flow simulator that deals only with the overland and channel flow routing immediately following a rainfall event. It is structured in such a way that any new features needed for water quality and sediment transport simulations can easily be installed.

Overland Flow Elements

An overland flow element is conceptualized as an overland flow plane at the top of a vertical column of watershed elements, as illustrated in figure 20. It is characterized by slope and slope direction, grid size, surface roughness, coordinates, and/or flow sequence order. A computer program (TOPO) has been developed which can use the topographical surface elevations of the corners of the elements and compute the slopes and the slope directions of the elements. The slope direction of an element is the angle α in degrees measured counterclockwise from the positive horizontal axis as shown in figure 20. The slope direction is used for determining the fraction of outflow from that element going into the adjacent row and column elements as follows:

$$\beta = (90 \cdot N - \alpha) \qquad (33)$$

where N — quadrant number, and

$$RFL = \frac{\tan \beta}{2} \qquad \text{if } \beta \le 45 \qquad (34a)$$

$$RFL = 1 - \frac{\tan (90-\beta)}{2} \qquad \text{if } 45 < \beta < 90 \qquad (34b)$$

where RFL = the fraction of outflow going into the adjacent row element.

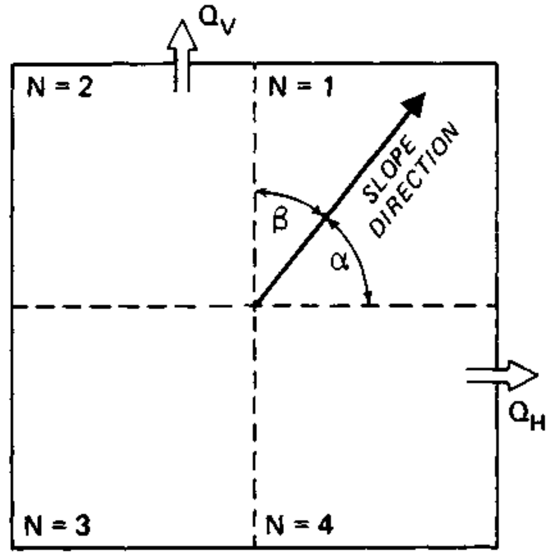

Figure 20. Partitioning of overland flow with respect to slope direction in the overland flow element

The horizontal and vertical components of the outflow from the element can then be calculated by:

$$Q_H = Q \cdot RFL \tag{35a}$$

$$Q_V = Q(1-RFL) \tag{35b}$$

where

Q_H = horizontal component of the outflow

Q_V = vertical component of the outflow

Q = total outflow from the element

Outflow from overland flow is not permitted to go into the adjacent diagonal elements.

The slope directions are also used in determining the flow sequence order (FSO) of the elements. The FSO basically controls the sequence in which the flow routing computations are performed on any element. For example, an element with an FSO of N can receive flow from elements with FSO values of less than N. Since during any given time interval the outflow from an element is also the inflow to adjacent downstream elements, it is necessary to calculate the outflows starting from the upstream elements (with smaller FSOs) to be able to perform routing on the downstream elements (with larger FSOs). This is achieved by starting the routing on elements with FSOs — 1, since they are usually the boundary elements where the only inflow is due to precipitation, and then proceeding with increasing FSOs. The computer program ORDER reads the output from the program TOPO, calculates the RFL and FSO values of the elements, and sorts them according to their FSO values.

The overland flow routing is performed by using Manning's equation in conjunction with the continuity relationship. Water in excess of retention storage is assumed to flow in the direction of the maximum slope in accordance with Manning's equation. The detention volume (water in excess of retention storage) is considered to be spread uniformly over the element, and thus the hydraulic radius of the detention flow is approximated by the detention storage depth (wide-channel assumption). Therefore the total overland flow rate is:

$$Q_{i,j} = \frac{1.486}{n_{i,j}} \; \Delta X \; D_{i,j}^{5/3} \; SL_{i,j}^{1/2} \tag{36}$$

where

$Q_{i,j}$ = outflow (total overland flow rate)

$n_{i,j}$ = Manning's roughness coefficient for overland flow

ΔX = element size (width of overland flow)

$D_{i,j}$ = flow depth (detention storage depth)

$SL_{i,j}$ = slope

$_{i,j}$ = element column and row numbers

The flow depth D in equation 36 is actually the runoff volume (detention volume) computed in the soil moisture component plus the inflow from the adjacent elements divided by the surface area of the element. However, to provide an efficient solution for the explicit solution of the continuity equation, the flow depth will be calculated in terms of detention volume. The details of this calculation are given in the presentation of the solution technique for the continuity equation.

Channel Flow Elements

Channel elements are considered to be dual elements with the characteristics of channel and overland flow. The flow routing is still performed by using Manning's equation of the form shown in equation 36 and the continuity equation, except that the definitions of the parameters are slightly different.

Each channel element may have only one rectangular channel segment with a specified slope direction, channel bottom width, and Manning's roughness coefficient for the channel bottom. Besides that, the outflow from a channel element has to go to another downstream channel element. Outflow proportioning, which can be used with the overland elements, is not permitted, but diagonal flow to downstream channel elements is permitted. Slope direction must be one of the cardinal angles between 0 and 360 degrees with 45 degree increments, i.e., 0, 45, 90, ..., 315, 360 degrees. The length of the channel segment (LC) is equal to ΔX if the slope direction aligns with the x or y direction, or is equal to $\sqrt{2} \cdot \Delta X$ if the slope direction is diagonal.

The FSOs of the channel elements are determined similarly to those of the overland elements, but since channel elements can only receive inflow from adjacent overland and upstream channel elements (they cannot flow into an overland flow element), they are sorted and placed behind the stack of sorted overland elements. This is usually done by adding a large number like 900 to their FSOs. The flow routings for the channel elements are performed only after the routing computations for ail overland elements are completed. Usually the highest FSO for the watershed belongs to a channel element which is the outlet of the catchment area.

As with the overland flow elements, channel flow is assumed to conform to Manning's equation, for which the discharge is as follows:

$$Q_{i,j} = \frac{1.486}{nc_{i,j}} \; WC_{i,j} \; DC_{i,j}^{5/3} \; SL_{i,j}^{1/2} \tag{37}$$

where

$Q_{i,j}$ = outflow (discharge from the channel element)

$nc_{i,j}$ = Manning's roughness coefficient for the channel

$WC_{i,j}$ = width of the channel bottom

$DC_{i,j}$ = channel flow depth

The channel flow depth is the total detention volume (excess precipitation plus inflows from adjacent elements) divided by the channel segment area LC • WC. As with overland flow, the channel flow depth is represented differently for computational convenience.

The channel elements are first treated like overland flow elements, and their detention storages are calculated on the basis of the excess precipitation falling on the element and the inflow from adjacent elements. The total overland flow from a dual element is, however, collected in its channel segment together with the inflow from the upstream channel segment. The inflow from ground-water infiltration and tile drainage is also collected in the channel segment. No overland routing is performed for dual elements, but channel routing is performed on the basis of the channel FSOs.

Surface Flow Routing Equations

During each time increment Δt, the continuity of inflow and outflow and the rate of accumulation of storage are calculated for each overland flow element and channel segment by using the equation of continuity:

$$I - Q = d(\text{storage})/dt \tag{38}$$

where I and Q are the inflow and outflow rates, respectively, and d(storage)/dt is the time rate of change of the storage in the element. Equation 38 can be written in discrete form for average inflow, outflow, and storage terms within a small time interval Δt as:

$$\frac{(I1 + I2)}{2} - \frac{(Q1 + Q2)}{2} = \frac{(S2 - S1)}{\Delta t} \tag{39}$$

where I1, Q1, and S1 are the inflow, outflow, and storage values at the end of the previous time increment and are therefore known. For overland flow elements, I2 consists of accumulated discharge (Q1) from adjacent overland flow elements plus net rainfall. For each channel element, I2 consists of the I2 of its dual overland element plus the flow from the upstream stream segments, as well as ground-water infiltration and tile drainage. Since for the current time increment all the elements of the I2 are calculated or estimated, we can combine all the known terms to obtain:

$$FHS = I2 + I1 + 2\frac{S1}{\Delta t} - Q1 \tag{40}$$

Furthermore, combining equation 39 with equation 40 gives:

$$FHS = Q2 + 2\frac{S2}{\Delta t} \tag{41}$$

where Q2 and S2 are the unknown values. The second equation needed for solving Q2 and S2 is given by equation 36 or 37, depending on the type of element.

For practical purposes, the flow depth D or DC in equations 36 and 37 is expressed in terms of SST = 2(S2)/Δt. Thus equation 41 becomes:

$$FHS = Q2 + SST \tag{42}$$

Neglecting the element subscripts, equations 36 and 37 can be rewritten for overland and channel flow elements, respectively, as:

$$Q2 = B_o \cdot SST^{5/3} \qquad \text{for overland flow elements} \tag{43}$$

where

$$B_o = \frac{1.486}{n} \Delta x \left(\frac{\Delta t}{2\Delta X^2}\right)^{5/3} SL^{0.5} \tag{44}$$

is the modified conveyance factor for the overland flow, and

$$Q2 = B_c \cdot SST^{5/3} \qquad \text{for channel flow elements} \tag{45}$$

where

$$B_c = \frac{1.486}{nc} WC \left(\frac{\Delta t}{2 \cdot WC \cdot LC}\right)^{5/3} SL^{0.5} \tag{46}$$

is the modified conveyance factor for the channel flow.

Equations 42 and 43 or 45 should be solved simultaneously for SST and Q2 for all elements in the watershed. This requires an implicit solution technique, which is iterative and very time-consuming. The solution requires an initial estimate for SST, which is obtained by projecting the SST of an element at the end of the previous time increment by adding the incremental SST (ASST) during the previous time increment.

An iterative solution of the continuity and Manning's equations can be obtained by using the Newton-Rapson iterative method, but this method is very lengthy. However, a direct and explicit solution is available if SST and Q2 are assumed to be linked with a depth-discharge relationship. If the discharge is assumed to be proportional to depth or depth squared and the flow is turbulent so that Manning's equation can be applied, then a "segmented curve" method suggested by Huggins et al. (1976) can be used. In this method, discharge is taken proportional to depth to the 5/3 power, to obtain a direct explicit solution by avoiding lengthy iterations. This procedure, the details of which are presented below, basically employs a piecewise linear segmented curve to approximate Manning's equation and thereby eliminates the iteration process that would otherwise be necessary for solving the continuity equation.

Direct Solution of Continuity Equations by Linearization

The direct solution of the continuity equation by the segmented curve method will be explained in a step-by-step procedure.

1. Determine the average slope $\overline{SL}$ and the average Manning's roughness coefficient n for the watershed. This can be done by averaging slopes and roughness coefficients of each element over the entire watershed or by obtaining separate values for overland and channel flow elements.
2. Determine the average modified conveyance factors of the watershed as:

$$\bar{B} = \frac{1.486}{\bar{n}} \cdot \Delta X \cdot \left(\frac{\Delta t}{2\Delta X^2}\right)^{5/3} \cdot \overline{SL}^{0.5} \tag{47}$$

   where $\bar{n}$ is the average Manning's roughness coefficient of all the elements in the watershed. $\bar{B}$ values for overland and channel flow elements can be obtained and used separately if the variation between them is significant; otherwise a single $\bar{B}$ value is used for the entire watershed.
3. Choose a maximum expected runoff, Q_{max}. from the watershed. Since the element with the highest FSO will have to pass Q_{max}, everything must be designed according to that discharge.
4. Assume that the maximum detention storage SST_{max} can be obtained with $\bar{B}$ and Q_{max}. Then by equation 43 or 45 we have:

$$SST_{max} = \left(\frac{Q_{max}}{\bar{B}}\right)^{3/5} \tag{48}$$

5. Now divide the range 0 to SST_{max} into NQ equally spaced intervals to obtain:

$$SC = \frac{SST_{max}}{NQ} = \frac{1}{NQ} \cdot \left(\frac{Q_{max}}{\bar{B}}\right)^{3/5} \tag{49}$$

Remembering that $Q2 = B \cdot SST^{5/3}$, we can generate a piecewise linear curve with the abscissa being $(m - 1)$ SC, $m = 1, \ldots, NQ + 1$ and ordinates $QA_m = [(m-1)\ SC]^{5/3}$ as shown in figure 21.

6. Estimate the storage for the next time increment by using the storage and the incremental storage at the end of the previous time increment as:

$$SST_{est}^{t+1} = SST^{t} + \Delta SST^{t} \tag{50}$$

7. The SST_{est} lies between sections m and m + 1 of figure 21 where

$$m = \frac{SST_{est}}{SC} + 1 \tag{51}$$

8. Now let's enlarge the area between sections m and m + 1 (see figure 22) and define the two new variables as shown on that figure:

$$QL = B_{i,j}\ QA_m \tag{52}$$

$$QD = B_{i,j}\ (QA_{m+1} - QA_m) \tag{53}$$

where $B_{i,j}$ is the calculated conveyance factor of element i,j.

By proportion from figure 22 we get:

$$\frac{\Delta Q}{\Delta SC} = \frac{QD}{SC} \tag{54}$$

where $\Delta SC = SST_{est} - (m - 1)\ SC$, or, by defining $Y = m - 1$:

$$\Delta SC = SST_{est} - Y \cdot SC \tag{55}$$

Therefore

$$\Delta Q = QD\ \frac{SST_{est} - Y \cdot SC}{SC} \tag{56}$$

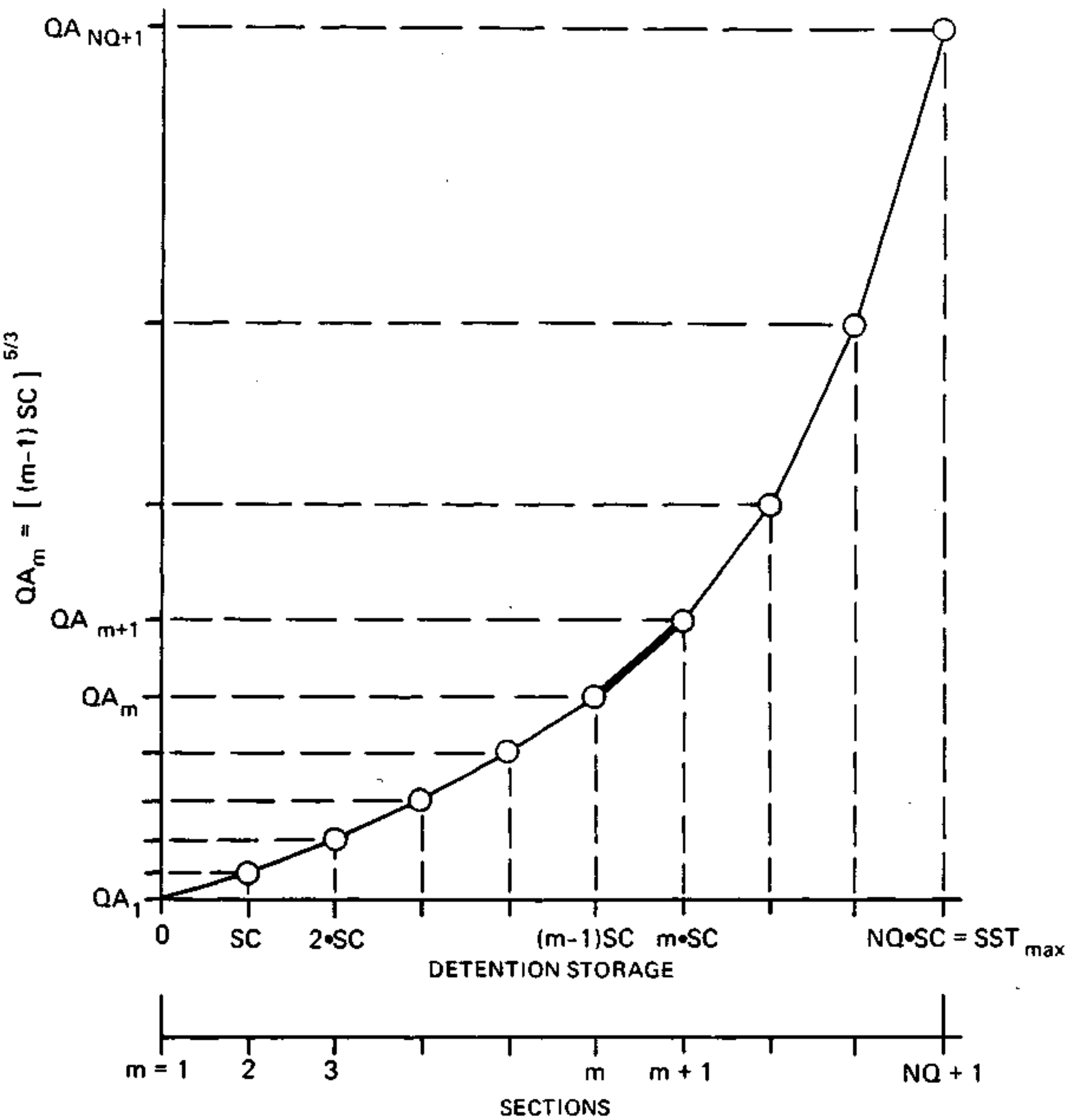

Figure 21. Pieoewise linear representation of segmented detention storage versus detention storage raised to the 5/3 power

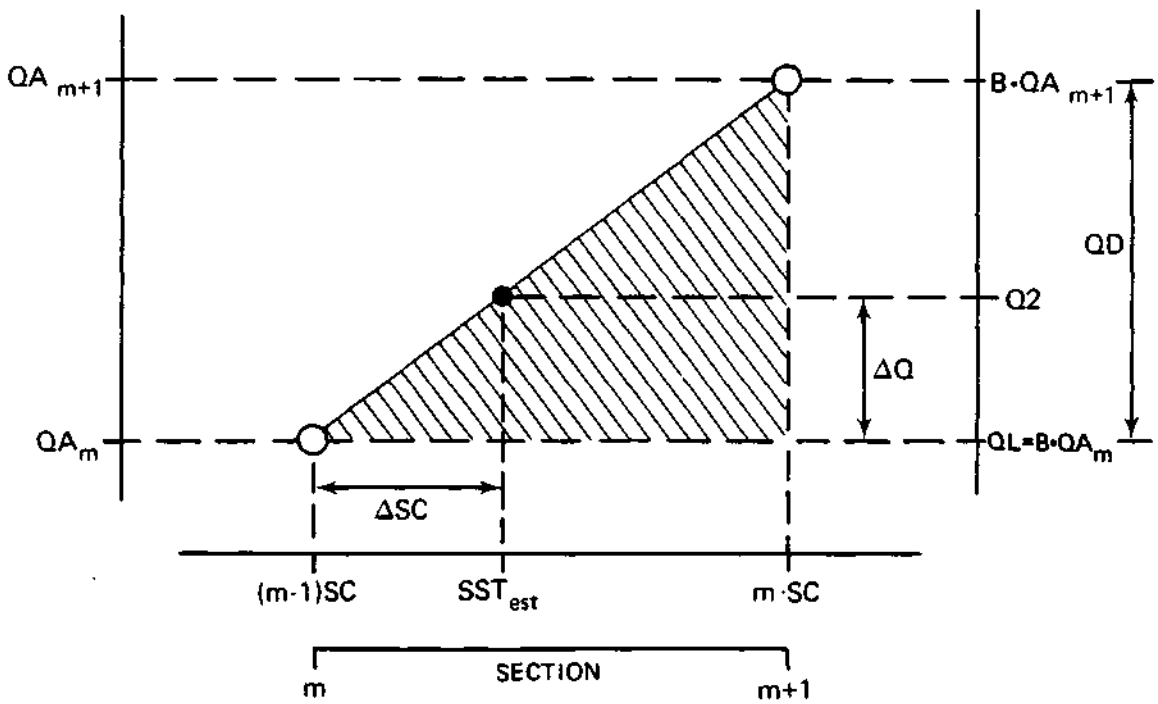

Figure 22. Enlargement of area between sections m and m+1 in figure 21

9. From figure 22 the flow Q2 from an element is

$$Q2 = QL + AQ \tag{57}$$

By defining SCI = 1/SC and inserting equation 55 into 56 we get

$$Q2 = QL + QD \bullet SCI \bullet SST_{est} - Y \bullet QD \tag{58}$$

Substituting equation 57 in equation 43 or 45 gives

$$SST = FHS - Q2 \tag{59}$$

and assuming SST_{est} = SST, we get

$$SST = \frac{FHS - QL + QD \bullet Y}{1 + QD \bullet SCI} \tag{60}$$

Since equation 60 gives the corrected storage in an element, we can now insert it back in equation 59 for the SST_{est} value and obtain Q2 after rearranging the terms as

$$Q2 = QL + QD\ (SCI \bullet SST - Y) \tag{61}$$

10. If SST > 0, equation 61 is used to calculate Q2. Otherwise, Q2 is set equal to zero. In some cases where the retention storage of an element is known, SST can be replaced by SST-RET, where RET is the retention storage. In that case Q2 should be set equal to zero if SST-RET ≤ 0.

To implement this algorithm, the SC value and the QA array should first be determined and stored in the program. Then for any element, the SST_{est} value and consequently the QL and QD values should be obtained. Inserting these values in equation 57 yields the corrected SST value, and finally the Q2 value can be obtained by substituting the SST value in equation 61. This procedure must be repeated for each element in order of the magnitudes of their FSOs.

DATA INPUT

The PWM is a quasi-distributed-parameter model that requires an extensive amount of data. Actually, the most difficult part of implementing the PWM is to prepare the data input files. The data files used by the PWM provide a very detailed description of the watershed surface and subsurface topography, drainage networks, soil and crop types and their distributions, surface and channel conditions, and subsurface characteristics. In addition to physiographic information, extensive amounts of data pertaining to climatic conditions are needed. Although the volume of data used by the model is large, most of the data are readily available through USGS topographic maps, county soil maps, well-drilling logs, aerial photographs, and records of meteorological stations. The data needed for the PWM should be obtained from field measurements, available maps and records, or calibration studies performed on watersheds with similar features, so the model can be implemented for new watersheds with no streamflow records.

Input information required for the implementation of the PWM is grouped under four major data files:

Element information file
Climate information file
Soil information file
Crop information file

Element Information File

The element information file is used by the surface flow and ground water components and is the second-largest data file used in the PWM. (The climate information file is the largest.) It contains most of the information about the element coordinates; surface slope and slope direction; element type (overland or channel flow); type of soil, surface, and channel in each element; initial and boundary conditions; surface and subsurface topography; and tile drainage parameters (where applicable). Because of its wide and extensive coverage of information, preparation of this data file is time-consuming. The element information file also contains some global information needed by the ground water and surface flow components, such as the total number of overland and channel elements (or total number of nodal points), grid size, and time increments for the ground and surface flow routing computations.

Most of the information needed for the element information file is obtained by using the corner elevations of the watershed elements. Corner elevations are obtained by overlaying the grid map on a topographical map of the same scale. This information is then input to the TOPO program to obtain the slope and the slope direction of the grid elements, as well as the fraction of the surface flow going to adjacent elements. The output from TOPO is not sorted with respect to flow sequence of the elements, so it is processed through the ORDER program, which sorts the elements according to their FSOs. Other information pertaining to the soil, crop, surface, and channel types and to initial and boundary conditions is entered manually either before or after using ORDER.

Attached to the element information file are three secondary files which are accessed through the element information file: a) channel file; b) soil file; and c) surface file.

The channel file contains the widths, Manning's roughness coefficients, thicknesses, and permeability coefficients of the bottom deposits for all the channel types included in the element information file.

The soil file contains subsurface soil permeability and storage coefficients for all the soil types included in the element information file. A different soil file from the soil information file is used in the element information file, for better representation of the vertical variation of the soil properties in the top layers of soil (up to 6 feet depth) and the deeper subsurface soil. Each soil type entry in this file is actually a combination of soil and crop types used in the soil moisture component. Actually, crop type has no effect on the subsurface permeability and storage coefficients, but the same soil types with different crop types have different transpiration and thus different deep percolation values.

Finally, in the surface file, the surface Manning's roughness coefficients of the overland elements are given. The roughness of the overland elements is assumed to vary with different crop types and farming practices.

Climate Information File

The climate information file is the largest file used in the PWM. The following data are stored in this file:

1. Average daily temperature, which is an arithmetic average of the daily maximum and minimum temperatures.
2. Daily or sub-hourly precipitation data.
3. Mid-afternoon wind speed.
4. Relative humidity, measured at its minimum level during mid-afternoon.
5. Total possible sunshine in minutes per day. This value is constant for any day of the year.
6. Actual percent of possible sunshine, calculated as a function of the observed cloud conditions.

Although the volume of the data included in the climate information file is large, the data are usually available from a single source. The most common source is local climatological data, which are available for all first-order National Weather Service stations. The hourly precipitation data can be obtained from the National Weather Service.

Almost all the data included in the climate information file are measurable and need no calibration. In the case of missing data, estimates are obtained in correlation with data for available neighboring stations.

Soil Information File

The soil information file contains two sets of parameters. The first set pertains to initial or average conditions which can be obtained from county survey maps; these are needed for the soil calibration process. For any given soil type, the following initial conditions are required: permeability, saturation, and plant available soil moisture (volume of water between the field capacity and the wilting point) for various depths of soil. These initial conditions are required only if the particular soil type has not been calibrated earlier. If calibrated parameter values are available, the initial conditions are not needed in the soil information file.

Calibration is performed for all soil parameters by using soil moisture measurements for a period of four to five years. The following soil parameters are calibrated and added to the soil information file:

1. Soil evaporation (a function of soil texture)
2. Unsaturated hydraulic conductivity
3. SCS curve number (moisture condition I)
4. Potential daily transpirative uptake by roots, EPMAX (a function of soil texture)
5. Permeability (for 7 soil layers)
6. Wilting point (for 7 soil layers), in percent of total soil volume
7. Field capacity (for 7 soil layers), in percent of total soil volume
8. Upper limit of storage (saturation) (for 7 soil layers), in percent of total soil volume

Once these soil parameters are calibrated they may be considered as permanent values, and they can then be used with soils of similar characteristics without further calibration.

Crop Information File

Parameters used in the crop information file are not measurable, but all are obtainable from certain handbooks or reference manuals. The crop parameters are used to describe the root distribution and the growth stage of a particular crop type. These parameters are:

1. Root distribution at time of maximum growth, for a given crop type, as a percent of the total root distribution within each of the seven soil layers. One suggested reference for this parameter is Users Manual for SPAW (Saxton et al., 1984).

2. Distribution of leaf-area index (LAI) through the entire calendar year. LAI is usually input as a discrete function in the form of

DAY:	1	122	135	150	......	365
LAI:	0	0	0.3	0.5	......	0

The LAI values in between the given points are interpolated by the program. LAI values can be obtained by using the crop growth stage curves in Irrigation Water Requirements (U.S. Department of Agriculture, Soil Conservation Service, 1970).

Both parameters may vary from year to year, depending on the planting date, and from one crop to another.

SUMMARY

The PWM, a physically based quasi-distributed-parameter watershed model, has been developed for simulating impacts of increased precipitation on agricultural products and water resources.

The hydrologic processes that can be simulated by the PWM are infiltration, evapotranspiration, soil moisture, ground-water flow, and surface flow. The model can use variable time steps, enabling it to operate as either a sequential or an event model. The model is also capable of handling a wide range of watershed areas. The only limitation in using short time intervals (required for operation as an event model) and large watershed areas is the amount of data preparation needed, computer time required, and storage restrictions.

The PWM is also capable of optimizing necessary soil parameters if sufficient records of measured soil moisture are available. Once a particular soil type is calibrated, this information can be applied directly to other locations that have the same soil properties. Most of the remaining parameters used in the model are measurable.

The inputs to the model are precipitation; climatic factors (temperature, wind speed, cloud conditions, and relative humidity); and crop distribution. Initial conditions such as soil types, topography, water-table configuration, drainage network, and watershed boundaries are also input to the model. The model outputs are soil moisture distribution at the top 6 feet of soil; crop development and crop water use; evaporation; deep percolation; baseflow; streamflow; and water-table configuration.

Future developments and applications recommended for the PWM are:

1. Improve the method for estimating average runoff, given daily precipitation values.
2. Improve the feedback mechanism between soil moisture and plant growth.
3. Develop the software necessary for the PWM to be used in forecasting in a real-time operation mode.
4. Test the surface flow component extensively.
5. Calibrate a variety of soil and crop types in Illinois.
6. Apply the PWM to a wide range of watersheds.
7. Improve the surface flow component to handle sediment and chemical transport.

This report covers the development of the PWM. Calibration and testing of the model components for a small watershed in Illinois, and the simulation results for several cases of weather modification, are discussed in the accompanying report, *PACE Watershed Model (PWM): Volume 2, Weather Modification Simulations.*

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