A REVIEW OF MODELS
FOR
INVESTIGATING THE INFLUENCE OF WETLANDS ON FLOODING

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Introduction

After the recent devastating flood of 1997 in the Red River of the North, questions were raised regarding the value of wetlands for flood control. While some believe that wetlands have a moderating influence on flood volume and peak, others argue wetlands and their drainage have no impact on flooding. The wetlands when drained and farmed provide agricultural benefits contributing to the economy of agriculture. Lack of understanding and the propagation of misinformation has confused the public about the role of wetlands on flooding. This seemingly conflicting role of wetlands for flood control versus agricultural benefits has spurred interest in investigating the impact of wetlands on flooding on a scientific basis.

In order to assess the impact of wetlands on flooding, a study was initiated to model the influence of wetlands more accurately. In order to quantitatively assess the effectiveness of wetlands in flood control measures, modeling the hydrology of wetlands and the watersheds in which they are located will be necessary. The purpose of this study is to assess existing hydrologic models for their usefulness in simulating wetland hydrology, review previous studies of simulation of wetland hydrology, and recommend a modeling approach applicable to assessing the effectiveness of wetlands in flood control.

As a first step, the current hydrologic and hydraulic models used for modeling floods need to be carefully studied for their capability or lack of it for representing wetland hydrology. A critical review of watershed runoff models is presented in this report with a view to assess their suitability for modeling the influence of wetlands on flooding.

Wetlands and Flooding

Wetlands have been claimed to provide benefits such as wildlife habitat, water quality improvement, groundwater recharge, and flood control by decreasing peak flows and/or the total volume of runoff. When drained and farmed they provide agricultural benefits. The flood control benefit should not be taken for granted, however.

Some believe that wetlands can act as storage reservoirs, slowing storm runoff, and decreasing runoff volume and peak. Draining such wetlands would result in increased flooding. Some favor restoring drained wetlands for their flood control benefit. However, It can also be argued that draining wetlands may reduce flooding by providing greater storage in the wetland, and by allowing the soil to dry providing capacity in the soil column to store more runoff.

Whether or not a wetland can store significant amounts of runoff depends on the hydrology of the wetland. The prairie potholes prevalent in the Red River Valley could theoretically provide depression storage of runoff, but the amount of available storage will depend on the antecedent conditions. If the wetlands are full, or partially full, available storage is reduced. If the wetland recharges the groundwater, or there is significant evapo-transpiration, the levels of water in the wetland may be drawn down during dry periods. If the wetland is being recharged by groundwater, then even during dry periods the level of water may not appreciably decrease. Complicating the wetland hydrology is the presence of man-made drainage, such as drain tiles and enhanced surface drainage by ditch systems.

Wetland Hydrology

The hydrology of wetlands can be very complex. Some wetlands discharge to the groundwater, while others are recharged by groundwater. Some will retain water year round while others may be dry for part of the year. Depending on the type and condition of vegetation and the amount of open water, evapotranspiration rates will vary greatly. The wetland may be affected by a subsurface drainage system such as drain tile, or by surface drainage. Antecedent conditions of soil moisture and amount of water already stored in the wetland will affect how much storage is available for runoff. Prairie potholes, which are shallow wetlands formed through glacial action, lose water through evapo-transpiration and infiltration. In a wet year, the level of water in such wetlands may drop very little, or actually rise and thus their effectiveness in flood control will be reduced.

In addition to the natural hydrologic processes occurring in wetlands, man-made drainage can complicate the hydrology. Drainage may consist of subsurface tile drains, or ditches to carry off surface drainage, or combinations of both. Drainage can directly lower the water levels in wetlands, or indirectly by lowering the water table in the vicinity of the wetland, causing increased infiltration.

The hydrology of wetlands need to be modeled in detail only when the focus of interest is in the hydrologic budget of wetlands and other wetland functions. When modeling for flood events, it may not be necessary to model all the hydrologic processes. Evapo-transpiration, infiltration, and groundwater flow may not be significant during a flood event. Generally overland flow and streamflow dominate. This would simplify the requirements of a watershed hydrologic model for assessing the impact of wetlands on flooding. Also, when there are hundreds of small depressions in a single subwatershed, and thousands within the entire watershed, it will not be possible to represent each one in a model. Lumping the wetlands to some degree will be necessary.

Modeling Needs for Investigating the Effects of Wetlands on Flooding

Ideally, a watershed hydrologic model capable of simulating wetland hydrology should include the ability to model rainfall, snowmelt, evapotranspiration, surface runoff, subsurface infiltration, groundwater flow, storage within the wetland, and flow through man-made drainage structures, as well as streamflow. The model should be capable of routing flows through wetland depressions in addition to routing overland flow, streamflow, and subsurface flow (US Army Corps of Engineers, 1988.)

The location of wetlands within a watershed affects their ability to control floods. For instance, if the wetlands are all located in the upper portion of the watershed and drain only a small percentage of the total contributing area, they may have little impact on downstream flood peaks and runoff volume. A model that can capture the spatial distribution of the wetlands and other hydrologic features in the watershed would better simulate the effect of the location and distribution of wetlands.

To model the effect of wetland depression storage, the location and storage volumes of the wetlands would be required. A DEM (Digital Elevation Model) might be used to develop a digital terrain model which could delineate the wetland depressions if the resolution of the DEM is adequate to capture these shallow depressions. Chen (1996) developed the Object Watershed Link Simulation model (OWLS), a physics-based hydrologic model which incorporates a geomorphological submodel. The geomorphological submodel uses a DEM to develop a three-dimensional model of the watershed subdivided into cells. As in a geographic information system, attributes such as length, area, slope, and soil type can be linked to each cell. The model also determines the flowpaths from cell to cell, delineates the streams, and determines the watershed boundaries and outlet from the DEM data. OWLS might seem to be a useful model for analyzing watersheds with wetlands, but it has only been applied to a small forested watershed at this time. This watershed had been studied by the USEPA since 1987 as part of the Watershed Manipulation Project, and there is an extensive database available including a detailed DEM. The model is not proven on a large watershed with sparse data.

Another way to represent the various features such as depression storage, overland flow, and streamflow of a watershed is using a hydraulics-based model with a network of nodes and interconnected links. This approach requires extensive amounts of topographic data including cross sections for streams and wetlands. Hydraulics-based models are typically applied to the mainstem of a river and its significant tributaries, and not to overland runoff. Alternatively, hydrologic watershed models may be used to model rainfall-runoff processes and thus provide input to hydraulics-based models. Ogawa and Male (1986) utilized HEC-1, a hydrologic model, and HEC-2, a hydraulic model to simulate subwatersheds to assess flood control measures. HEC-1 was used to model the upper portion of the studied watersheds, with individual wetlands represented as reservoirs at the outlets of the subwatersheds in which they were located. The outflows were then routed downstream using the HEC-2 model.

Watershed Hydrologic Models

Since the late 1950s many models have been developed to simulate the hydrologic processes occurring on watersheds. They are of many different types and were developed for different purposes. Many have structural similarities due to the same underlying assumptions used in developing the models, and some are markedly different. Some of the popularly used models are discussed in relation to their capability of accurately representing the effects of wetlands.

Hydrologic models compute runoff from precipitation in a drainage basin. Then the runoff is routed to the outlet of the basin. Excess precipitation is determined by subtracting what is intercepted by vegetation, stored in surface depressions, evaporated from such depressions, and infiltrated into the soil. The output of a hydrologic model is usually a hydrograph, which shows the outflow from the basin over time. From the hydrograph the peak flow magnitude and time to peak can be determined. Information on the water surface elevation within the basin cannot be determined with a hydrologic model. Hydrologic models cannot determine flood-plain boundaries, for example. This would require a hydraulic model. The output from a hydrological model and detailed information about the geometry of the flow cross-sections are necessary for successful implementation of a hydraulic model.

Types of Hydrologic Models

Figure 1 illustrates a scheme for classifying hydrologic models on which the following discussion is based.

Statistical and Deterministic Models

Statistical models include consideration of uncertainties in both the parameters and input data. Simple statistical analysis could include techniques such as double mass curve analysis, regression, and flood frequency analysis. Miller and Frink (1982) used such techniques to study how changes in landuse and increases in manmade drainage have affected the flood response in the Red River Valley Basin. Brun et al (1981) and Vining et al (1983) performed regression analyses of streamflow with time, with precipitation, and with drainage area to determine if streamflow had increased over time, with precipitation, or with increased drainage area due to increased agricultural land drainage. These techniques can be used to show changes in hydrologic response in a watershed, but it may be very difficult to determine what underlying factors have contributed to the changes.

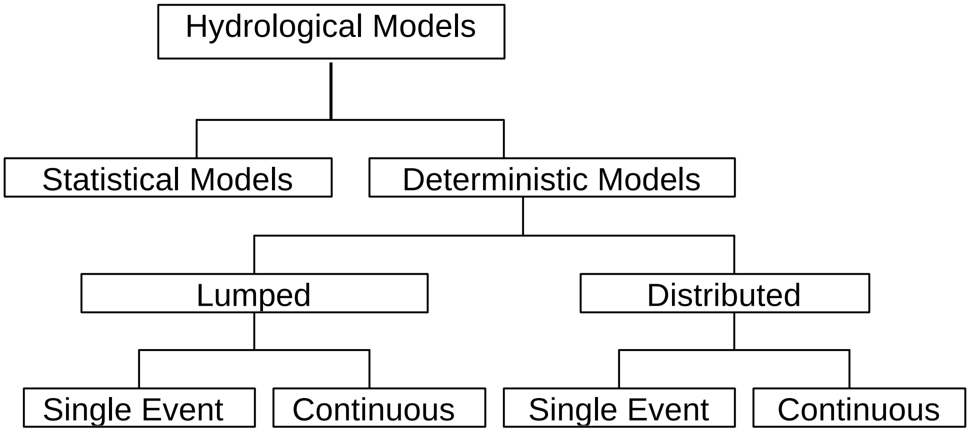

Figure 1. Classification of Hydrologic Models.

Deterministic simulation models describe the behavior of the hydrologic processes in a watershed using mathematical expressions that interrelate the various phases of the hydrologic cycle. The desired output of these models is usually streamflow. These models are verified or calibrated by comparing the model output with existing data, if available. Models such as the HEC-1 Flood Hydrograph Package (HEC-1), Hydrological Simulation Program - FORTRAN (HSPF), Precipitation-Runoff Modeling System (PRMS), EPA Storm Water Management Model (SWMM), DRAINMOD, and Agricultural Nonpoint Source Model (AGNPS) are all considered deterministic models.

Lumped vs. Distributed Models

A lumped hydrologic model takes no account of spatial variability in parameters describing the watershed, the hydrologic processes, the input data or the boundary conditions. Processes may be described by differential equations based on hydraulic laws and by empirical equations. An example of a lumped hydrologic model would be a tank model, as used by Kadlec (1994) to model detention and mixing in a wetland. In this approach the wetlands are conceptualized as a single tank or cascade of tanks. This approach models the wetlands as a tank or series of tanks with no attempt to model the physics of infiltration, surface runoff, evaporation, streamflow, or other hydrologic processes. The parameters describing the tank or tanks are determined by calibrating the outflow of the tank with measured outflow from the wetland. In a sense this is a 'black box' approach. Another example will be those models in which the parameters and the hydrologic variables take on single lumped values over large areas without regard to their spatial variability. In this sense, HEC-1, HSPF, and PRMS are considered to be lumped models, although they might better be described as quasi-distributed, since the watershed can be subdivided. In order to model watersheds with spatial variability, these models use the same approach of subdividing the watershed into subbasins where hydrologic processes such as precipitation and infiltration are assumed to occur uniformly over the subbasins. These models typically include river reaches, reservoirs, and confluences or junctions where flows from subbasins, river reaches, and/or reservoirs are combined.

Distributed models such as AGNPS account for spatial variability of hydrologic processes, input data, boundary conditions, and watershed characteristics. Rather than subdividing the watershed into hydrologically homogeneous subwatersheds, it is divided into uniformly sized cells. The hydrologic processes are modeled in each cell and runoff is routed to neighboring cells based on the direction of the cell's slope until it reaches the basin outlet. This is the finite difference approach to solving the differential equations that describe some of the processes.

In practice, there is seldom enough data available to justify using distributed models. The data requirements are much greater than for lumped models. Many times the watershed characteristics, the input (e.g., there may be only one precipitation gage in the watershed), and boundary conditions may be lumped, while only rainfall-runoff processes may be treated in a distributed way. These are considered quasi-distributed models. SWMM is a quasi-distributed model, while AGNPS is considered to be a distributed model. Distributed models are more commonly found in groundwater simulation rather than surface water modeling. This is partly due to the fact that groundwater modeling involves far fewer hydrologic processes than surface runoff modeling, and is more amenable to modeling with differential equations using finite difference or finite element solution methods.

Event-Based vs. Continuous Models

Many hydrologic models including HEC-1 and AGNPS are classified as event-simulation models as they are used for modeling a single precipitation-runoff event. They generally use time intervals on the order of hours or even minutes. These models are meant to produce a detailed runoff hydrograph, with the main interest being only the peak flow . In the vast majority of these models, the precipitation that infiltrates into the soil “disappears” and is not further accounted for in the hydrologic processes. These models usually do not model interflow or groundwater flow from infiltrated water directly, although they may include a baseflow component from groundwater recharge into a river reach. They also generally do not model evaporation and transpiration, or changes in soil moisture. The reason why these processes are not considered is that they usually do not contribute significantly to the runoff over the relatively short time period that runoff occurs from a precipitation event.

Continuous (or sequential) models are generally used to model flow over longer periods of time such as months and even years accounting for all the precipitation-runoff events during the period. In addition to the hydrologic processes included in the event-based models, continuous models keep an accounting of soil moisture by routing infiltration into the soil and partitioning it to subsurface flow, groundwater flow, and evapo-transpiration. These may also be referred to as water-balance models, as they account for all the precipitation that falls in a watershed.

Continuous models include HSPF, PRMS, and SWMM. SWMM can also be run as an event-based model. These models can be operated in two time scales in the same simulation: daily and storm mode. The daily mode simulates hydrologic processes as daily average values and uses longer time steps. This mode is used between precipitation events. The storm time scale is used to simulate precipitation events. A much shorter time step (1 hour or shorter) is used to obtain the runoff hydrograph of the precipitation event. Output for daily mode reports daily average or total values of runoff, while output for storm mode includes a runoff hydrograph.

Small vs. Medium vs. Large Watershed Models

Watersheds with areas of 100 km^2 or less are generally considered small, those with areas of 100 to 1,000 km^2 medium-sized, and those over 1,000 km^2 large. These are somewhat arbitrary limits, but models have been developed specifically for small, medium, or large watersheds. Certain hydrologic processes dominate at different scales. For example, in small watersheds infiltration and overland flow predominate and channel flow is less important. Small watersheds are also more sensitive to high-intensity, short-duration precipitation events. Such events require a short simulation time-step, on the order of minutes or less. In larger watersheds spatial variations in data and watershed characteristics have less effect on the hydrologic response, and the simulation time-step size may be larger.

HEC-1, SWMM, HSPF, PRMS, and AGNPS, have all been successfully applied to small, medium, and large watersheds.

Model-Use Based Classification of Hydrologic Models

Models are also classified according to their typical application. AGNPS is generally used for agricultural applications, while the EPA-developed SWMM is generally used to model urban storm runoff. HEC-1 and PRMS were developed to be all-purpose hydrologic models. HSPF was initially developed as an all-purpose hydrologic model, but the capability to model pollutants was added, and now the model is most commonly used for water quality studies.

Application of Hydrologic Models to Wetlands

This section discusses applications of hydrologic models to study the hydrology of wetlands. A review of the literature in this area reveals that , in general, most models used for this purpose are continuous water-balance models, applied to single wetlands or a single wetland complex.

The U.S. Army Corps of Engineers Hydrologic Engineering Center prepared a report on comparison of modeling techniques for wetland areas (USACE, 1988). They considered several methods and models including HEC-1, the Iowa State University Hydrologic Watershed Model, the Minnesota Model for Depressional Watersheds, and DRAINMOD. The last three models were developed specifically to analyze wetland and agricultural drainage, and can simulate precipitation, evapotranspiration, infiltration, surface runoff, and streamflow. They can also route flow through depressions having subsurface and surface drainage. The Iowa model was developed to simulate a series of depressional wetlands. When Haan and Johnson (1968) applied the Iowa Model to watersheds with depressional wetlands, they found that wetland drainage appeared to increase runoff volumes, with a greater impact on higher frequency storm events. When Campbell (1973) attempted to develop a branched flow system, the resulting model was deemed too complex for practical use. Since 1973 no further work has been done. The Minnesota model is similar to the Iowa model. No further work has been done on the model since 1979. Neither the Iowa or Minnesota model have been adapted for use on a personal computer, nor have they been upgraded in any other way since the early 1970s. DRAINMOD does not have a depression routing component, but a volume of depression storage can be defined that must be filled before overland runoff can occur. Such depression storage can also be defined in HEC-1 as a component of the infiltration loss.

Ogawa and Male (1986) presented a general simulation approach to evaluate the potential of wetlands to mitigate flooding and applied the approach to a case study. They utilized the HEC-1 and HEC-2 models. HEC-1 was used to model the upper portion of the studied watersheds. The individual wetlands were represented as reservoirs at the outlets of the subwatersheds in which they were located. The emphasis was on modeling individual wetlands for regulatory purposes in the evaluation of flood mitigation. The results implied that a small degree of encroachment on wetlands would not affect peak flood flows significantly except for wetlands along a main-stem stream. Also, any change in the peak flow resulting from the encroachment is significant for only short distances downstream. Their findings also suggested that downstream main-stem wetlands were more effective than upstream wetlands in reducing downstream flooding.

Anderson (1994) performed a hydrologic analysis of restored wetlands in the Red Lake Watershed District and the Bois De Sioux Watershed district. Each of three wetlands was studied individually in a pre-restoration state (drained) and post-restoration using the Hec-1 and Hec-2 models. The storage potential of each drainage basin was defined by stage versus area curves developed from a topographic survey. For each wetland studied, outflow rating curves were developed for pre- and post-restoration conditions using normal depth analysis, weir equations, and the HEC-2 hydraulic model where appropriate. Using HEC-1 allows various starting depths to be modeled in a wetland to see how storage might affect the volume of flow and peak flow.

Gumb, DeNicola, Mehrotra, and Smith (1995) studied a small watershed (372 ha or 920 acres) located on Staten Island, NY using HEC-1 and HEC-2 to determine the viability of wetlands along a stream located in the watershed. The model was used to assess the effectiveness of improvements in the watershed to reduce the peak discharge for a 5-year design storm. The recommended improvements included diverting stream flow through a wetland upstream of a culvert. The simulation results indicate that the improvements could reduce the peak discharge for the 5-year design storm by about 25 percent. No information was supplied on how the wetland was modeled.

Meyer (1998) represented wetlands as individual reservoirs within synthetic watersheds to investigate the effect wetland location, initial water levels, storm intensities, and watershed shape have on flood hydrographs. The HEC-1 model was used to model the watersheds. Individual wetlands were modeled as square reservoirs with streamlined weirs to best represent overtopping of the wetland. Meyer found that in the synthetic watershed upland wetlands provided the greatest reduction in peak flows, but that location of the wetlands did not affect total flow. Total flow was affected by the initial level of storage in the wetlands, but the peak flow was not affected. Wetlands provided more effective mitigation for high frequency storm events than for low frequency events.

Nichols and Timpe (1985) used HSPF to simulate the dynamics of phosphorus in floodplain wetlands over a wide range of hydrologic regimes in South Florida. They modified HSPF to better model hydrologic processes in wetlands*.* This included developing a flow-routing algorithm with a depth-discharge functional relationship for the wetlands. This allowed the outflows from wetlands to be modeled as a function of volume or depth. The main purpose of the study is to study phosphorus dynamics in the watershed.

Nath et al (1995) discussed hydrologic evaluation of wetland restoration measures by continuous simulation with HSPF. HSPF was chosen because it can simulate the behavior of various soil storage zones. The PERLND module does not allow simulation of ponding and saturated soil conditions, and they recommend inclusion of a dynamic routing algorithm in the RCHRES module to better simulate the multiple flow regimes in a complex canal network. The interest is in modeling runoff patterns and the soil moisture storages.

Clemetson (1990) and Franklin and Newbold (1992) presented a system for hydrologic evaluation of wetlands in which is embedded the Wetland Hydrologic Analysis Model (WHAM) used to screen sites for wetland restoration and preservation based on hydrologic parameters. WHAM was developed by the US Army Corps of Engineers Hydrologic Engineering Branch, Omaha District. The model computes the hydrologic budget of the wetland on a daily basis. It models single wetlands and can be used as a design tool for constructed wetlands. The Streamflow Synthesis and Reservoir Regulation (SSRR) model was used to derive synthetic inflows to the HAM model. This model simulates individual wetlands.

Brooks and Kreft (1989) discuss the Peatland Hydrologic Impact Model (PHIM) developed for Minnesota peatlands. PHIM is a continuous simulation computer model of the hydrologic functions of peatlands and upland-peatland watersheds. It is applied to individual peatlands or fens, and may be used to estimate effects of peat mining and changes in upland land use on streamflow. PHIM was developed over a 12 year period including extensive field measurements to test the model.

Skaggs and Evans (1989) used DRAINMOD to evaluate effects of drainage of wetland hydrology. This field-scale study simulated water table depths in drained wetlands for two North Carolina soils over a 38 year period of climatological record. Various ditching schemes were modeled.

Konyha et al (1995) discussed the advantages of using SWAMPMOD, a continuous hydrologic water balance model for modeling constructed or depressional wetlands using reservoir routing methods. The model is driven by daily rainfall and watershed inflows. Among other results, simulated annual and monthly water balances, flood frequency distributions, and retention time distributions were provided in the output. SWAMPMOD is best suited to modeling small constructed palustrine marshes or natural depression wetlands, but not very large riverine, floodplain, or natural lacustrine wetlands. A single hypothetical constructed wetland was modeled to evaluate hydroperiods and wetland functions such as hydrologic suitability for plants and retention time distribution for evaluation of pollutant removal in the wetland.

Walton et al (1995) discussed the preliminary development of the Wetlands Dynamic Water Budget Model. Future development is planned to enable investigations of a variety of wetland types including prairie potholes. The model is a pseudo two-dimensional hydrodynamic model using links and nodes to model interlinked waterways and overbank areas. It allows modeling of roads, channels, culverts, gates, and inflows from upland basins, and was applied to the Cache River bottomland. Walton et al (1996) applied the Wetlands Dynamic Water Budget Model to the Cache River and the Black Swamp wetlands to support a large field investigation of processes in the Black Swamp wetlands. Only the surface-water module was applied in this study. Results showed that the riverine wetlands were inundated from backwater, rather than from the flood wave. The model defines flows along one-dimensional channels (links) between nodes. It has only been tested on riverine and tidal wetlands. The developers intend to develop the model further for other types of wetlands including prairie potholes.

Peterson and Hamlett (1997) used the SWAT (Soil and Water Assessment Tool) model to model the hydrologic response of a watershed in northeastern Pennsylvania. The area is characterized by 3% wetlands and frangipan soils (75%). Monthly flows were simulated. The model was found to adequately simulate monthly runoff volumes in absence of snowmelt events. The results suggest that SWAT is better suited to long term simulations, and not to single events.

Mercado et al (1993) used a water budget model (a hybrid of the SFWMD’s Interactive Seasonal Water Balance Model with CREAMS-WT (modification of CREAMS by U. of Florida). Data input was on a monthly basis. The main purpose was to develop an interface between a GIS and model. The model was applied to a 50,000 acre watershed, but no calibration had been performed at the time of the article’s publication. The main use for the model is wetland management, simulating the impact of drainage, and ecological concerns.

Pietroniro et al (1996) applied a distributed hydrologic model called SPL7 to a 10,000 km^2 area of permafrost and wetlands to model snowmelt, infiltration, surface runoff, and groundwater flow. The watershed was divided into Grouped Response Units (GRU) characterized by spatially constant rainfall and/or snowmelt and small travel times. Runoff generation, overland routing, and interflow dominate the response of GRUs. The individual GRUs were 10 km^2 in area, resulting in 1000 GRUs. The model was calibrated satisfactorily using the original physical parameters for application in a southern temperate climate, but validation was unsuccessful showing deficiencies in the model for a cold, northern, wetland-dominated regime. Other obstacles to validation included scarcity of representative hydrometeorological data.

Poiani and Johnson (1993) developed a spatial simulation model of hydrology in semi-permanent prairie wetlands. This is a water balance model based on precip, runoff, and potential evapotranspiration used to estimate water depths. The main use for the model was to simulate vegetation dynamics . The hydrology is a submodel to estimate water depths. Groundwater processes were not directly considered. Groundwater seepage loss or gain was not simulated. The Cottonwood Lake study site in North Dakota is a long-term study site (since 1975). The wetlands simulated were only 1-2 ha in size, and the cell size in the model was 9.3 m^2. Runoff from precipitation was simulated using a nonlinear regression equation. Initial spring water elevation was simulated using a regression equation including snowmelt runoff. Potential evaporation was estimated using the climatic water-budget method which is a function of average daily temperature, an annual heat index, and a parameter based on a nonlinear function of the heat index. The main use will be for managing prairie wetlands for wildlife to produce optimum ratios of emergent cover to open water. Another use is to predict changes in vegetation due to land use changes near the wetland. Poiani et al (1995) studied a single wetland basin using this model to investigate the effects of climactic change (increased temperatures and altered seasonal precipitation) on the sensitivity of wetland hydrology.

Spieksma and Schouwenaars (1997) developed a simple quasi two-dimensional model to predict water level fluctuations in partially inundated wetlands. This model is incorporated into the soil water flow model SWATRE. The 2-D approach takes into account the areal fraction of the inundated or open water portion of a wetland and the non-inundated portion.

Franques and Townsend (1993) discussed a GIS-based stormwater management model. The model consists of a rainfall-runoff model and hydrodynamic channel routing model, integrated with a water quality spreadsheet model to provide screening level water quality impact evaluation for analysis of alternatives. The model was developed for a 120 sq. MI basin in Pasco County, Florida. A one-foot contour coverage and natural features were used to delineate subbasin boundaries and create arc-line hydrologic pathways. Wetland and waterbody coverages were used to map the channel network of the basin to generate network topology for the hydrodynamic routing model. Channel cross-section data was extracted from the GIS contour coverage using a TIN (triangulated network terrain modeling package).

Giraud et al (1997) used a coupled model to simulate the hydrology of a 22 km^2 agricultural marsh. The marsh is characterized by a very dense channel network of 1800 storage basins closely connected with 500 km of ditches. They used the field-scale drainage model SIDRA with the hydraulic model MAGE to study how much subsurface drainage, in combination with land use and channel water storage, affect flow paths and flow rates within the marsh and discharge at the marsh outlet. The water management goal is to drain excess water during the wet season and store water in the channel network during the dry season. Water is managed by a series of sluice gates.

Hammer and Kadlec (1986) developed a distributed finite-difference model for overland flow through vegetated areas. It was applied to a single peatland in Michigan, for which information on flows, depths, and other hydrologic variables had been collected for 13 years. The model simulates overland flow through vegetated areas. It may be useful as a subroutine for a complete hydrologic rainfall-runoff model.

Hey et al (1994) discussed the hydrology of four constructed, experimental wetlands in northeastern Illinois. Detailed water budgets were constructed during 1990 through 1991. A level reservoir routing program (PREPEWA) was used to compute hourly changes in surface water storage and surface discharge for each wetland. The main goal was to determine the effect of hydraulic loading rates to the wetlands on chemical and biological functions such as nitrogen removal and sediment trapping, and to help determine the assimilative capacity of the wetlands. This approach is applied to single wetlands.

Havno and Dorge (1993) presented a description of an integrated mathematical modeling system based on deterministic hydraulic and hydrological descriptions. The purpose is to model wetlands for effectiveness in pollution control by trapping nutrients. Attention has been focused on scientific models where the ecology in specific wetlands is modeled . The hydrologic/hydraulic components of the model are not presented.

Scarlatos and Tisdale (1989) developed a hydrodynamic model to simulate wetland flow dynamics. It is a one-dimensional depth-integrated system to simulate flooding and drying of wetlands and the effects of groundwater infiltration. The model was applied to an experimental wetland area in Florida.

Tisdale and Scarlatos (1989) discuss a hydrodynamic model to simulate wetland hydrodynamics, including precip, runoff, groundwater seepage, and evapotranspiration. Wetlands are characterized by flat topography, frequent wetting and drying, high groundwater tables, dense vegetation, and slow water movement. Water balance is function of precip, groundwater seepage, evapotranspiration, surface runoff, tributary inflow, discharges to receiving water, and detention of water in surface ponds. This was applied to a single wetland in southern Florida. A sensitivity analysis showed that the selection of coefficients, especially those related to friction, is essential van Walsum and Joosten (1994) applied a hydrodynamic model that incorporates groundwater, surface water and soil moisture (SIMGRO) to a bog reserve in the Netherlands. Emphasis was on modeling the groundwater (saturated flow) system. The area modeled was 10000 ha (about 25000 ac or 38.6 sq. mi.). A finite element scheme is used to simulate the groundwater flow. Due to attempts to raise the water level inside the bog to preserve habitat for waterfowl, local farmers began to install subsurface drainage, which has drained about 38% of the wetter soils surrounding the reserve. A buffer zone was then set up. Plans are to provide surface water to the area surrounding the bog, raising the hydraulic head in the subsoil and reducing downward seepage from the bog, improving the hydrologic conditions for bog growth.

Roig (1995) discussed numerical hydrodynamic modeling of wetland surface flows. This is a detailed modeling using finite element analysis of the hydrodynamics in a wetland. Some of the special concerns for wetlands are flooding and drying fronts, flow resistance due to emergent vegetation, and hydraulic control structures.

Gerla and Matheney (1996) monitored water-table wells and staff-gauges in a single 500 ha wetland with a surrounding area of 8 km^2. The saturated zone was monitored to determine recharge/discharge of groundwater and the changes in water table depth. MODFLOW was used to model vertical saturated flow in the wetland.

Wiseman et al (1993) describe the hydrology of two wetland wastewater treatment systems. Water budgets were determined from field monitoring data and compared with a regional steady-state water budget using a groundwater flow model (DYNFLOW) - a 3-D groundwater flow model. Determining the water budget is important to managing the wetland to optimize treatment, and determine hydraulic residence time, which is related to the treatment that can occur in the wetland.

Larson (1986) suggested that the wetland/watershed ratio, the percentage of wetlands comprising the total watershed area may be an effective method for quickly estimating the potential for flood mitigation due to wetlands. This information could be obtained from a database such as the National Wetlands Inventory. Once potential storage areas are identified, the wetlands could be surveyed to determine their storage capacities. This method was found to be useful in the Charles River Study (Larson, 1986.)

Hydrologic Models Considered

Several watershed hydrologic models were considered for use in modeling the effect of wetlands on flooding. They included the HEC-1 flood hydrograph model (US Army Corps of Engineers); PRMS, the Precipitation-Runoff Modeling System (US Geological Survey); HSPF, the Hydrological Simulation Program - FORTRAN (Environmental Protection Agency); and AGNPS, the Agricultural Nonpoint Source Model (Agricultural Research Service, Minnesota Pollution Control Agency, and Soil Conservation Service).

The major factors influencing the choice of hydrologic model included the model's capability to:

1. simulate the major hydrologic processes occurring during a flood event including snowmelt, precipitation, infiltration, runoff, streamflow, and routing through storage reservoirs;
2. vary model parameters spatially;
3. simulate the attenuation that may occur in a subbasin due to the influence of wetlands on flood flows;
4. simulate explicitly the flood storage theoretically available in wetlands under a variety of initial conditions such as empty, partially full, and full;
5. simulate large watersheds greater than 1000 mi^2.
6. interface with geographic information systems (GIS) and digital elevation models (DEM) for preparation of input data and model parameters.

Table 1 summarizes the major features of the hydrologic models considered. HEC-1 and AGNPS can model single precipitation events, while PRMS and HSPF are continuous simulation models, which simulate the changes in soil moisture between precipitation events. During flooding, the most significant hydrologic processes are precipitation, infiltration, runoff, and streamflow and reservoir routing. Generally evaporation, interflow, and groundwater flow are not considered to be significant in comparison with overland flow. Although HEC-1 and AGNPS do not model evaporation, interflow, and groundwater flow, their capability to model the other hydrologic processes makes them viable candidates. HEC-1 can include a groundwater component to flow if a baseflow quantity is specified.

Summary of model capabilities

1. Model's capacity to simulate major hydrologic processes occurring during a flood event

HEC-1 offers the most choice of methods for simulating the major hydrologic processes occurring during a flood event, namely precipitation, infiltration, runoff, streamflow routing, and reservoir routing. This allows the user to choose the most appropriate method depending on the watershed characteristics, such as flat slopes, presence of wetlands, backwater affecting streamflow routing, land uses, and soil types. PRMS and HSPF offer limited choices in overland and streamflow routing. Both utilize the kinematic wave method of streamflow and overland routing, which may not effectively model

Table 1. Hydrologic Models Considered

Model Features	**HEC-1**	**PRMS**	**HSPF**	**AGNPS**
Model Type	lumped-parameter	lumped-parameter	lumped-parameter	distributed
Simulation Type	single-event	continuous	continuous	single-event
Watershed subdivision unit	subbasins	Hydrologic Response Units	subbasins	cells
Precipitation	single hyetograph	multiple hyetographs	multiple hyetographs	single hyetograph
Snow Melt	yes	yes	yes	no
Evapotranspiration	no	yes	yes	no
Infiltration	SCS curve number Initial and uniform loss Exponential loss rate Holtan loss rate Green-Ampt loss rate	Green-Ampt during storm mode	empirical equation based on soil type and available storage	SCS curve number
Rainfall Excess to Runoff	SCS unit hydrograph Clark unit hydrograph Snyder unit hydrograph Kinematic wave	Kinematic wave	Manning's equation based on the depth of surface detention of excess precipitation	SCS curve number and TR55 or empirical method
Reservoir storage and routing	Modified-Puls routing Level pool routing	Modified-Puls routing Linear-storage routing	Outflow can be volume or time dependent or user-specified	impoundment terrace systems with pipe outlets
Subsurface Soil Water Flow	Baseflow quantity can be specified	yes	yes	no
Channel Routing	Muskingum Weighted Inflow Kinematic Wave Muskingum-Cunge Modified Puls Normal Depth Working R and D	Kinematic wave	Kinematic wave	Steady-state flow using Manning's equation and continuity equation
GIS interface	WMS, Geo-STORM, GISIWAM	In development as a component of MMS	no specific interface	Interface with GRASS

subbasins where stream slopes are fairly flat, or when the slope is variable, or there are depressions such as wetlands which may attenuate the overland flow. AGNPS also offers few choices for simulating hydrologic processes. For instance, streamflow routing is limited to a steady-state assumption using the Manning's equation and the continuity equation. Any backwater or storage in the stream cannot be modeled.

The variety of hydrologic simulation choices in HEC-1 is due to the fact that HEC-1 was developed specifically to simulate floods and assess the effectiveness of flood control measures. HSPF and PRMS were developed to be general purpose hydrologic simulation programs, and include processes that may not be significant during flood events, such as evaporation, changes in soil moisture, interflow, and groundwater flow. In particular, HSPF has become most commonly used for modeling of nonpoint pollutants, and the hydrologic processes have not been much different than the precursor to HSPF, the Stanford Watershed Model (Singh, 1995). AGNPS was chiefly developed to model erosion and nutrient transport on agricultural fields, not to model flood flows, and typically has only one or two methods for infiltration, runoff, and streamflow routing.

2. Model's capacity to vary model parameters spatially

HEC-1, PRMS, and HSPF are all considered lumped-parameter models. These models represent a watershed as subdivided into subbasins connected by streams and reservoirs, with the ability to combine flows at junctions. Figure 2 shows a conceptual representation of a watershed in HEC-1. The parameters for each subbasin are assumed to be uniform across the entire subbasin. It is possible to incorporate the spatial variability of parameters and physical properties in a watershed if the subbasins are small enough so that their hydrologic properties can be assumed to be homogeneous.

Figure 3 shows the hydrologic components modeled in PRMS on a daily basis. The current version of PRMS has an upper limit of 50 subbasins, 50 flow planes for modeling overland flow, and 50 stream and reservoir routing segments. The current version of HSPF is limited to 75 discrete operations (the sum of the subbasins, reaches, reservoirs, and water quality processes modeled.) HEC-1 can accommodate many more subbasins, streams, reservoirs, and junction elements.

AGNPS is a distributed model, in that the watershed is subdivided into square cells with the input parameters assigned to each cell. Figure 4 shows a watershed subdivided into cells. Parameters are assumed to be uniform across the cell. For watershed areas of particular interest or requiring more detail, the cells can be further subdivided. The cell structure allows modeling of spatial variations in slope, land use, soil types, and other parameters.

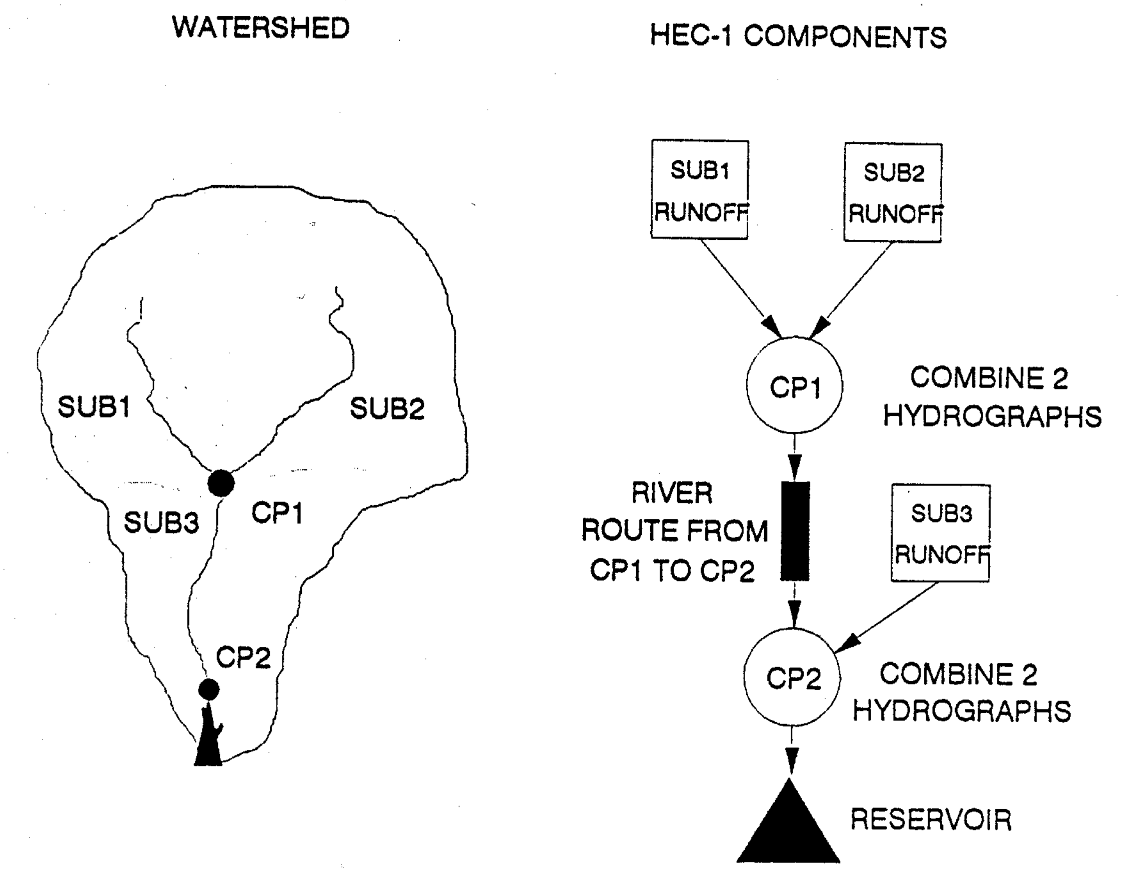

Figure 2. Conceptual representation of a watershed in HEC-1. (From: *Computer Models of Watershed Hydrology*, V. P. Singh, Ed. 1995. Figure 4.1, pg. 127)

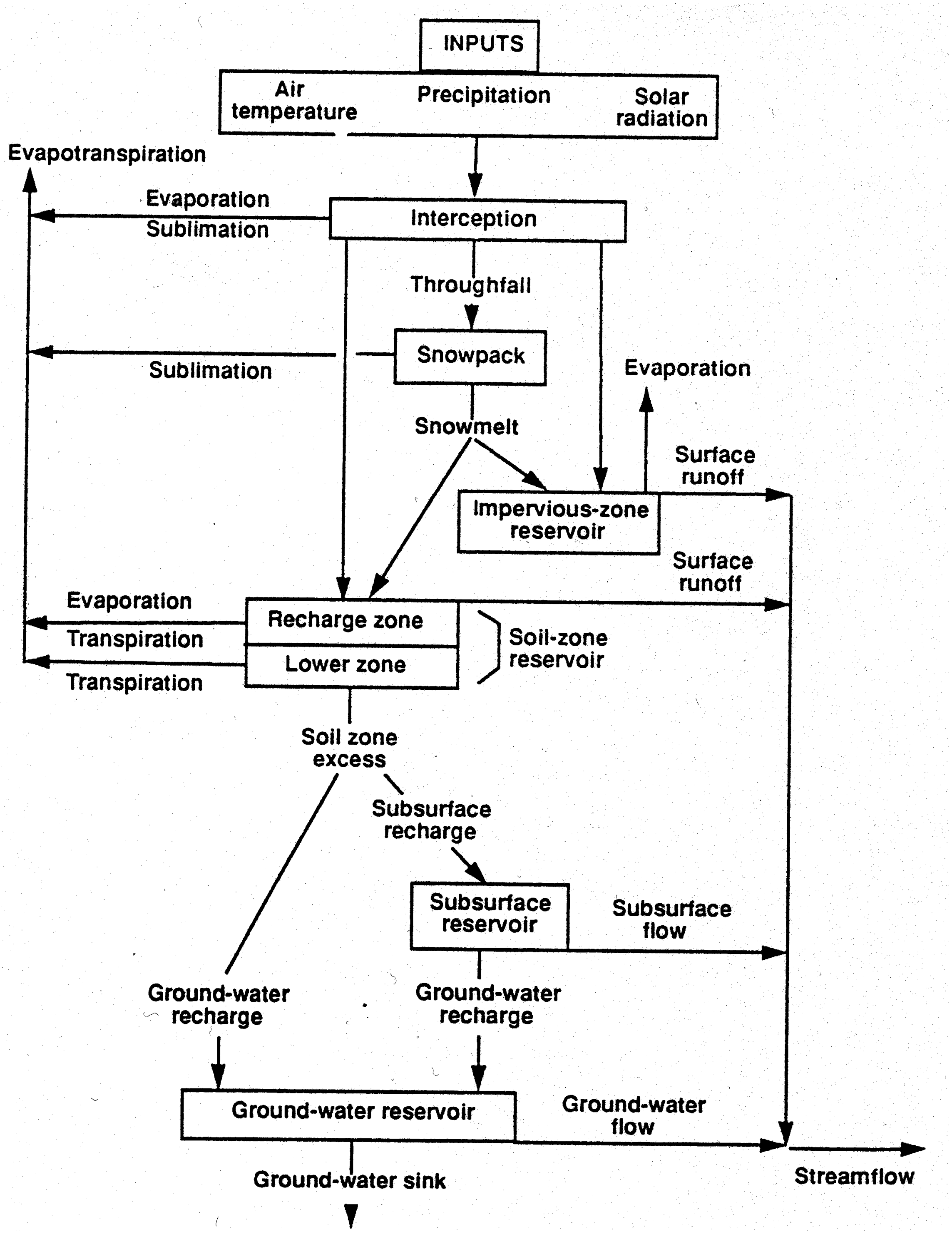

Figure 3. Daily-mode components of a hydrologic response unit in PRMS. (From: *Computer Models of Watershed Hydrology*, V. P. Singh, Ed. 1995. Figure 9.2, pg. 284)

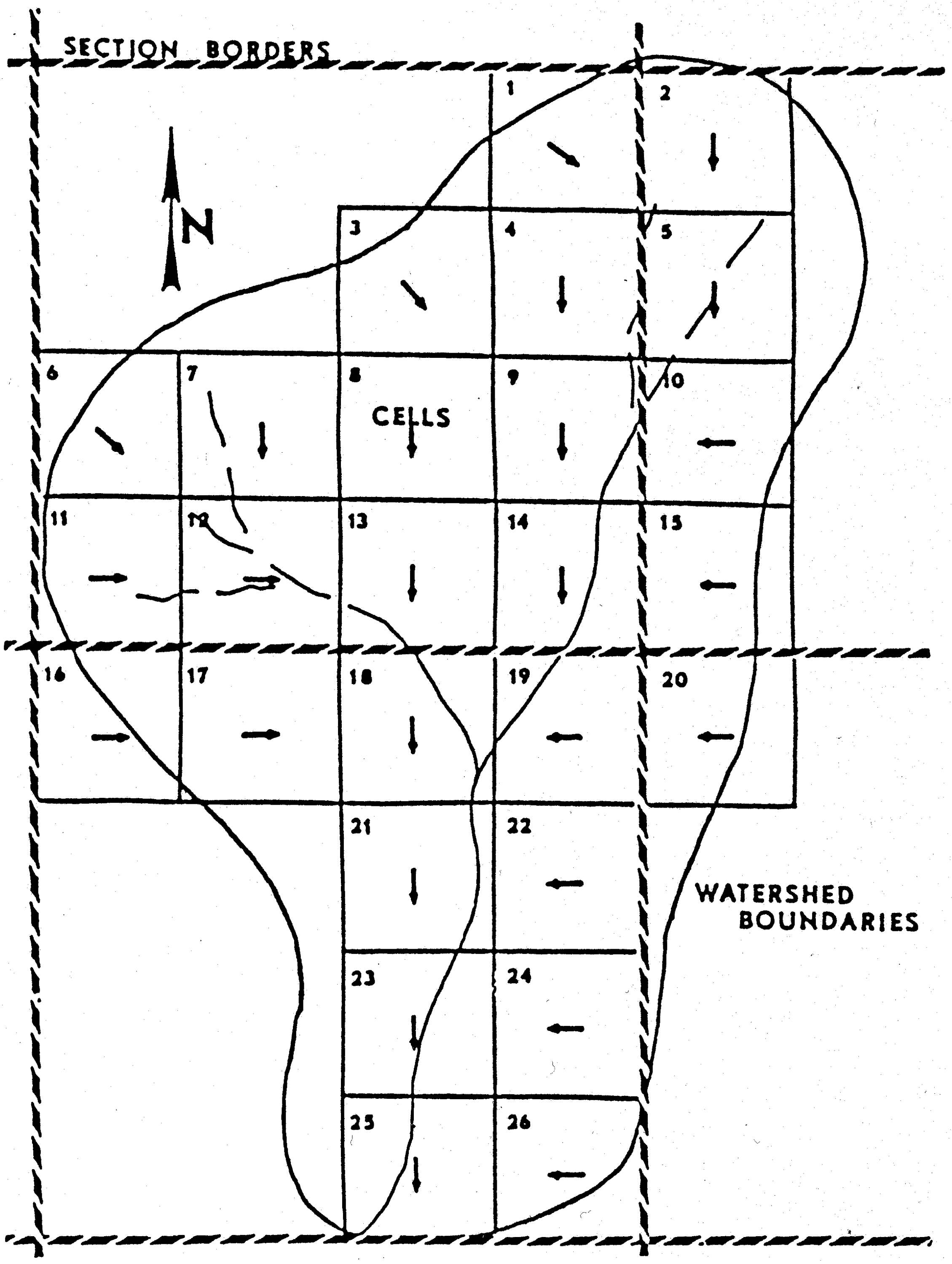

Figure 4. Watershed representation in AGNPS. (From: *Computer Models of Watershed Hydrology*, V. P. Singh, Ed. 1995. Figure 26.1, pg. 1003)

Theoretically, AGNPS can handle up to 30,000 cells. The developers of AGNPS suggest that the cell size should be no larger than 40 acres In the case of a watershed with an area of 1000 mi^2, a minimum of 16,000 cells would be required. Assigning parameters and input data to such a large number of cells and calibrating such a large model would be very difficult. Also, since many of the wetlands have areas much smaller than 40 acres, some lumping of the wetlands would still be required.

3. Model's capacity to simulate the influence on flood flows by wetlands:

HEC-1 offers a variety of overland routing techniques. In a study done by the US Army Corps of Engineers to assess models for simulating wetland hydrology, HEC-1 was discussed (US Army Corps of Engineers, 1988). In that report it was suggested that the Clark unit hydrograph be used to model overland flow in subbasins containing wetlands. The Clark unit hydrograph is a two-parameter hydrograph, with the parameters defining the shape and peak of the hydrograph. This allows considerable flexibility in modeling runoff, as attenuation of flow in the subbasin will affect the shape of the hydrograph. PRMS and HSPF both use the kinematic wave technique to route overland flow. This is a hydraulic routing routine which uses properties of the subbasin such as the average slope. With this technique, it is difficult to incorporate the lag or attenuating effect that may occur due to numerous wetland depressions.

AGNPS uses the SCS curve number method to calculate runoff volume, and an empirical relationship utilizing the cell's area, channel slope, runoff volume, and channel length to obtain a peak flow. The channel slope is actually the slope in each cell. Similarly to the kinematic wave technique, it would be difficult to model any lag or attenuating effect that may occur due to wetlands in the cell.

4. Model's capability to simulate flood storage available in wetlands

All of the models have the capability to model and route flows through reservoirs, which could represent the flood storage capacity of wetlands. HEC-1 can model unregulated reservoirs with a variety of overflow structures, such as weirs and spillways. It cannot model reservoirs with controlled outflows, but most wetlands would behave as unregulated reservoirs. Some restored wetlands may have regulated overflow structures, but most use an overflow spillway type of structure. PRMS has similar capabilities. HSPF allows the user to specify the reservoir outflows in a variety of ways, such as time-varying outflows reflecting demand downstream, or as a function of depth in the reservoir. AGNPS can model terrace-type impoundments drained by a pipe.

5. Model's capability to simulate large watersheds

The watersheds modeled in this study are approximately 1200 mi^2 and 2000 mi^2 in area. HEC-1 has been used on watersheds ranging from small urban catchments with areas of 0.4 mi^2 or less up to large river basins with drainage areas over 40,000 mi^2. PRMS was developed to model a variety of watershed sizes. HSPF has been applied to watersheds as large as the Chesapeake Bay, with a drainage area of more than 68,000 mi^2. Any of the three are suitable to model large watersheds.

AGNPS has been used on watersheds ranging in size from a few acres up to 119 mi^2. Applying AGNPS to a watershed larger than 1000 mi^2 with the maximum suggested cell size of 40 acres requires 16,000 cells. Many of the prairie pothole wetlands are less than 1 acre in area. To model each wetland individually, some of the 40 acre cells would need to be further subdivided, requiring even more cells. Also, there are 27 input parameters required for each cell. Managing such a large model, and assigning parameters and input data to each cell would be very difficult even with utilizing a GIS or other preprocessor, and analyzing the output would also be daunting.

6. Availability of GIS interface or preprocessor software

Early work in GIS-based hydrology at HEC involved developing methodology to automate the data preparation process for HEC-1 and other HEC models. Recently research has been carried out to develop methods for combining spatial GIS data with hydrologic networks. Presently the NexGen project is investigating incorporation of GIS methods including analyzing DEMs to automatically capture spatial processes of watershed runoff and link them to a river network.

Organizations other than the Corps of Engineers have developed specific preprocessor and postprocessor software incorporating GIS for HEC-1 and other event-based models such as TR-55 and TR-20. One of the best known is WMS (Watershed Modeling System) developed at Brigham Young University. This is an integrated terrain and hydrologic modeling program to delineate subwatershed and subbasin boundaries from DEMs or other digital terrain data, and can be used to develop subbasin parameters and distribute precipitation over the watershed. WMS includes interfaces to HEC-1, TR-20, and a few other models. 1:250,000 scale DEMs are available for the Red River Valley, and WMS will be used to help develop parameters for the watersheds in this study. The resolution of these DEMs is not likely to be adequate for subbasin and stream delineation, but GIS coverages of subbasin boundaries and streams may have already been developed or may be available from other sources. These pre-existing coverages can be imported into WMS along with the DEM and be used to determine other model parameters. Other similar GIS-based modeling systems with interfaces to several hydrologic models such as HEC-1, TR-55, TR-20, SWMM, and other urban runoff models include Geo-STORM and

GISIWAM (developed by R. K. R. Hess Associates and ESRI). GIS software such as GRASS, ArcView, and ArcInfo could also be used.

The development of user-friendly, commercially available GIS-based interfaces to the HEC-1 model is well ahead of development of such interfaces to the other models considered for this study. This is largely due to the popularity of HEC-1, as it is widely used by consulting firms and government agencies.

Some work has been done to develop GIS tools to delineate HRUs (Hydrologic Response Units, or subbasins) for PRMS applications. Both a polygon HRU approach and a gridded HRU approach have been investigated. Remotely-sensed snow cover data was coupled with a GIS to compare measured and simulated snowcover. The commercially available preprocessor software that uses GIS to delineate watershed boundaries, slopes, areas, and other basin characteristics do not include an interface for PRMS, but their output could probably be adapted to PRMS.

A new, more flexible modular system has been in development to eventually replace PRMS. The new system is termed the Modular Modeling System (MMS) and presently has been developed only for UNIX-based workstations. It features a graphical user interface. Along with MMS a GIS interface is currently being developed. At this time the GIS interface will run on UNIX-based workstations and Windows NT. Once a Windows based MMS becomes available, it should be more user-friendly than the present PRMS model, particularly with an integrated GIS interface.

There is not presently a commercially available GIS based preprocessor to develop parameters and input data for HSPF. Any GIS package could probably be used to develop and assign data and parameter values for HSPF models, however.

GIS software is an effective tool to develop and assign input data and parameters to a distributed model such as AGNPS. Yoon and Padmanabhan (1994) developed a decision support system for nonpoint source pollution management directly linking AGNPS, Geo/SQL (a vector-based GIS), and the relational database management system ORACLE. Disrud and Yoon (1997) linked AGNPS to the ArcCAD GIS software package from the Environmental System Research Institute, Inc., which was applied to the Oakes Test Area in North Dakota to assess and manage surface water quality. R. Srinivasan and B. Engel of the Department of Agricultural and Biological Engineering developed a GRASS/AGNPS interface at Purdue University. GRASS (Geographic Resources Analysis Support System) is a public domain GIS currently maintained at Baylor University in Texas.

Table 2 lists the major data requirements for the models. The data requirements for the lumped models are quite similar, with the exception of additional data and model parameters required to model evapotranspiration, interflow, and groundwater flow. All the lumped models basically require meteorological data such as precipitation; topographical data such as the subbasin area, length, average slope, channel lengths, channel cross sections (if available; hydrologic soil types, permeability, and infiltration capacity; land use data; and stream gage data for calibration. Data is expressed at the subbasin level. For instance, if there are several soil types within a subbasin, an average soil type is determined for the subbasin. On the other hand, there may be one or two precipitation gages for the entire watershed, and the rainfall data for a particular gage will be distributed over a number of subbasins. The distributed model AGNPS requires 23 input data items for each cell to describe the watershed. Those inputs directly related to the water quality and erosion modeling processes are not presented.

Each model is discussed in greater depth, detailing the hydrologic processes modeled, model structure, data requirements, model applications, and current developments including GIS-based interfaces in Appendix A.

Hydrologic Modeling Approach for Watersheds Containing Wetlands

Currently, when modeling watersheds with wetlands for flood flows, wetlands are typically represented as special topographic surface areas with certain hydrologic characteristics. For example, the wetland area may be assigned a high value of curve number in the NRCS curve number method of determining runoff, as may be done in the HEC-1 model. This will account for the influence of wetlands on the runoff volume generated in the watershed, but will not account for their capability of storing water and the consequent influence on the hydrograph at the watershed outlet. Wetlands are depressions potentially capable of storing large quantities of water. However, the antecedent water level, the elevation controlling the outflow, and the depth-storage and depth-outflow relationships of the wetland will determine its flood absorbing capacity and the downstream hydrograph. In order to determine the influence of wetlands on the storm hydrographs, the flow routing through the wetlands need to be modeled accurately.

Methods of routing flow through a reservoir or a pond can theoretically be used for routing flow through wetlands. However, scarcity of data such as depth-storage, depth-outflow relationships, and water level variations in the wetland with time of year pose significant difficulties with this approach. Also, there may be numerous wetlands widely dispersed in a watershed. Is it practicable to model each wetland, or can they be lumped together at a certain threshold level? Can some of the wetlands be neglected as not providing

Table 2. Hydrologic Model Input Data Requirements.

Data Requirements	HEC-1	PRMS	HSPF	AGNPS
Meteorological	Precipitation Storm type Air temperature (snowmelt) wind speed, air temperature, albedo, dewpoint temperature, and solar radiation (alternate snowmelt method)	Precipitation maximum and minimum air temperature Solar radiation Pan evaporation data	Precipitation Potential evapotranspiration Air temperature Dewpoint temperature Wind Solar radiation	Precipitation Storm type
Topographical	Subbasin area Subbasin average slope Subbasin shape	Subbasin area Subbasin average slope Subbasin shape	Subbasin area Subbasin average slope Subbasin shape	Aspect Land slope Slope length Slope shape
Soils	Hydrologic soil type Hydraulic conductivity Infiltration capacity	Soil type Hydraulic conductivity Infiltration capacity	Soil type Hydraulic conductivity Infiltration capacity	Soil type (texture)
Land Use	Land use type % impervious area Land treatment or practice Hydrologic condition	Vegetation Land use type Impervious area	Vegetation Land use type Impervious area	Cover and management factor Surface condition SCS curve number
Streamflow	Baseflow component Stream gage data Stream cross-sections Stream slope Roughness coefficient	Stream gage data Stage-discharge relationship for stream reaches Roughness coefficient	Stream gage data Stage-discharge relationship for stream reaches Roughness coefficient	Manning’s roughness Channel slope Channel side slope Channel slope length

significant storage? Can the antecedent water level be accurately specified in the wetland models?

Regardless of the answers to the questions above, it is clear that a detailed topographic representation of the watershed and a model capable of routing flow through numerous storage depressions may be necessary to study the impact of wetlands on flooding.   High-resolution digital terrain models with sufficient resolution to capture the depressions with reasonable accuracy may give a detailed topographic representation of the watershed. Then a model combining the ability to route flows through depressions, channels, and streams should be able to accurately estimate the flow hydrograph at the outlet of the watershed. The necessity for a high-resolution digital elevation model (DEM) to evaluate the surface storage potential in a watershed is demonstrated by the case of the Devils Lake Basin. A high-resolution DEM of a subbasin of the Devils Lake basin was produced using contour and other information from standard USGS 1:24,000-scale maps. This high-resolution DEM has elevations reported to the nearest one-tenth of a foot and elevations recorded at 10-meter horizontal intervals. This resolution was found to be adequate to obtain hydrological parameters such as basin boundaries and areas, depression areas and volumes, and flow networks between wetlands.

High resolution DEMs such as the ones derived for the Devils Lake basin are not available for the watersheds being studied in the Red River Valley. Even if high-resolution DEMs were available, the thousands of wetlands present in these watersheds would overwhelm the capabilities of the hydrologic models investigated. A possible solution would be to subdivide the watersheds further, and apply the model separately to each subdivision, then combine the outputs in yet another model. This greatly increases the modeling effort. Typically there are only a few stream gages and weather stations within a watershed. Many of the subareas modeled may end up with no gages making it difficult to calibrate.

Most studies to model hydrology of watersheds containing wetlands have been performed on small-scale watersheds containing a single wetland or a wetland complex. In some cases, only the wetland itself is modeled. Generally, water balance models, such as HSPF, SWAT, SWAMPMOD, DRAINMOD, or models specifically developed for the study area are used. In general, these models keep track of precipitation, infiltration, evaporation and transpiration, and soil moisture during the simulation as well as routing the excess precipitation overland and in stream channels.   Such models require significantly more data concerning soil infiltration properties and have many more parameters to calibrate than single-event models such as the Corps of Engineers HEC-1 model. Continuous simulation of watersheds can produce large estimation errors when modeling periods with high discharge (Potter, 1994)

The HEC-1, a single event model, although not suitable for long-term studies of watersheds with wetlands, has been widely used in floodplain studies. As the purpose of this study is to assess the influence of wetlands on flooding, it should be satisfactory to use a single-event model such as HEC-1 rather than a continuous water-balance model.

Many of the well-known and documented water balance models typically lack choices of overland and streamflow routing techniques. Most use a variation of the kinematic wave method for both overland flow and stream routing. The kinematic wave streamflow routing technique is not generally used in floodplain applications, particularly where the slopes of watershed and streams are fairly flat, as in the lake plain region of the Red River Valley. HEC-1 offers several routing options including the Modified Puls, which can be used to model streamflow in watersheds where flood storage capacity is significant. HEC-1 also offers several options for routing runoff overland to streams.

The reservoir routing option in HEC-1 can be used to model wetlands and their capacity to store runoff. Ogawa and Male (1986) simulated wetlands in a watershed with HEC-1 using reservoir routing for each wetland. Meyer (1998), using HEC-1, also represented wetlands as individual reservoirs within a hypothetical watershed to investigate wetlands' effect on flooding. The initial level of water in the wetland reservoirs can be set at various levels to investigate wetlands' impact on peak flows for various antecedent moisture conditions in the watershed. Due to the large number of wetlands in the chosen watersheds, a general relationship will have to be developed between depth and storage for the wetland reservoirs, and the individual wetlands storage capacity will have to be lumped or combined.

The National Wetlands Inventory includes information on the area of the wetlands, but no information on their depth or storage volume. Estimating the volume of storage available from the wetlands for this study will have to be based on typical depths and volumes measured for similar types of wetlands gathered from studies such as the one performed in the Devils Lake Basin to quantify depressional storage capacity of natural wetlands (Ludden et al., 1983). Aerial photos were used in the Devils Lake Basin study to develop contour maps of the wetlands, from which volumes were estimated and checked with topographic surveys. The average maximum depth of the measured depressions was about 2.5 ft. Studies performed by the Minnesota Department of Natural Resources indicate that during wet periods, 1.5 ft or more of storage is available in most depressional wetlands (Terry and Aadland, 1997), and estimate that the average storage potential is approximately 1 ac-ft/wetland acre, with an average depth of 1.7 ft below the wetland outlet elevation. These data may be used to develop depth-storage and depth-outflow relationships for the wetlands as a function of their surface area.

While the available DEMs are inadequate to estimate the water storage capacity of individual wetlands, they may be used to estimate subbasin parameters such as average slope. The Watershed Modeling System (WMS) is a software package developed to provide hydrologic parameters for models such as HEC-1. It uses DEMs developed from the 1:250,000 scale USGS maps. It can also utilize GIS coverages including subbasin boundaries, stream coverages, land use and soil coverages which are available for both the Maple and Wild Rice watersheds selected for this study.

Most floodplain studies use synthetic storms or design storms rather than historical events to determine the watershed's rainfall-runoff response. It is difficult to exactly simulate an historic event, but modeling the watershed's response to design storms with varying return periods can give a better idea of wetlands' effectiveness in flood control at various levels of flooding. Rainfall hyetographs can be developed for 2-year up to 100-year events (U. S. Department of Commerce, 1964.)

In conclusion, the HEC-1 model was chosen to investigate the influence of wetlands on flooding. HEC-1 offers a variety of infiltration, overland routing, and streamflow routing routines allowing it to be applied to a variety of watersheds. Snowmelt and rainfall events can be modeled. The reservoir routing option allows modeling of wetland storage by specifying depth-storage and depth-outflow relationships. The model can accommodate more subbasins, reservoirs, and stream reaches than can PRMS or HSPF, and there are commercially available GIS-based preprocessor software packages specifically designed for use with HEC-1.

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Appendix A

Discussion of Hydrologic Watershed Models

1. HEC-1 Flood Hydrograph Package, Hydrologic Engineering Center, U.S. Army Corps of Engineers
2. PRMS (Precipitation-Runoff Modeling System), U.S. Geological Survey
3. HSPF (Hydrologic Simulation Program - FORTRAN), U.S. Environmental Protection Agency
4. AGNPS (Agricultural Nonpoint Source Model), the Agricultural Research Service (ARS) in cooperation with the Minnesota Pollution Control Agency (MPCA) and the Soil Conservation Service (SCS).

HEC-1 FLOOD HYDROGRAPH PACKAGE

The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers developed HEC-1 to simulate hydrologic processes for analyzing historical floods and projects to reduce flood damage. HEC-1 is a lumped-parameter, event-based model which has been widely used on small urban catchments (1 km^2 or less) up to large river basins with drainage areas over 100,000 km^2.

Hydrologic simulation in HEC-1 can only be performed with a uniform time step. This can be a problem when more detail in some portion of the model is necessary than in other portions. If some of the watershed is urbanized, it would be desirable to use smaller time steps to model the urban subbasin's response. One way to handle this is to simulate these urban areas separately at a shorter time step and input the results into a separate simulation for the remainder of the watershed. The minimum time step in HEC-1 is 1 minute, and the maximum number of time steps for modeling an event is 2000. Time-series input data such as precipitation may occur at different intervals than the computational time step, as the data will be interpolated to the computational time step.

HEC-1 has no provision to simulate soil moisture during periods with no precipitation. Therefore if there are significant dry periods between storm events, each event should be simulated separately. During flood events the precipitation lost to soil moisture is usually small compared to overall flood runoff, so this is not generally a concern if a single flood event is modeled.

River Basin Representation

As shown in figure A-1, a watershed consists of several components. Subbasins are the smallest unit of watershed area. It is assumed that hydrologic processes such as precipitation and infiltration occur uniformly over the subbasin. This is the lumped-parameter model approach, which is similar to most other hydrologic models. It actually does not have to be limiting, since subbasins can be made small enough to accommodate spatial variation in the watershed. River reaches allow overland runoff from subbasins to be routed downstream. Combine components allow runoff from subbasins and routed flow in river reaches to be combined at their junctions. Reservoirs on river reaches can also be represented. Other features include diversions and pumping from river reaches or reservoirs which can be saved and retrieved to route and combine with other flows if necessary.

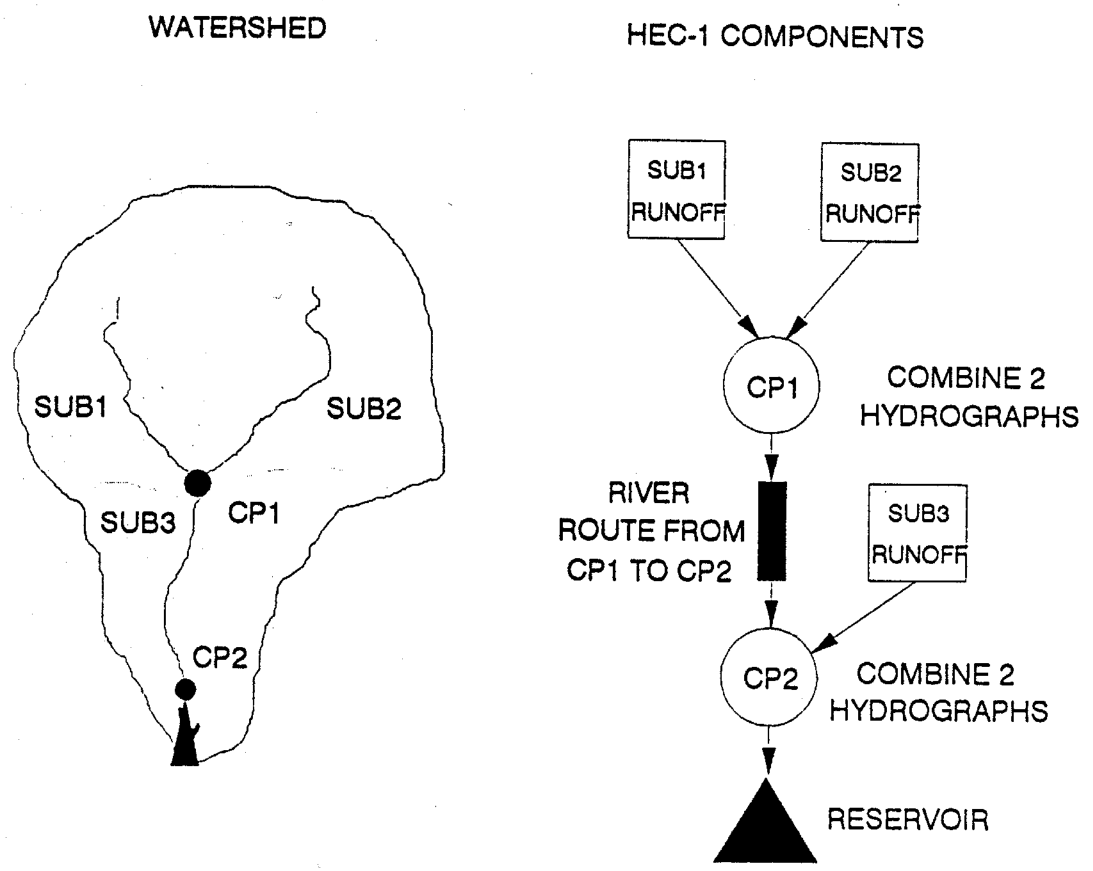

Figure A-1. Conceptual representation of a watershed in HEC-1. (From: *Computer Models of Watershed Hydrology*, V. P. Singh, Ed. 1995. Figure 4.1, pg. 127)

Hydrologic Processes Modeled by HEC-1

The main hydrologic blocks simulated by HEC-1 include watershed runoff, river routing, reservoir routing, confluences, and diversions. There is generally more than one option available for each process.

Subbasin Runoff

The subbasin runoff block consists of four processes: precipitation, losses (interception, infiltration, and detention storage), excess-to-runoff transformation, and baseflow.

Precipitation: precipitation can be input as rain or snow depending upon air temperature. Gaged precipitation data can be used or hypothetical storms such as the Standard Project or Probable Maximum. Gaged data must be calculated for each simulation time interval. If there is more than 1 precipitation gage in the subbasin, the gage values must be weighted and combined for an overall average precipitation.

Snow: snow and snowmelt can be simulated in each subbasin. There are 2 methods. The degree-day approach requires air temperature data for each time interval. Depending on the temperature, the precipitation falls as snow or rain. If snow, it is accumulated. If rain it is subject to loss and runoff. If the air temperature becomes warm enough, the snow pack melts. The energy-budget method is similar except that wind speed, incoming solar radiation, and dew point data is also necessary for each time interval.

Losses: losses include all precipitation not available for direct runoff because it has been intercepted (on vegetation), infiltrated into the soil, or detained in storage (such as depressions). Once these losses are extracted, they are no longer available to the model. This means that the outflow hydrograph for a subbasin is only due to direct runoff and base flow, with no interflow or groundwater contribution. HEC-1 has several loss rate methods:

1. Initial & Constant: once the loss has satisfied an initial specified volume, the losses continue at a constant rate
2. HEC exponential: uses a logarithmic decay function based on accumulated losses
3. SCS curve number: there is an initial abstraction and continued infiltration based on the SCS curve number which if a function of land use and soil type
4. Holtan: an empirical equation where infiltration is based on accumulated losses. The equation parameters are based on soil and land use characteristics.

5. Green & Ampt: an equation based on Darcy's law for groundwater flow. The parameters are based on soil characteristics such as permeability and porosity.

Which method is used generally depends on the available information.

Excess-to-Runoff Transformation: there are two basic methods (with variations) in HEC-1 to transform excess precipitation to runoff. These are the unit hydrograph and kinematic wave methods.

The unit hydrograph consists of a hydrograph developed for a subbasin based on actual flow measurements of a runoff hydrograph resulting from a particular storm, which is normalized for 1.0 inches of excess precipitation. Thus the ordinates of the unit hydrograph, which are streamflow, can be multiplied by the rainfall excess to obtain the hydrograph for a different storm. If the unit hydrograph is known, its ordinates can be input. They must be of the same duration as the simulation time interval. Other methods to estimate the unit hydrograph available in HEC-1 include the Clark, Snyder, or SCS methods. The important features to capture in the hydrograph is the peak and the shape. The Clark method uses 2 parameters and can fit a wide variety of hydrograph shapes.

The unit hydrograph method results in a runoff hydrograph from a subbasin whose calculation requires no information such as slope, area, and overland flow length. It does require streamflow and rainfall data. The method also assumes that rainfall has the same temporal and spatial pattern for all storms. For ungaged subbasins it may have to be assumed that a unit hydrograph for a gaged subbasin can be applied to the ungaged subbasin.

The kinematic wave technique is a nonlinear runoff transformation function developed from the momentum equation of fluid mechanics. It is a hydraulic routing technique and assumes no backwater effects which usually works well for overland flow. The necessary parameters are often developed from Manning's equation for flow relating the depth of flow to the flowrate. A differential equation is developed which is solved numerically for flowrate. In order to develop the parameters the slope, roughness (a function of landuse), and overland flow length of the subbasin must be known. This can be applied to ungaged subbasins if the parameters can be measured or determined.

Base Flow: Base flow represents the equilibrium or near-equilibrium flow present between storm events generally attributed to groundwater recharge. HEC-1 uses a simple method of representing base flow because base flow typically does not contribute much to flood hydrographs. Base flow is described by an initial value, a recession threshold, and a logarithmic decay recession rate. Base flow rate starts at the initial value and decays until it reaches the threshold level where it remains constant. Base flow is added to the flood hydrograph for a total flow. In place of this procedure, a value for base flow can be specified.

Channel Routing

Overland runoff that enters river reaches can be routed downstream using several different methods. Channel infiltration may be considered with any of these methods. The various routing methods are discussed below.

1. Weighted Inflow: this method averages flows over a time period and lags the result from the upstream to the downstream end of the reach.
2. Muskingum: used for upland (relatively steep), nonfloodplain rivers. Two parameters, K and x are used to characterize the river reach. K is a storage time constant and x is a weighting factor. K is usually close to the wave travel time through the reach. If X = 0.5, there is no storage in the reach and the inflow hydrograph is the same as the outflow hydrograph for the reach. K and x can be determined from streamflow gage data if available or estimated based on the channel shape.
3. Muskingum-Cunge: has performed well for all but the flattest rivers and /or sharply rising hydrographs. The method combines a hydraulic routing technique called the diffusion wave method with the Muskingum method. The parameters can be estimated from streamflow gage data or estimated from the channel shape. This method is a close approximation to the full unsteady flow hydraulic computations.
4. Kinematic Wave: the same technique as discussed in overland flow routing. It is a nonlinear runoff transformation function. The flood wave is translated without attenuation, so it is unsuitable for river reaches where floodplain storage is significant. It is a hydraulic routing method which requires a relationship for flow as a function of depth. The slope of the river and the roughness of the river bed must also be known.
5. Modified Puls: uses floodplain storage-outflow characteristics that must be developed from steady-flow backwater calculations. It must be calibrated to each flood event modeled, which is difficult in ungaged subbasins. This method may be used when floodplain storage considerably attenuates the flood wave. It models the river reach as a series of reservoirs. Each reservoir has a level surface and the outflow from each reservoir is a function of the storage or elevation of the reservoir.
6. Normal Depth Storage method: a special case of the modified Puls method using channel characteristics to compute the channel storage and outflow, assuming uniform flow conditions.

7. Working R and D method: A variation of the modified Puls method including a coefficient to account for the effects of inflow rate on storage volume within the routing reach.

The coefficient methods (Muskingum and weighted inflow) are more dependent on calibration data, while the kinematic wave, Muskingum-Cunge, and Modified Puls methods have the advantage of being based on the physical characteristics of the routing reach. Often there is not flow data available for a particular routing reach, so the coefficient methods may be difficult to apply. The Modified Puls and Working R and D can model a steady state backwater effect on storage, which often occurs in floodplains.

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Lake or Reservoir Routing

Flow through lakes or reservoirs is simulated with the Modified Puls storage-outflow relationship as used for river reaches. This method assumes a level pool surface whose outflow only depends on the storage or elevation of the lake. If the outlet can be modeled as a weir (like a low dam over which the water flows out), the outflow is a function of the length of the weir, the depth of flow above the weir, and two coefficients which are characteristic of a weir (discharge coefficients.) Reservoirs with controllable gates or outlets cannot be modeled in HEC-1.

Confluences

Confluences or junctions are locations where hydrographs are combined into a single hydrograph. Since they are used to compute a new hydrograph, they are treated as a separate, stand-alone building block in the watershed.

Other

HEC-1 can include flow diversions. Diversions can be used for several reasons: if a channel splits, such as in the case of a braided stream; flow constrictions which cause some of the flow to take a different path; and channels with inadequate capacity so that some of the flow will pond until there is sufficient capacity. The user specifies the path which the diversion will take and where it will re-enter the system.

Pumps can be included in the model. This allows the user to incorporate pumps used in urban storm water systems and in cases where flow behind levees or other obstructions is pumped over and into the river.

Typical Data Requirements

1. Meteorological data: daily precipitation (hourly or 15-minute precipitation for storm events); snowfall amounts, daily maximum and minimum temperatures, wind speed, incoming solar radiation, dew point (all for snowmelt simulation)
2. Streamflow data: gaged streamflow data to calibrate streamflow routing
3. Subbasin geometric data: drainage area, average slope, aspect, overland flow length
4. Subbasin characteristics: hydrologic soil type, land use
5. River reach data: slope, shape, roughness, storage for hydraulic routing routines
6. Reservoir data: storage-outflow relationship parameters based on outlet characteristics

Current Developments Including GIS Hydrology

Early work in GIS hydrology at HEC involved developing methodology to automate the data preparation process for HEC-1 and other HEC models. During the last decade HEC has not been very active in this area. Recently research has been carried out to develop methods for combining spatial GIS data with lineal hydrologic networks. Presently the NexGen project is investigating incorporation of GIS methods including analyzing DEMs to automatically capture spatial processes of watershed runoff and link them to a river network. Current methods are rather cumbersome for use in delineating subbasins and rivers, particularly in flat terrain if the DEMs do not have high enough resolution.

Specific preprocessor software incorporating GIS have been developed for HEC-1 and other event-based models such as TR-55 and TR-20. One of the best known is WMS (Watershed Modeling System). This is an integrated terrain and hydrologic modeling program to delineate subwatershed and subbasin boundaries from DEMs or other digital terrain data. WMS includes interfaces to HEC-1, TR-20, and a few other models. Other similar GIS-based modeling systems with interfaces to several hydrologic models such as HEC-1, TR-55, TR-20, SWMM, and other urban runoff models include Geo-STORM and GISIWAM (developed by R. K. R. Hess Associates and ESRI).

HEC-HMS (the newly developed Windows version of HEC-1) had its first release in the spring of 1998. There is still a good deal of work to be done before it replaces HEC-1, and eventually surpasses it with additional features. Version 1 does not include all of the various options for streamflow routing and does not even have the capability of printing reports. Presently HEC-HMS has a simple soil-moisture accounting routine allowing multiple-event simulations. The snowmelt routine from PRMS is to be incorporated next. The model currently has the capability to use precipitation data from radar, although at this time this feature is difficult to use. Ultimately the model is to become a continuous, distributed parameter model utilizing built-in GIS capabilities for preparation of data and for presentation of results.

THE PRECIPITATION-RUNOFF MODELING SYSTEM - PRMS

The Precipitation-Runoff Modeling System (PRMS) is a modular-design, continuous, distributed-parameter, physical-process-based watershed model. It was developed by the U.S. Geological Survey (USGS) to simulate the effects of precipitation, climate, and land use on watershed response. In addition PRMS has parameter-optimization and sensitivity-analysis capabilities for fitting selected model parameters. Other model enhancements include a data-management program, ANNIE.

While the program's authors describe PRMS as a distributed-parameter model, it is more truly a lumped-parameter model. The watershed is subdivided into units that are assumed to be hydrologically homogeneous, called hydrologic response units (HRU), similar to the subbasins modeled with HEC-1. The lumped-parameter approach is applied to each HRU, but the subdivision of the watershed allows for spatial variation of parameters.

Unlike HEC-1 and AGNPS, which require a uniform time step, PRMS can run on both a daily time scale and a storm time scale. The daily mode is used for times in between precipitation events. Hydrologic components such as streamflow are simulated as daily average or total values. The storm mode uses time steps of less than one day, down to a minimum of 1 minute. This mode simulates storm hydrographs. Also, during storm mode an HRU may be further subdivided into a series of flow planes, or modeled as a single flow plane.

ANNIE

ANNIE is used to prepare data, model parameters, and options for input into PRMS and how results from PRMS can be input to ANNIE for graphic analysis. ANNIE is designed to help users interactively create, check, and update input to hydrologic models including PRMS. ANNIE also provides statistical and graphical tools to help analyze model input and output. Input such as meteorological, hydrologic, and snow data, plus watershed parameters are reformatted by ANNIE and placed in a Watershed Data Management (WDM) file.

PRMS Daily-Mode Components

Figure A-2 shows the daily-mode components for a single HRU. The components simulate daily accretion, depletion, storage, and movement of water based on

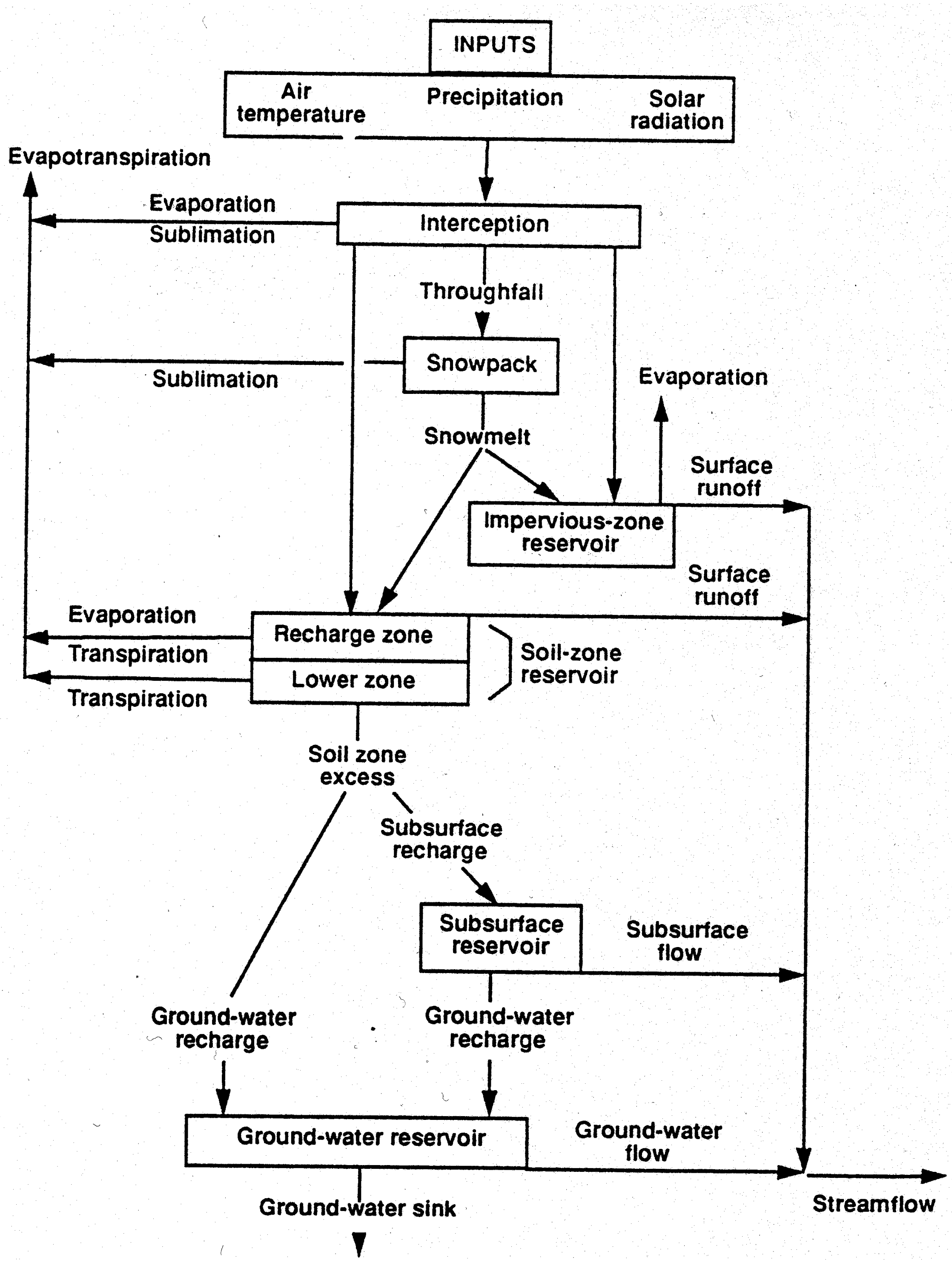

Figure A-2. Daily-mode components of a hydrologic response unit in PRMS. (From: Computer Models of Watershed Hydrology, V. P. Singh, Ed. 1995. Figure 9.2, pg. 284) the physical, hydrologic, and climatic characteristics of the HRU. Each component will be briefly discussed.

Climate Components: inputs are daily precipitation, maximum and minimum air temperature, and solar radiation. Precipitation is decreased by interception by the canopy vegetation. Air temperatures and solar radiation are used to compute evapo-transpiration, sublimation, and snowmelt.

Maximum and minimum daily air-temperatures are adjusted using monthly or daily lapse rates and the elevation difference between a climate station and each HRU. This is of most concern in mountainous areas, or wherever there is a large elevation difference between various HRUs and climate stations.

Precipitation is computed for each HRU and can be corrected for effects of elevation, spatial variation, topography, gage location, and other factors. Up to 5 precipitation gages can be used to define the spatial and temporal variation of precipitation on the watershed. Precipitation form (snow or rain) depends on maximum and minimum daily air temperature.

Daily solar radiation is used in snowmelt computations and may be used to estimate evapotranspiration.

Land Phase Components: interception of precipitation is a function of vegetation cover density and storage available on the predominant vegetation for each HRU. Storage is further defined and adjusted by season and precipitation form: winter snow, winter rain, and summer rain. Intercepted rain is assumed to evaporate. Intercepted snow is assumed to sublimate or melt.

In PRMS, the watershed is conceptualized as a series of reservoirs. For soil-moisture accounting, a soil-zone reservoir represents the part of the soil that loses water through evaporation and transpiration. The depth of this zone is defined by the root depth of the predominant vegetation. The amount of storage in this reservoir is the difference between field capacity (full) and the wilting point (essentially empty). The reservoir actually consists of two layers. The upper layer is the recharge zone. The lower layer is called the lower zone and can lose water only by transpiration. Water in storage increases by infiltration of precipitation and decreases by evapotranspiration. When the soil-zone reservoir is filled, additional infiltration is routed to the subsurface and groundwater reservoirs. If the soil-water excess exceeds the groundwater recharge capacity, the excess flows into the subsurface reservoir.

Potential evapotranspiration (PET) can be computed three different ways. One procedure uses daily pan-evaporation data and a monthly pan-adjustment coefficient. The second procedure computes PET as a function of daily mean air temperature and possible hours of sunshine. The third computes PET using air temperature, solar radiation, and 2 coefficients which depend on air temperature, elevation, vapor pressure, and vegetation data. Each method requires correspondingly more data. Actual evapotranspiration (AET) is a function of soil type, water currently available in the soil-zone reservoir, and the reservoir's storage capacity. When available water is not limiting, AET equals PET. Three soil types are defined: sand, loam, and clay.

Surface runoff occurs when the precipitation rate exceeds the infiltration rate. Daily surface runoff from rainfall on pervious snow-free HRUs is computed by determining the percent of an HRU contributing to surface runoff. The percent contributing is a function of antecedent soil moisture and rainfall amount. Then the runoff is computed by multiplying the daily net precipitation by the percent contributing area.

Surface runoff from snowmelt is computed on a daily basis. Snowmelt in excess of the maximum infiltration rate is assumed to become surface runoff. In impervious areas, any retention storage is first satisfied and then the remaining snowmelt becomes surface runoff.

Subsurface flow is modeled in the subsurface reservoir. This is a relatively rapid moving flow that can occur in the saturated-unsaturated and groundwater zones during precipitation events. The outflow from this reservoir is computed using a linear or nonlinear routing routine which is a function of the storage volume in the subsurface reservoir.

The groundwater zone simulates a slower component of flow from the groundwater reservoir. It is a linear reservoir which is assumed to be the source of all baseflow in the watershed. Inflow to the groundwater reservoir can be from excess soil-moisture and subsurface reservoirs. This movement is modeled as a vertical movement and is a function of the subsurface storage and a linear routing coefficient. Any groundwater that would move to points outside the surface drainage boundary is routed to a sink.

*Reservoir Components: Re*servoirs can be simulated. Inflows are the sum of streamflow contributions of all HRUs and flow from the subsurface and groundwater reservoirs above the channel reservoir. Inflow can also come from up to three upstream channel reservoirs. Two types of routing are available. The first is a linear-storage routing procedure where outflow is a linear function of storage in the channel reservoir. The second is a modified-Puls routing procedure.

PRMS Storm-Mode Components

For storm-mode simulation, the watershed is configured into flow-plane and channel segments. The flow-plane simulates overland runoff and channel flow simulates rivers. An HRU can be considered a single flow plane or subdivided to account for variations in slope and surface roughness. All flow planes must discharge into a channel, however - they cannot be arranged in a cascading sequence. Channel segments can receive upstream inflow from up to 3 other segments, and each channel segment can receive lateral inflow from either or both banks.

Surface Runoff: storm precipitation is reduced by interception. The excess is available for infiltration. Infiltration is modeled using the Green & Ampt equation in which infiltration is a function of the hydraulic conductivity of the soil, the moisture deficit in the soil, and the accumulated infiltration. After infiltration is satisfied, the rainfall excess is routed as surface runoff over the flow planes into the channel segments using the kinematic wave approximation which requires two parameters relating the flowrate to the depth of flow.

Channel flow is routed using the kinematic-wave approximation as well. An additional term is provided for the lateral inflow from the surface runoff. Parameters such as slope and roughness for each channel are required to describe the relationship of flowrate with the area of flow. The kinematic-wave routing method discussed earlier for the HEC-1 model does not incorporate lateral inflow. In the case of HEC-1, inflows can only occur at confluences.

Flow can be routed through channel reservoirs using the same methods as for the daily mode, but with shorter time steps.

Data Requirements

PRMS requires daily precipitation values for the daily mode, and preferably 1-hour or even 15-minute precipitation values for the storm mode. In order to model snowmelt, maximum and minimum daily temperatures, daily solar radiation and wind speed are also necessary. Maximum and minimum daily temperatures may also be necessary to compute evapotranspiration. An alternative for computing evapotranspiration requires pan evaporation data.

Characteristics required for each HRU include area, land use, hydrologic soil type, vegetation, average slope, and overland flow length. Channel characteristics required are the slope, roughness, and stage-discharge data. Channel reservoir characteristics require a storage-elevation curve. Streamflow gage data is necessary for calibrating the model. Soil data required includes permeability and storage capacity, and the depth of the root zone.

Optimization and Sensitivity Analysis Components

PRMS has the capability to allow the user to optimize selected parameters. There are two optimization techniques available, and one of four possible objective functions can be used with either technique. A major assumption is that the initial estimates of parameter values are correct with respect to their relative differences in space or time.

The sensitivity analysis components allow users to determine how significantly uncertainty in the parameters results in uncertainty in predicted runoff. By combining the optimization and sensitivity analyses, the magnitude of parameter errors can be assessed, as well as correlations between parameters.

System Applications and GIS

PRMS is probably not as well known as HEC-1, AGNPS, and HSPF. It was used in a number of studies to investigate the impact of coal mining on basin hydrology. More recently it has been used to investigate the potential effects of climate change on hydrologic response.

Some work has been done to develop GIS tools to delineate HRUs for PRMS applications. Both a polygon HRU approach and a gridded HRU approach have been investigated. Remotely-sensed snow cover data was coupled with a GIS to compare measured and simulated snowcover. The commercially available preprocessor software that uses GIS to delineate watershed boundaries, slopes, areas, and other basin characteristics do not seem to have a direct interface for PRMS, but their output could probably be adapted to PRMS.

A new, more flexible modular system has been in development to eventually replace PRMS. The new system is termed the Modular Modeling System (MMS) and presently has been developed only for UNIX-based workstations. It features a graphical user interface. Along with MMS a GIS interface is currently being developed. At this time the GIS interface will run on UNIX-based workstations and Windows NT. It is still undergoing testing. Once a Windows based MMS becomes available, it should be more user-friendly than the present PRMS model, particularly with an integrated GIS interface.

HYDROLOGICAL SIMULATION PROGRAM - FORTRAN (HSPF)

The Hydrological Simulation Program - FORTRAN (HSPF) is a lumped parameter, continuous watershed model, developed under EPA sponsorship by Hydrocomp, Inc. Its parent models were the EPA Agricultural Runoff Management Model (ARM), the EPA Nonpoint Source Runoff Model (NPS) and the Hydrologic Simulation Program (HSP), a privately-developed proprietary model. The hydrologic model portion of HSPF originated from the Stanford Watershed Model (SWM) developed by Crawford and Linsley, one of the first comprehensive hydrologic models which has undergone many modifications, additions, and revisions since. HSPF can be used to model nonpoint source pollution and sediment transport as well as hydrologic processes. This discussion will be limited to the hydrologic simulation portion of HSPF.

HSPF has been widely applied to a great diversity of applications all over the world ranging from the 62,000 square mile tributary to the Chesapeake Bay to plots of a few acres near Watkinsville, Ga. Since 1981, the USGS has developed several software tools to provide interactive model input development, data storage and analysis, output analysis, and calibration assistance. The ANNIE program facilitates data analysis and graphics, WDM (Watershed Data Management) is used to prepare data files, and HSPEXP is an expert system to aid the user in calibrating the model for a particular watershed. The procedure consists of a set of rules designed to guide the model calibration through systematic evaluation of model parameters. The USGS and EPA continue to cooperate in efforts to enhance the model's capabilities and provide support for the model.

Similarly to PRMS, HSPF can run on both a daily time scale between precipitation events and a storm time scale during precipitation events. In daily mode streamflow and other hydrologic components are simulated as daily averages, which in storm mode time steps can be considerably smaller, with a minimum of 1 minute.

Hydrocomp, Inc. has continued to develop a proprietary model also descended from the Stanford Watershed Model called the Hydrocomp Forecast and Analysis System (HFAM).

HSPF Model Structure

HSPF contains three application modules and five utility modules. The application modules simulate hydrologic, hydraulic, and water quality components. The utility models are used to transfer, analyze, plot, tabulate, transform, combine, or otherwise manipulate time series data such as precipitation and streamflow. The modules are summarized in table 2.

PERLND: this module simulates runoff and water quality constituents from pervious land areas in the watershed. This is the most frequently used part of HSPF. Water movement is modeled with overland flow, interflow, and groundwater flow. HSPF uses a series of storage zones or reservoirs to represent processes on the surface and in the soil column.

IMPLND: this module simulates runoff and water quality from impervious land areas. No infiltration, interflow, evapotranspiration, or groundwater flow is modeled since all the precipitation is assumed to run off overland to a channel or reservoir.

RCHRES: this module is used to route runoff through stream channel networks and reservoirs.

Interception: when precipitation falls on the watershed, all of it will be abstracted into the interception zone unless the intensity of precipitation is greater than the interception rate or the interception storage is full. Interception is a function of the watershed vegetation cover.

Evapotranspiration: evapotranspiration (ET) can occur from interception storage and from the upper storage zone. The upper storage zone includes depression storage. A lower soil zone links infiltration to groundwater storage. ET will also occur from stream and lake surfaces. Finally, ET can occur from the lower soil zone if the upper soil zone storage is depleted.

Infiltration: infiltration is a function of the moisture available for infiltration and the infiltration capacity, which depends on the soil type and the amount of storage available in the upper soil zone. Some of the infiltration will enter interflow storage, and some will percolate into the lower soil zone depending on the lower zone available storage.

Groundwater: groundwater storage occurs in the lower zone. Some of the groundwater will be routed to a stream or channel, while some may be permanently lost to deep storage or diverted across the drainage basin boundary.

Overland flow: HSPF uses a hydrologic routing scheme incorporating the Manning's equation and continuity equation for flow in open channels. As precipitation continues to fall on the subbasin, the excess after infiltration is detained on the surface until an equilibrium depth is established. An equilibrium detention storage of water retained on the surface is computed as a function of the precipitation rate, the slope of the subbasin, the overland flow length, and the roughness of the subbasin surface. Once this equilibrium rate is reached, excess precipitation will be routed over the subbasin surface. The flowrate from this water detained on the surface is computed as a function of the slope, overland flow length, roughness, and ratio of the average detention storage to the equilibrium storage.

Interflow: interflow storage is routed similarly to groundwater storage using a recession constant, where the amount of interflow gradually decreases over time. Interflow is routed to the channel or stream.

Channel routing: Overland flow, groundwater recharge, and interflow enter a channel to be routed to the watershed outlet. The hydrologic routing method used to translate streamflow is based on the kinematic wave assumption, in which the hydrograph is not attenuated by storage in the channel. The outflow from the channel can be distributed to normal outflow at the outlet, diversions, and reservoir outflows. For reservoirs with no control over outflow (where outflow is a function of the depth of flow over the outlet of the reservoir), the outflow is modeled as a function of the channel volume. The user must provide a relationship between water depth, surface area, volume, and discharge. The combination of routing the flows down the channel reach and then routing them through a reservoir simulates the attenuation of the flow due to storage in the channel.

Data Requirements

HSPF requires daily precipitation values for the daily mode, and preferably 1-hour or even 15-minute precipitation values for the storm mode. In order to model snowmelt, maximum and minimum daily air temperatures, dewpoint temperatures, daily solar radiation and wind speed are required. Estimates of potential evapotranspiration can be obtained from pan evaporation data.

Characteristics required for each subbasin include area, land use, hydrologic soil type, vegetation, average slope, and overland flow length. Channel characteristics required are the slope, roughness, and stage-discharge data. Channel reservoir characteristics require a relationship between water depth, surface area, volume, and discharge. Streamflow gage data is necessary for calibrating the model. Soil data required includes permeability and storage capacity.

Calibration and Optimization of Parameters in HSPF

Another version of HSPF, called HSPEXP, has been developed to act as an expert system to calibrate watershed models. Knowledge of experienced surface water hydrologic modelers has been incorporated into HSPEXP. The result is a set of hierarchical rules to guide in calibrating a model by systematically evaluating model parameters that drive the precipitation -runoff process. Previously to the development of HSPEXP, a self-calibrating version called OPSET was developed. HSPEXP has been tested on watersheds in Washington and Maryland. The system correctly identified the model parameters to be adjusted, which resulted in an improved calibration.

AGNPS: AGRICULTURAL NONPOINT SOURCE MODEL

The Agricultural Nonpoint Source Model (AGNPS) was developed by the Agricultural Research Service (ARS) in cooperation with the Minnesota Pollution Control Agency (MPCA) and the Soil Conservation Service (SCS). It is a distributed parameter, event-based model. AGNPS can simulate the behavior of runoff, sediment, and nutrient transport from predominantly agricultural watersheds. A distributed type of model is often preferred when pollutant or sediment transport is to be modeled. As this discussion is concerned with hydrologic modeling, only the runoff simulation aspects of the model will be discussed here.

AGNPS is intended to be applicable to watersheds from a few acres in size to upwards of 50,000 acres. The watershed to be modeled is subdivided into uniformly square cells. This allows the user to route pollutants through the cells step-by-step so flow at any point between cells can be computed. Watershed parameters and data are provided for each cell.

For large watersheds (> 2000 acres), the recommended cell size is about 40 acres. Smaller watersheds require smaller cell sizes. The smaller the cell, the more accurate the results, typically, but time and labor increase significantly.

River Basin Representation

Figure A-3 shows a watershed subdivided into cells. Notice that the shape of the watershed cannot be exactly reproduced by these square cells. The arrows in each cell indicate the direction of flow, or the major drainage pathway within the cell. Runoff is routed through each cell into a neighboring cell based on the direction of flow.

If more detail is desired in a particular cell, the cell can be subdivided into fourths. This subdivision can be repeated three times for cell sizes 1/64th the size of the original. This is useful for cells where better resolution is desired, or for analysis of critical areas of the watershed.

Hydrologic Processes

AGNPS models runoff volume and peak flow rates, which are in turn used to generate a triangular hydrograph for each cell.

Runoff volume: Runoff volume is estimated based on the SCS curve number method. The basic equation is:

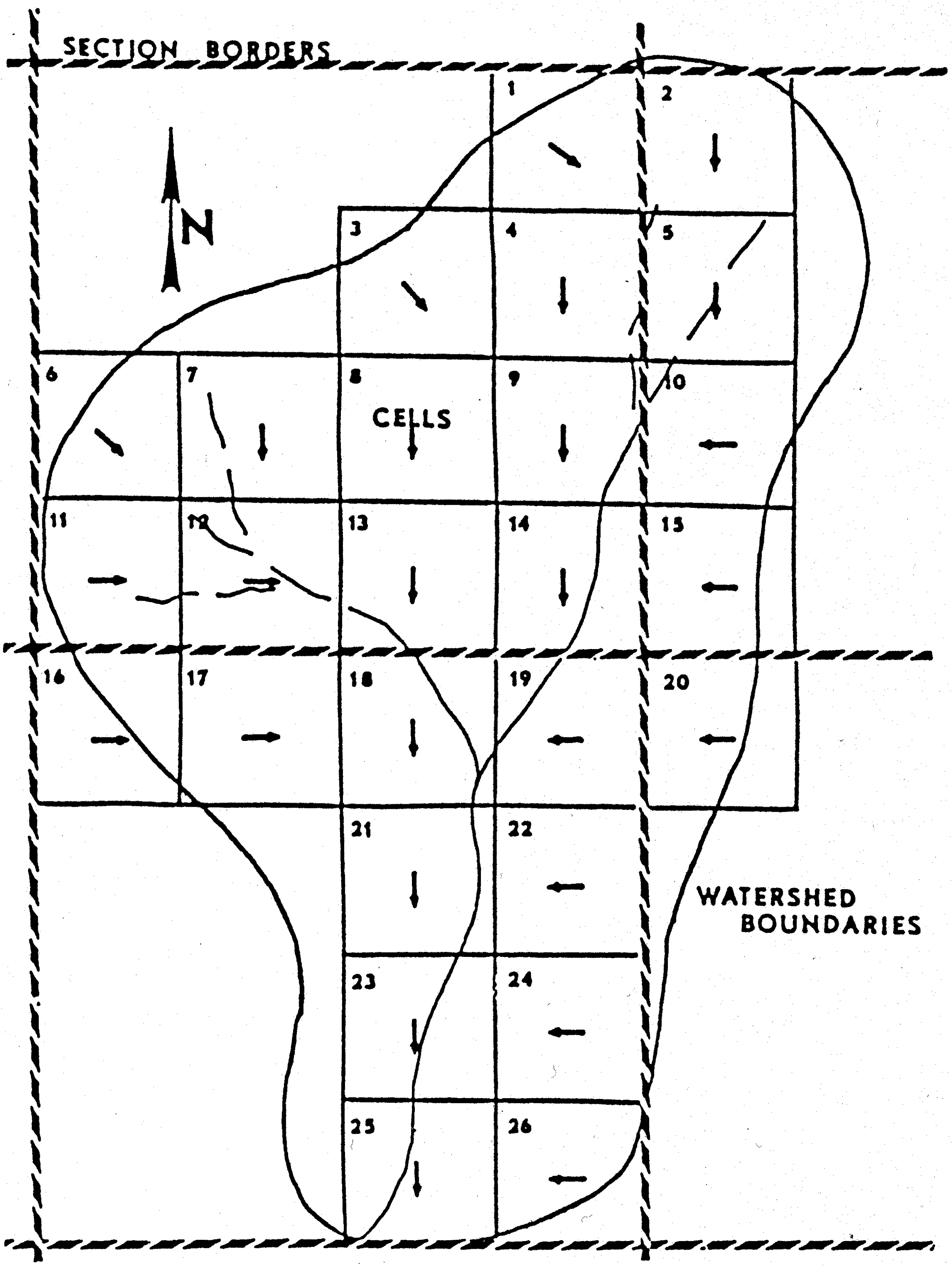

Figure A-3. Watershed representation in AGNPS. (From: Computer Models of Watershed Hydrology, V. P. Singh, Ed. 1995. Figure 26.1, pg. 1003)

$$Q = \frac{(P = 0.2S)^2}{P + 0.8S}$$

where Q is runoff volume, P is rainfall, and S is a retention factor. S is computed by:

$$S = \frac{1000}{CN} - 10$$

where CN is the curve number, which depends on land use, soil type, and hydrologic soil condition.

Peak Runoff Rate: There are two different ways to calculate peak runoff rates for each cell. The first is an empirical equation which assumes a triangular-shaped channel. The peak runoff rate is a function of the drainage area, the channel slope, the runoff volume (as computed using the SCS curve number), and the watershed length-width ratio.

The second method is based on TR55. A rectangular channel is assumed and peak flow is based on the time of concentration (T_c), which is the time it takes for water to travel from the most distant point in the watershed to the outlet. T_c is determined by summing travel times for consecutive cells in a particular flowpath in the watershed. Other parameters include the drainage area, the runoff volume, and coefficients based on 24-hour precipitation and initial abstraction (found using the curve number method.)

Hydrograph development: peak flow rates are used to determine a triangular shaped hydrograph for each cell. The user can define the shape. The hydrograph is divided into uniform increments. Flow rates are calculated for each increment using average time to peak, flow duration, and duration of each increment.

The output from the AGNPS hydrology model is the runoff volume in inches, the peak runoff rate in ft^3/s, and the fraction of runoff generated within each cell. Output is reported at the outlet and for any cell.

Data Requirements

Table 1 shows a list of input information required to run AGNPS. If you are not modeling soil erosion or nonpoint source pollution transport, the soils information, agricultural management, and other information are not required. Similarly to HEC-1, precipitation data including rainfall intensity is required. The runoff curve number is also necessary. Watershed data includes slope length, steepness, aspect, and shape, channel slope gradient, channel side slope or dimensions, and Manning's roughness coefficient.

AGNPS offers fewer options for hydrologic routing of overland flow and channel flow than does HEC-1. It is considered relatively simple to use.

Current Developments

AGNPS is being modified for use in continuous simulation mode by incorporating a weather generator to generate daily weather and calculate changes in soil moisture conditions. A set of routines to simulate snowmelt runoff and runoff from frozen soil is also incorporated. The frost routine estimates depth of frost development and thawing over the winter and changes in soil water content and infiltration capacity. The snowmelt routine estimates the amount of snowmelt occurring and how much is available as runoff. The snowdrift routing estimates depth, density, and the distribution of snow cover over the watershed.

A GRASS/AGNPS interface was developed by Raghavan Srinivasan and Bernie Engel of the Department of Agricultural and Biological Engineering at Purdue University. GRASS (Geographic Resources Analysis Support System) is a public domain GIS available from Baylor University in Texas. Yoon and Padmanabhan (1994) developed a decision support system for nonpoint source pollution management directly linking AGNPS, Geo/SQL (a vector-based GIS), and the relational database management system ORACLE. Disrud and Yoon (1997) linked AGNPS to the ArcCAD GIS software package from the Environmental System Research Institute, Inc., which was applied to the Oakes Test Area in North Dakota to assess and manage surface water quality.

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