

THE HYDROLOGIC RESPONSE TO LANDUSE CHANGE IN A SMALL
WATERSHED IN WESTERN OREGON

by

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A THESIS

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for the degree of
Master of Science

June 1993

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Sarah L. Shafer for the degree of Master of Science
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Title: THE HYDROLOGIC RESPONSE TO LANDUSE CHANGE IN A SMALL
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This study develops a rainfall-runoff model for simulating the hydrologic effects of changes in landuse on stream flow. The model uses mathematical representations of basic hydrologic processes to simulate daily stream flow for three small watersheds near Eugene, Oregon. The model was calibrated using data from Coyote Creek and Amazon Creek and then applied to Willow Creek to investigate both the effects of urbanization and of flow-retention by beaver ponds on the hydrology of the Willow Creek watershed.

Impermeable area is modeled to simulate the potential effects of increased urbanization in the Willow Creek basin. The model results show that urbanization would increase the number and size of stream discharge peaks. The effects of beaver ponds on

the hydrology of Willow Creek are also modeled. The results imply that beaver ponds may alter the hydrologic character of Willow Creek by functioning as important storage reservoirs in the basin.

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DEDICATION

For

Ann M. Schaening

1965-1986

Oberlin

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CHAPTER I

INTRODUCTION

Prior to European settlement, the Willamette Valley in Oregon was subject to regular flooding by the Willamette River and its tributaries (West Eugene Wetland Special Area Study (WEWSAS), 1991). Seasonal wetland prairie, dominated by tufted hairgrass (*Deschampsia cespitosa*), occupied many low-elevation sites; an estimated 500,000-750,000 acres of prairie could be found on the valley floor (Savonen, 1988; WEWSAS, 1991). As European settlers moved into the valley, their agricultural practices and the effects of urbanization drained and destroyed wetlands. Only very small remnants of the wetland prairie community exist today. In 1982, The Nature Conservancy took steps to preserve one of these wetland remnants by acquiring control of approximately 41 hectares (102 acres) of land in the Willow Creek basin on the western edge of Eugene, Oregon (Figure 1). This area is now part of the Willow Creek Preserve, within which The Nature Conservancy hopes to restore and preserve the wetland prairie as a functioning ecological community.

The existence of wetlands is strongly tied to the hydrologic cycle. Under the federal definition, three characteristics must be present for an area to qualify as a wetland: hydric soils, hydrophytic vegetation, and wetland hydrology (i.e., standing water or saturated substrate) (Federal Interagency Committee for Wetland Delineation, 1989). All three factors are linked to the local hydrologic regime of an area and to the presence of saturated substrate conditions at critical times during the growing season. In recognition of the dependence of wetlands on hydrology, The Nature Conservancy commissioned this study of the hydrologic regime of the Willow Creek basin.

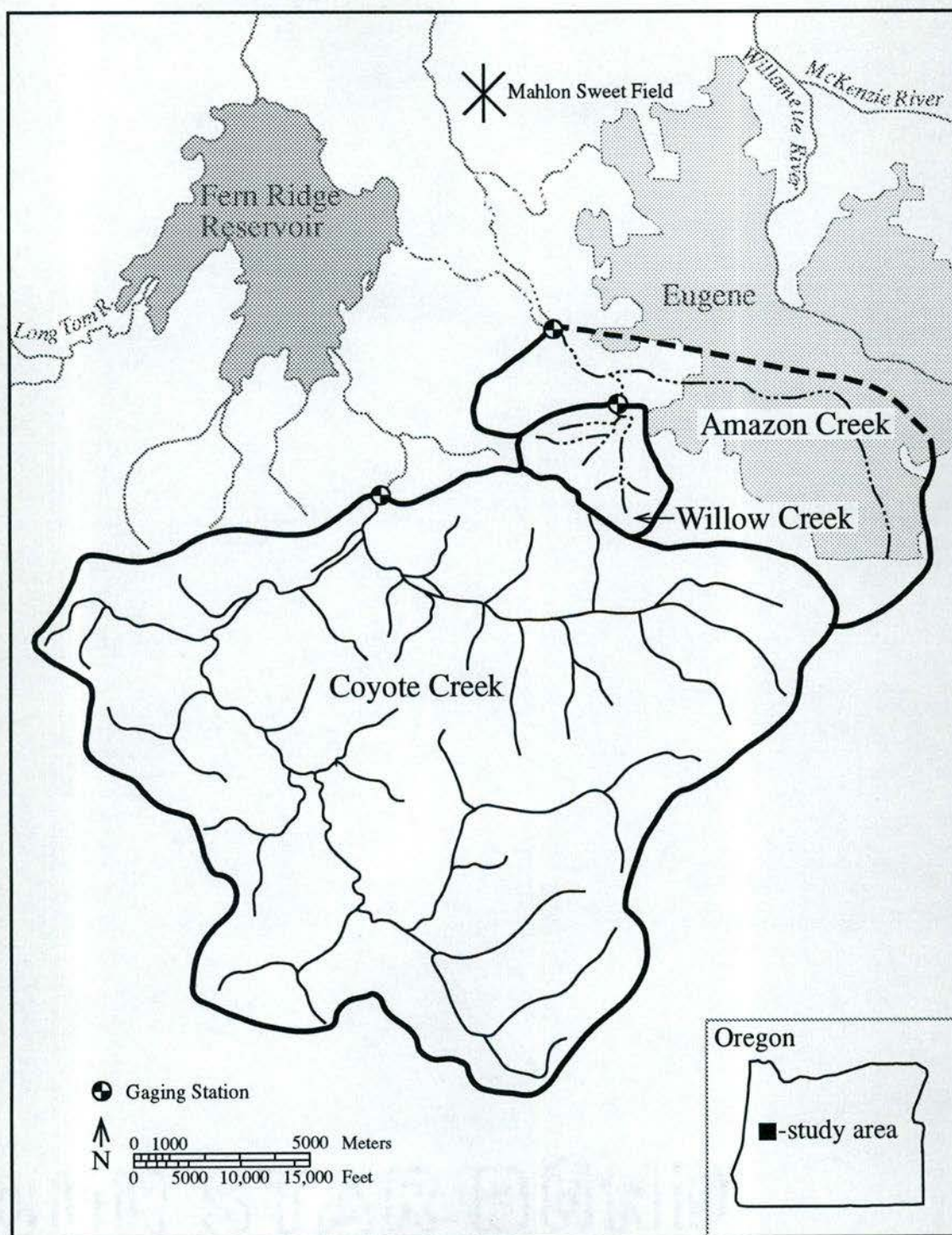


Figure 1. Map of the Coyote Creek, Amazon Creek, and Willow Creek basins showing their relative positions and sizes (USGS, 1979, 1980).

Given the proximity of the Willow Creek basin to the city of Eugene, a primary goal of this research was to assess the potential effects of urbanization on the watershed's hydrology. Urbanization severely disrupts natural hydrologic systems (Ferguson and Suckling, 1990; Booth, 1991). Pavement and buildings prevent infiltration by sealing the ground surface. Storm sewers and drainage ditches route water from these impermeable areas to stream channels much more quickly than would naturally occur. Development of only a portion of a watershed may disturb the hydrology of an entire basin as the hydrologic effects of urbanization, particularly channel incision and expansion, may migrate both upstream and downstream from the area of development.

Increased urbanization of the Willow Creek basin seems inevitable because of its close proximity to the city of Eugene. Predicting the future effects of urbanization on the hydrology of the Willow Creek basin is critical for the successful management of the wetland prairie preserve by The Nature Conservancy. These potential hydrologic changes can be simulated using hydrologic models (Booth, 1991). A rainfall-runoff model is used in this study to simulate the hydrologic effects of urbanization on the Willow Creek basin.

Paralleling the historic destruction of wetlands in North America was the decimation of its beaver populations. Trapping for the fur trade was directly responsible for the decline in beaver numbers as was habitat loss to those same forces--agriculture, urbanization, etc.--destroying wetlands. Seton (1929: 445) reported that the beaver was essentially extirpated from the continental United States by 1925, with only a few scattered colonies known to exist at that time.

Today, beavers are making a strong comeback throughout their former range. By building dams and forming ponds, beavers significantly alter the hydrology of streams and change the character of the riparian systems they inhabit. There are numerous beaver ponds along reaches of Willow Creek and, as a result of the small size of the Willow

Creek basin, the beaver ponds exert a significant effect on the basin's hydrology. These beaver ponds will also affect the hydrologic response of the basin to future urbanization. This study, therefore, attempts to model the effects of beaver ponds on the hydrology of Willow Creek.

Modeling Hydrologic Systems

As we try to determine the effects of human actions on the environment, modeling physical systems at all temporal and spatial scales is becoming increasingly common. The complexity of natural systems compels us to use models to create simple abstractions of natural systems in an attempt to understand them. Modeling simultaneously allows us to test our understanding of how natural systems function and to attempt to predict the response of natural systems to human or naturally induced changes.

Hydrologic systems are difficult to model. The processes that control the flows and storage of water in a watershed are both temporally and spatially dynamic. Runoff volumes for a given storm will vary depending on land cover and soil type. The time of year may affect infiltration rates. We rarely have field measurements at the scale of detail necessary to capture this complexity in a model. A common response to this dilemma is to obtain the hydrologic data that is most readily available, daily precipitation and stream discharge measurements, and use the relationship of rainfall and runoff as the basis for modeling. Making the leap from the simple empirical relationship of rainfall and runoff to the complexity of the entire hydrologic system is very problematic. If the limitations of the model are kept firmly in mind, however, the model results can be exceedingly useful, particularly in understanding the magnitude and direction of change of a hydrologic system in response to perturbation.

The rainfall-runoff model presented in this study offers an opportunity to gain insights into the hydrologic regime of small basins. It is used as a tool both for predicting the effects of landuse changes on the hydrology of small basins and for testing our assumptions about hydrologic processes. The following sections present the rainfall-runoff model developed specifically for this study and describe its calibration and application to Willow Creek. A model component that simulates the effects of beaver ponds on hydrologic systems is also presented and applied. Finally, a model subroutine that simulates the hydrologic effects of the increased impermeable area associated with urbanization is developed and used to simulate the effects of urbanization on the hydrologic regime of Willow Creek.

CHAPTER II

THE RAINFALL-RUNOFF MODEL

An Overview of Rainfall-Runoff Models

Hydrologic models attempt to simplify and abstract the functions of the very complex physical systems that operate within a watershed. An individual model may include simulations of climatic, biotic, and geologic systems that taken together describe the movement of water through a basin. Hydrologic models are of two general types: analog and symbolic. Analog models are those that try to replicate the hydrologic system by using a physical device, such as a circuit board upon which the flow of electricity is used to represent the flow of water. Of the symbolic models, those using mathematical relations are the most common. Mathematical models in turn can be divided into three groups: empirical, theoretical, and conceptual (Singh, 1988). Empirical models reflect relationships found in empirical data regardless of whether these relationships correspond to actual physical processes. By focusing on the observed data, they may provide good predictive models but relatively poor physical models because they often do not explicitly model physical processes. Theoretical models, in contrast, are based on our understanding of particular physical processes. Parameters in theoretical models are much more physically significant than those of empirical models but the models are generally poorer predictors because the complexity of physical processes prevents us from adequately modeling them (Singh, 1988). Conceptual models are a hybrid of theoretical and empirical models, and usually contain a mixture of physically based and empirically derived components. The rainfall-runoff model used in this study is a mathematical conceptual model (McCuen and Snyder, 1986: 320).

Rainfall-runoff models are one of the most commonly used hydrologic models (Singh, 1988). In their simplest form they are based on a mathematical relationship between observed series of precipitation and discharge data for a particular stream system. This relationship is used to predict discharge for various types and sizes of precipitation events. An advantage of rainfall-runoff models is that they require minimal field data and can be very efficient and economical to use. As a result, they are popular with planners and engineers trying to forecast stream flows for municipal water needs and flood control purposes. A major disadvantage of rainfall-runoff models is that they are based on a relationship that is a very simplistic, generalized representation of the hydrologic system of a basin. The limitations and assumptions incorporated into models are often not adequately presented to the model users, resulting in misapplication of the models and inappropriate interpretation of their results.

Model Structure

The structure of the rainfall-runoff model used in this study is schematically displayed in Figure 2. This specific model was derived from a textbook modeling exercise used by McCuen and Snyder (1986: 320). The model was subsequently modified to make it more faithful to certain hydrologic processes. In particular, subroutines were created to simulate the increase in impermeable area associated with urbanization, and the detention of water by beaver ponds.

The order in which the flow and storage subroutines are executed in the model are indicated by numbers in Figure 2. Water enters the system as precipitation (1); in this model there are no allowances for other inputs such as groundwater entering from outside the basin. Precipitation is divided between overland flow (2) that fills surface storage and infiltration (4) into subsurface storage. Water that moves out of subsurface storage may

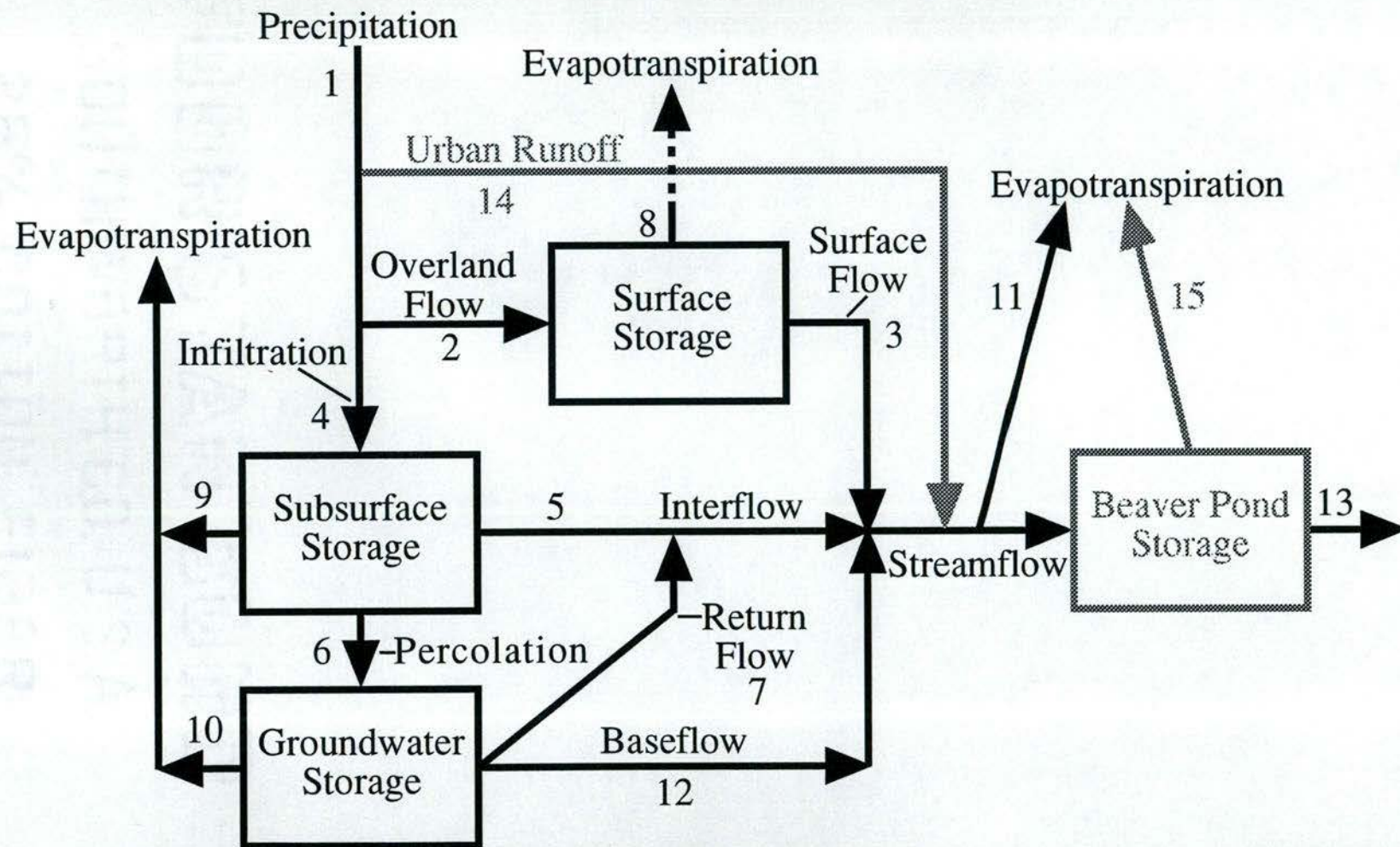


Figure 2. Schematic of the model structure, after McCuen and Snyder (1986).

percolate down to groundwater storage (6), evapotranspire from the soil (9), or move as interflow to the channel (5). Water entering surface storage from overland flow will either become part of the surface flow that enters the stream channel (3) or evapotranspire (8). Groundwater may be discharged as baseflow to the channel (7, 12) or may evapotranspire (10). Water in the channel may be detained in beaver pond storage. During dry periods channel flow may also contribute to evapotranspiration (11).

The two subroutines added to McCuen and Snyder's original model are used to change the way in which water is routed and stored. The beaver pond subroutine accepts water after all routing has been completed and detains it in a beaver pond storage reservoir. This "ponding" makes more water available for evapotranspiration (15) and for slow release into the channel (13). The urbanization subroutine simulates the effects of urban runoff from impermeable areas by routing a user-specified percentage of the incoming precipitation directly to channel flow (14), by-passing surface and subsurface storage.

Model Functions and Parameters

Throughout the model, functions and parameters are used to impose limits upon the storage volumes and flow rates in the basin. Four functions are used to calculate infiltration, percolation, evapotranspiration, and baseflow rates using general mathematical relations from McCuen and Snyder (1986: 320), modified to reflect the known physical characteristics of the three study basins (Figure 3). The functions rely on the ratio of the amount of water currently stored in one of the model's storage reservoirs (surface, subsurface, or groundwater storage) to the maximum storage available for that reservoir. The ratio is calculated for each daily iteration of the model to determine rates of discharge from the storage reservoirs.

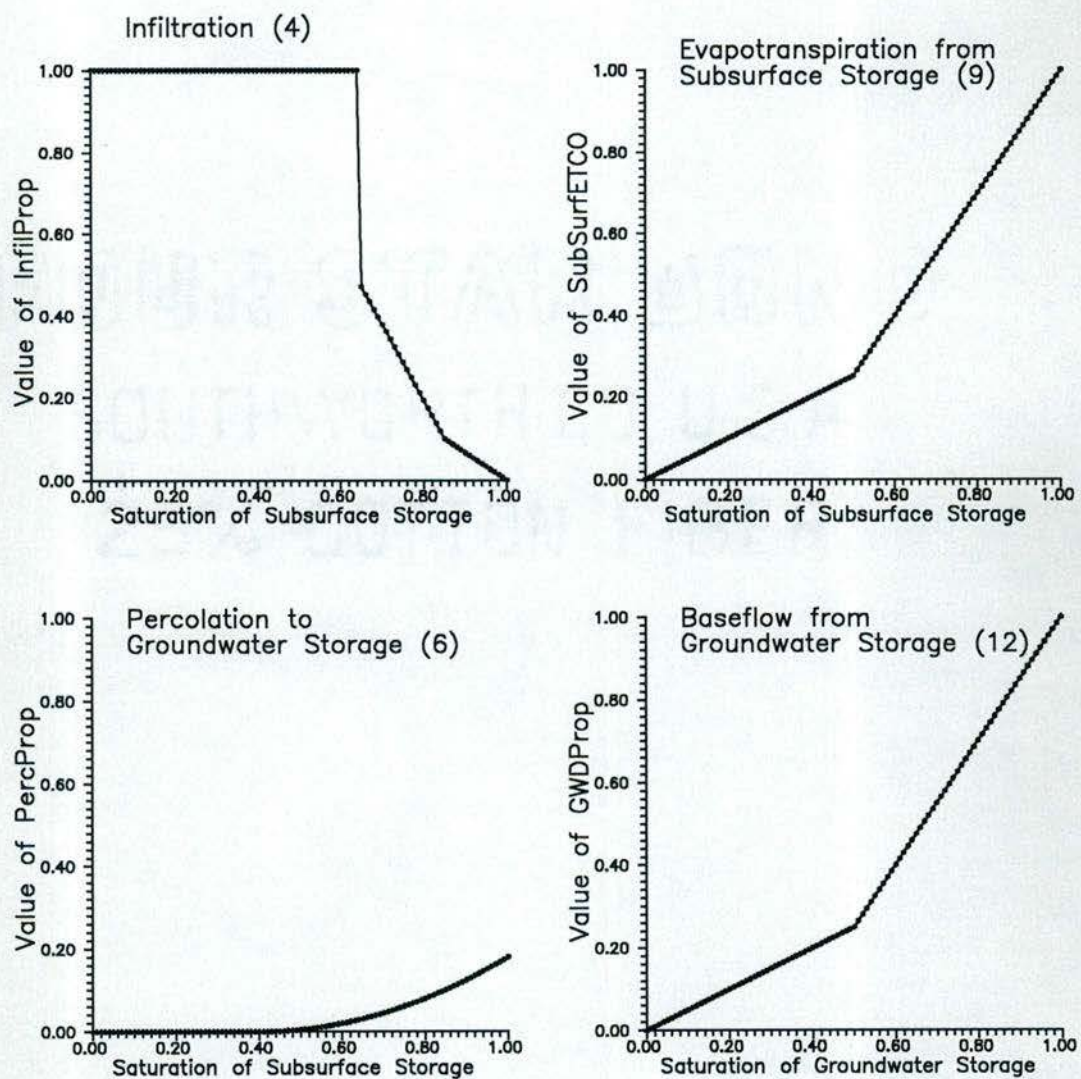


Figure 3. Function curves for governing four of the flows in the model: infiltration, evapotranspiration from subsurface storage, percolation to groundwater, and baseflow from groundwater.

Flows and storages are also governed in the model by nine user-specified parameters (Table 1). These parameters allow the user to define both maximum storage volumes and maximum flow rates. No measurements were available to provide the initial parameter values for model runs so parameter values were chosen from educated guesses based on an understanding of the physical properties of the basins (Table 2). An attempt was made to use a statistical optimization program to estimate parameter values that would optimize the fit between simulated and observed runoff. The parameter values chosen using this method produced good results for the overall two-year study period but failed to match the timing and volume of many of the individual runoff peaks within this period. In other words, the optimized parameter values succeeded in reducing the overall model error but at the expense of being able to simulate the rise of stream flow in response to individual precipitation events. Subjective optimization of the model parameter values produced a better simulation of individual discharge events as well as an acceptable overall fit between the simulated and observed runoff. The final parameter values used in the model runs are not unique; other combinations may exist that could produce results of equal or even better fit.

Initial Storage Volumes

The model has four storage reservoirs: surface storage, subsurface storage, groundwater storage, and beaver pond storage. Surface storage and beaver pond storage are known from field observations to be empty at the beginning of the wet season and are given starting volumes in the model of 0 mm. Subsurface storage and groundwater storage are each given an initial starting volume of 10 mm. This value is close to, though somewhat lower than, the level to which both of these storages drop during the end of a

Table 1. Descriptions of the user-specified model parameters.

Parameter	Description
UHShape	varies from 0 to 1.0 and controls the overall shape of the unit hydrograph. The larger the number, the broader the unit curve (Figure 4).
SurfStoreMax	defines the maximum volume for surface storage (mm). If SurfStoreMax is exceeded the excess water is routed to surface flow (Figure 2(3)).
PropIntF	is multiplied by daily subsurface storage values to obtain the proportion of subsurface storage that will become interflow. In all of the model runs this value was kept at 0.005 indicating that the model structure was prohibiting substantial interflow from subsurface storage. Most of the interflow in the model output, therefore, is generated from excess groundwater (Figure 2(7)).
SubSurfStoreMax	determines the maximum volume of subsurface storage (mm).
GWCap	imposes a maximum limit (mm) on the capacity of the model's groundwater storage component. If GWCap is exceeded the overflow is routed to the interflow component of the model as return flow.
GWDMax	controls the rate of baseflow generated from the model. After the amount of groundwater that is available to generate flow has been identified, it is multiplied by GWDMax to determine the amount of baseflow produced during any daily iteration.
ResStoreMax	is used to specify the total beaver pond storage (mm) of all the beaver ponds in the basin.
RunoffMin	is a parameter that defines the minimum contribution (mm/day) from beaver ponds to stream flow.

Table 1. (Continued)

Parameter	Description
ImpermeableProp	is used in the urbanization subroutine as a parameter that defines the percent of impermeable area (streets, parking lots, roofs, etc.) in the basin. Flow from impermeable areas is frequently routed through storm sewers and ditches directly to stream channels. To simulate this, the model multiplies the impermeable area parameter against precipitation and routes the product directly to stream flow.
Note: Volumes are expressed in units of mm, equivalent to the volume of water, 1 mm deep over the area of the watershed. Flow rates are expressed as mm/day, equivalent to the volume of water, 1 mm deep, over the area of the watershed, discharged in a single day.	

model simulated summer. Thus, though 10 mm may not be an accurate real-world value, it is an appropriate initial value with respect to the model environment.

Model Components

The governing equation for the rainfall-runoff model is a variation of a watershed water balance equation

$$Q = P - (E_s + E_b + E_g) - (\Delta S_s + \Delta S_b + \Delta S_g)$$

where Q is channel discharge, P is precipitation, E_s is evapotranspiration from surface storage, E_b is evapotranspiration from subsurface storage, E_g is evapotranspiration from groundwater storage, and ΔS_s , ΔS_b , and ΔS_g are net changes in the volumes of surface storage, subsurface storage, and groundwater storage, respectively. This equation

Table 2. Values of the user-specified model parameters and initial conditions for the storage components in the model.

User-specified parameters	Calibration on the Coyote Creek watershed	Application to the Willow Creek watershed	Simulation of beaver ponds for the Willow Creek watershed	Calibration of the urbanization subroutine on the Amazon Creek watershed	Simulation of urbanization of the Willow Creek watershed
UHShape	0.5	0.5	0.5	0.5	0.5
SurfStoreMax	5 mm	5 mm	5 mm	5 mm	5 mm
PropIntF	0.005	0.005	0.005	0.005	0.005
SubSurfStoreMax	200 mm	200 mm	200 mm	200 mm	200 mm
GWCap	200 mm	200 mm	200 mm	200 mm	200 mm
GWDMax	0.2 mm/day	0.2 mm/day	0.2 mm/day	0.2 mm/day	0.2 mm/day
ResStoreMax	-	-	430 mm	-	430 mm
RunoffMin	-	-	0.2 mm/day	-	0.2 mm/day
ImpermeableProp	-	-	-	0.2	0.2 (0.1)
<u>Initial values for storage volumes in the model (mm)</u>					
Surface storage (SurfStore)	0				
Beaver pond storage (ResStore)	0				
Subsurface storage (SubSurfStore)	10				
Groundwater Storage (GWStore)	10				

represents all the flow and storage components of a watershed. The particular flow processes explicitly included in the rainfall-runoff model are described below.

Infiltration

When precipitation reaches the ground it either soaks into the soil or runs off into local depressions, stream channels, storm sewers, etc. Precipitation in the model is therefore initially divided between infiltration and surface storage. The amount of precipitation that infiltrates is limited by the moisture content of the subsurface storage reservoir. This moisture content is represented in the model by the parameter InfilProp and calculated each day using a case function which defines the infiltration curve in Figure 3. The curve shows that at low subsurface moisture levels, the total volume of each precipitation event is allowed to infiltrate into the subsurface until a saturation level of 65% is reached. A break in the curve at this point reduces the amount of precipitation that infiltrates between subsurface saturation levels of 65-85%. Above saturation levels of 85% the proportion of precipitation that is added to subsurface storage is even smaller, simulating the slow infiltration rates of very wet soils.

The infiltration curve is represented in the model by the case function

$$\text{if ratio} < .65 \text{ then InfilProp} = 1$$

$$\text{if } .65 \leq \text{ratio} \leq .85 \text{ then InfilProp} = 1 - (.25 + (13 * (\text{ratio} - .5) / 7))$$

$$\text{if ratio} > .85 \text{ then InfilProp} = 1 - (.9 + ((\text{ratio} - .85) / 7))$$

$$\text{where ratio} = \frac{\text{SubSurfStore}}{\text{SubSurfStoreMax}}$$

SubSurfStore is the current amount of water in subsurface storage and SubSurfStoreMax is a parameter that specifies the maximum capacity of subsurface storage. InfilProp is then used in the equation

$$\text{Infiltration} = \text{InfilProp} * \text{Precip}$$

to calculate the total infiltration for each day.

Surface Flow

Precipitation may not infiltrate if the subsurface is saturated or if the daily rate of precipitation exceeds the rate of infiltration. To represent this in the model, precipitation that does not infiltrate is added to surface storage. When the capacity of surface storage is exceeded, the excess water becomes overland flow. Overland flow eventually reaches the channel to become the surface flow component of stream flow. In this model stream flow is composed of three parts: surface flow, interflow, and baseflow.

The overland flow generated by a particular precipitation event may take more than one day to reach the channel. Its travel time is dependent on factors such as surface cover conditions and the distance the water needs to travel. The model used in this study partitions the overland flow generated by a particular precipitation event into components delivered to the channel over a four day period, with 55% of the overland flow reaching the channel on the first day, and 28%, 14%, and 3% reaching the channel on the second, third, and fourth days, respectively. The relative percentages are determined by a user-specified parameter, UHShape, which defines the shape of the unit hydrograph for each basin. UHShape can be given a value from 0 to 1.0. Figure 4 shows the unit hydrograph curves defined by a UHShape value of 0.25 and 0.75. Smaller values of UHShape create narrower, higher curves. Such curves represent small watersheds in which a large proportion of the overland flow from individual precipitation events can reach the channel within a day or less. Larger values of UHShape, such as 0.75, produce broader unit hydrograph curves that represent the slower response times representative of larger basins. UHShape is used to calculate a unit hydrograph coefficient, UHCoeff, for the day of the precipitation event ($k = 1$) and the three succeeding days ($k = 2, 3, 4$) by the equation

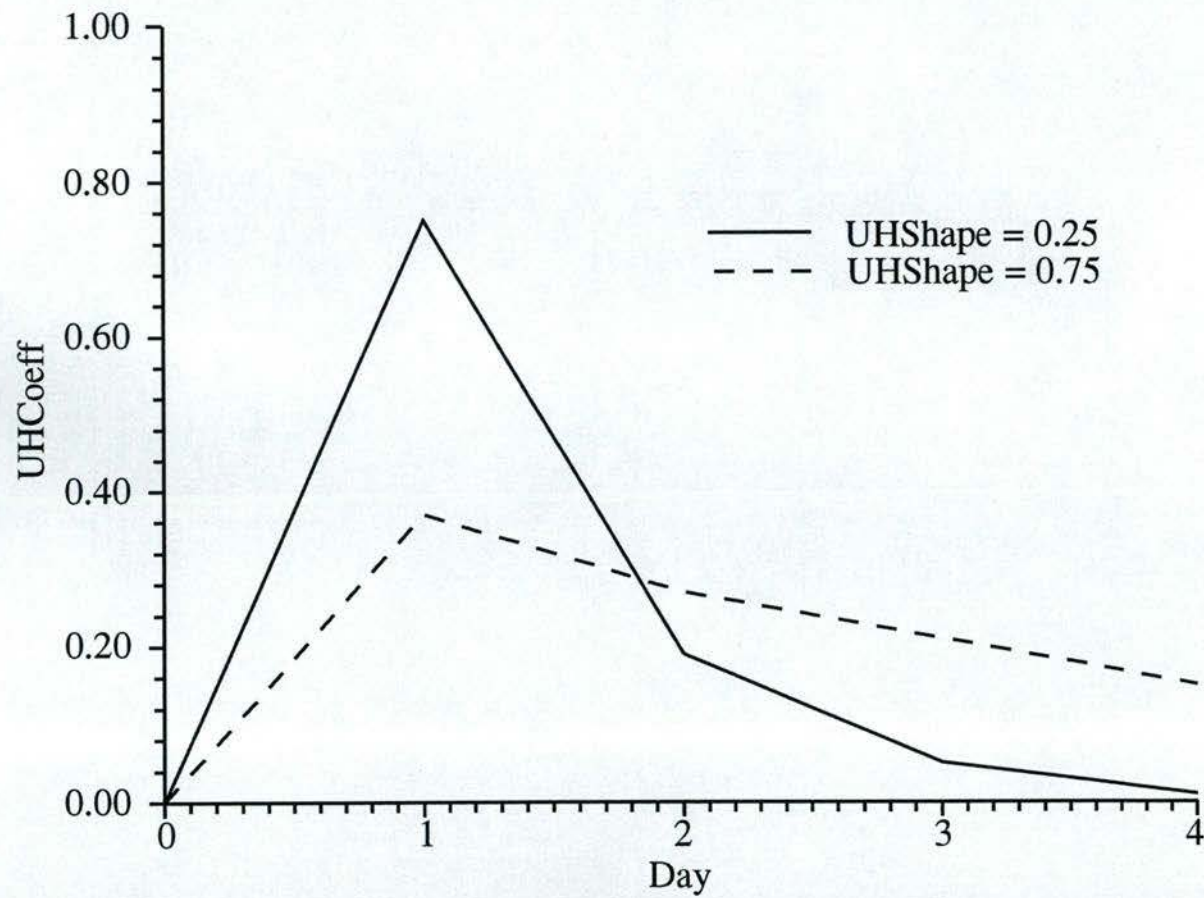


Figure 4. Unit hydrograph curves for UHShape values 0.25 and 0.75.

$$UHCoeff_k = \frac{UHCoeff_k}{1 + \sum_{j=1}^3 (UHShape)^j} \quad \text{for } k = 1, 2, 3, 4$$

where $UHCoeff_1 = 1$, and $UHCoeff_k = UHShape^j$ for $j = 1, 2, 3$; $k = 2, 3, 4$.

The contributions from overland flow to surface flow for a particular day is the summation of the proportion of overland flow that reaches the channel for that day plus the proportions that were generated during the three preceding days that reach the channel on the current day. For example, using a $UHShape$ of 0.5 creates $UHCoeff_k$ values of 0.55, 0.28, 0.14, and 0.03. The surface flow for a particular day of a model run, such as day 10, will therefore be the summation of 55% of the precipitation from day 10, 28% of the precipitation from day 9, 14% from day 8, and 3% from day 7. This summation uses the following equation

$$SurfFlow = \sum_{k=1}^4 (UHCoeff_k * OverlandFlow(j - k + 1)) \quad \text{for } j = \text{julian day}$$

where $SurfFlow$ is the contribution to stream flow from overland flow (McCuen and Snyder, 1986).

Interflow

Water that infiltrates into the ground is held in the soil matrix by capillary forces. The amount of water a particular soil can hold by capillary force alone is termed its field capacity. As the soil becomes saturated, field capacity is exceeded and the soil's ability to hold water in place is overwhelmed by the force of gravity pulling the water along flow gradients (Brooks *et al.*, 1991). The water that moves under the force of gravity from subsurface storage through the soil into the channel is called interflow. Interflow rates will vary depending on soil type. The average field capacity for the major soil groups in the study area is approximately 40% of total water holding capacity (Patching, 1987). If

subsurface storage in the model is at or below 40% of capacity then no water will be routed to interflow. Above 40% interflow is determined by the equation

$$\text{Interflow} = \text{PropIntF} * \text{SubSurfStore}$$

where Interflow is interflow, PropIntF is a user-specified parameter, and SubSurfStore is subsurface storage.

A second component of interflow in the model consists of water initially routed to groundwater storage and then re-routed back to interflow when the groundwater storage capacity is exceeded (Figure 2(7)). This flow path indirectly simulates the rise of the groundwater table during wet periods. Interflow and baseflow are often discussed as separate parts of a unit hydrograph. The distinction is artificial because the soil zone of saturation and the groundwater table are so closely linked. In this model the flow path represented by Figure 2(7) was included to better simulate the traditional relationship of interflow to baseflow in which a rise in interflow precedes an increase in baseflow in response to a precipitation event.

Percolation

The same processes which move water from subsurface storage to the channel will also move water from subsurface storage downwards to the groundwater storage reservoir in a process termed percolation. The amount of water that percolates out of subsurface storage increases with the saturation level of the subsurface. The rate at which water moves from subsurface storage into groundwater storage is determined by the percolation proportion parameter, PercProp, in the equation

$$\text{GWRecharge} = \text{SubSurfStore} * \text{PercProp}$$

where GWRecharge is the amount of groundwater recharge and SubSurfStore is subsurface storage (after interflow has been removed). The case function for determining

the value of PercProp defines the percolation curve shown in Figure 3. No water is allowed to percolate from subsurface storage until its saturation level has reached 40%, which approximates field capacity for the soils in the study area. Above 40%, the value of PercProp increases gradually with saturation of the subsurface. The percolation curve is determined by the case function

$$\begin{aligned} \text{if ratio} < .5 \text{ then PercProp} &= .5 * \text{ratio} \\ \text{if } .5 \leq \text{ratio} \leq .85 \text{ then PercProp} &= .25 + (13 * (\text{ratio} - .5) / 7) \\ \text{if ratio} > .85 \text{ then PercProp} &= .9 + ((\text{ratio} - .85) / 1.5) \\ \text{where ratio} &= ((\frac{\text{SubSurfStore}}{\text{SubSurfStoreMax}}) - .4)^2. \end{aligned}$$

SubSurfStoreMax is a user-specified parameter indicating the maximum capacity of subsurface storage.

Evapotranspiration

During each daily step of the model, actual evapotranspiration is calculated after all other routing of water except the creation of baseflow has been completed (Figure 2). Water is removed first as evapotranspiration from surface storage, then from subsurface storage, groundwater storage, and finally from the surface flow and interflow components of stream flow. The total amount of water that evapotranspires is limited to the amount of potential evapotranspiration calculated for that particular day as supplied in the input file.

The water in surface storage is considered to be directly available for evapotranspiration and is the most accessible to satisfy potential evapotranspiration. If the amount of water in surface storage does not exceed daily potential evapotranspiration then evapotranspiration from subsurface storage occurs next. The volume of water removed by evapotranspiration from subsurface storage is calculated by the equation

$$\text{SubSurfET} = \text{PotEvap} * \text{SubSurfETCoeff}$$

where SubSurfET is the amount of water evapotranspired from subsurface storage and PotEvap is the amount of potential evapotranspiration unsatisfied by surface storage. SubSurfETCoeff is a coefficient determined by the case function defined by the evapotranspiration curve in Figure 3. The more saturated the subsurface storage reservoir, the more water is available for evapotranspiration. The break in the curve at a saturation level of 0.5 has no direct empirical basis. It could be taken to represent the point at which evapotranspiration is no longer limited by capillary forces holding water in the subsurface. The evapotranspiration curve is calculated by the case function

$$\begin{aligned} \text{if ratio} < .5 \text{ then SubSurfETCoeff} &= .5 * \text{ratio} \\ \text{if ratio} \geq .5 \text{ then SubSurfETCoeff} &= (\text{ratio} * 1.5) - .5 \end{aligned}$$

$$\text{where ratio} = \frac{\text{SubSurfStore}}{\text{SubSurfStoreMax}}.$$

The amount of evapotranspiration from groundwater storage is calculated in a similar fashion using a coefficient, GWETCoeff, which is the ratio of the amount of water in groundwater storage to the maximum capacity of groundwater storage (GWStore/GWMax). If, after evapotranspiring the water available from groundwater storage there is still excess potential evapotranspiration, water is taken directly from the surface flow and interflow components of the stream flow.

Baseflow

Baseflow is the water released from groundwater storage that makes its way directly into the channel. In large basins, baseflow may account for a significant proportion of total stream flow; some rivers rely almost exclusively on baseflow during dry periods of the year. Baseflow in the model is calculated by the equation

$$\text{Baseflow} = \text{GWDDProp} * \text{GWDDMax}.$$

A user-specified parameter, GWDMax, sets the maximum volume of water that can be discharged from the groundwater storage reservoir on any given day. GWDProp is a calculated parameter that determines the proportion of GWDMax which will be discharged. It is based on the saturation level of the groundwater storage reservoir and uses the same case function as evapotranspiration to calculate baseflow (Figure 3). The break in the baseflow curve in Figure 3 can be interpreted as the point at which groundwater saturation is high enough to overcome friction retarding the movement of water. As with the evapotranspiration curve, there is no empirical basis for this breakpoint. The curve is determined by the case dependent function

$$\text{if ratio} < .5 \text{ then GWDProp} = .5 * \text{ratio}$$

$$\text{if ratio} \geq .5 \text{ then GWDProp} = (\text{ratio} * 1.5) - .5$$

$$\text{where ratio} = \left(\frac{\text{GWStore}}{\text{GWDMax}} \right)^2.$$

CHAPTER III

DATA

Basins

Data were collected from three small contiguous basins in the hills at the southern end of the Willamette Valley, Oregon (Figure 1). Although the Willow Creek watershed was the primary focus of this study, data from the upper basins of Coyote Creek and Amazon Creek were also used to calibrate the rainfall-runoff model and its urbanization subroutine. Coyote Creek is the largest of the three study basins (246.2 km^2 , 95.1 mi^2) (Figure 1). It is a rural basin and its predominant landuses are pasture and woodland. Amazon Creek, to the north and east of Coyote Creek, drains the southern part of the city of Eugene, Oregon. The gaging station on its lower reach measures a drainage area of approximately 55.2 km^2 (21.3 mi^2). Since the basin is almost entirely urbanized, its storm sewer network makes estimation of the current watershed boundary difficult as indicated by the dashed line in Figure 1.

The Willow Creek watershed is a part of the Amazon Creek watershed. It is the smallest of the three study basins (9.8 km^2 , 3.8 mi^2) and is characterized by rural landuses similar to those in the Coyote Creek watershed. The upper reaches of the basin are forested, with agriculture and grazing prevailing on the middle and lower slopes. There are homes scattered throughout the basin. A significant hydrologic component of Willow Creek is the presence of a large number of beaver ponds along its lower reaches. Though Amazon Creek and Coyote Creek may also contain beaver ponds, it is, in part, the number of beaver ponds relative to the small size of the basin which allow the beaver ponds to have a particularly significant effect on Willow Creek.

Study Periods

Field data, consisting of stream stage and discharge measurements, and visual observations of overland flow and surface storage volumes, were collected for Willow Creek during water years 1989 (10/1/88-9/30/89) and 1990 (10/1/89-9/30/90). United States Geological Survey (USGS) gaging stations on Amazon Creek and Coyote Creek were discontinued in 1982 and 1987, respectively, making it impossible to use the same study period for all three basins. Water years 1980 (10/1/79-9/30/80) and 1981 (10/1/80-9/30/81) were therefore chosen to build the Coyote Creek and Amazon Creek data sets since local solar radiation data were available for these years.

Input Data Sets for the Model

Rainfall-runoff models, in their simplest form, use precipitation to simulate or predict runoff. For the model used in this study, two time-series--daily precipitation and potential evapotranspiration--are required. In addition, daily observed stream discharge data are used to assess the accuracy of the model's runoff simulations. All data are expressed in units of millimeters per day (mm/day), averaged over the total area of the watershed. This unit of measurement accounts for the difference in the areas of the watersheds, and allows for a direct comparison of the model results for the three basins.

Precipitation Data

Daily total precipitation data for all three sites were obtained from the National Weather Service, Mahlon Sweet Field station (Eugene, Oregon; 44°7'N, 123°13'W) (National Climatic Center (NCC), 1979, 1980, 1981, 1988, 1989, 1990). The station is located approximately 9.5 km (5.9 mi) north of the Willow Creek gaging station and is the closest reliable source of meteorological data for the region. Other precipitation records

for the area exist, but are of questionable accuracy or are discontinuous (OTAK, 1990a; Northwest River Forecast Center, unpublished data; L. Nakama, unpublished data; S. Shafer, unpublished data). Snowfall in the study area is rare; when it occurred in the record its water equivalent was included in daily precipitation totals.

Potential Evapotranspiration Data

Daily meteorological data (air temperature, dew point temperature, wind speed, and cloud cover) were also obtained from the Mahlon Sweet Field monthly summaries. They were combined with daily global solar radiation measurements (Solar Monitoring Lab, 1986) and estimated albedo to calculate daily potential evapotranspiration (mm/day) (E) using the Penman equation:

$$E = \frac{\Delta H + \gamma E_a}{\Delta + \gamma}.$$

H is net radiation which is the sum of total daily incoming global radiation in Watts per square meter (W/m^2) minus reflected shortwave radiation (W/m^2) plus emitted longwave radiation (W/m^2) minus reflected longwave radiation (W/m^2). E_a is the drying capacity of the air (mm/day) which is calculated using Penman's wind function multiplied by the difference between saturation vapor pressure at air temperature and vapor pressure. Δ is the slope of the saturation vapor pressure curve at a particular temperature and γ is the hygrometric constant (0.27 mm of mercury/ $^{\circ}\text{F}$) (Penman, 1948; Singh, 1992: 352). Albedo was considered to be constant, and was assigned a value of 0.2 (see Appendix A) (Satterlund and Adams, 1992: 113).

Discharge Data

Average daily discharge records for Coyote Creek and Amazon Creek were obtained from USGS gaging station records (stations #14167000 and #14169500, respectively) (USGS, 1981, 1983). Gaging station locations are shown in Figure 1.

A gaging station for this project was installed on Willow Creek, approximately 700 m south of its confluence with Amazon Creek. Stream stage was recorded at 15 minute intervals for water years 1989 and 1990. The rating curve for the stream was calculated from discharge measurements made at the gaging station and fit using a piece-wise linear equation to account for channel constraints affecting the stage-discharge relationship. The fitted equation was

$$Q = (4.92 * \text{Stage}) + (10.3 * D1)$$

where Q is discharge in cubic feet per second (cfs), Stage is stream stage in feet above an arbitrary datum, and D1 is an indicator variable (see Appendix D) (Neter *et al.*, 1983: 346). D1 equals 0 for stages less than 0.6 ft and equals the value of the stage minus 0.6 ft for stage values equal to or greater than 0.6 ft.

CHAPTER IV

MODEL CALIBRATION AND APPLICATION

This chapter describes the results of the calibration of the rainfall-runoff model and subsequent applications. Five model runs are presented. The model was calibrated on Coyote Creek (1) and then applied to Willow Creek (2). To obtain better results, the model was modified to include a beaver pond subroutine and then applied again to Willow Creek (3). The final two sections describe the calibration of the model's urbanization subroutine on Amazon Creek (4) and then the simulation of urbanized conditions for the Willow Creek watershed (5).

In each of the following sections, the purpose of the simulation is stated and then the input data, the model parameters, and changes to the model structure are described. Finally, the results of each model run are presented and briefly discussed.

Model Calibration on the Coyote Creek Watershed

The success of a model is judged by the original goals of the modeler; these goals in turn dictate the criteria on which a determination of calibration success should be made. The goal of this study was to develop a model that would be sensitive to significant changes in the controls of the hydrologic regime of a small basin. Although Willow Creek was the primary study basin, the model calibration was carried out using data from Coyote Creek to prevent the model from being specifically biased towards the Willow Creek basin during the calibration process. Using data from Coyote Creek also allowed a test of the model's general flexibility.

Calibration success was based on how well the model's simulated daily runoff matched the observed runoff both in timing and volume. This match was evaluated qualitatively by visually comparing plots of simulated and observed runoff over time and by displaying simulated and observed runoff values on a scatter diagram. Regression analysis was also used as a statistical measure of how well the model simulated observed runoff.

Model Inputs

Meteorological and Hydrological Data

Daily meteorological input data from water years 1980 and 1981 were obtained from National Climatic Center (NCC) summaries (Figure 5) (NCC, 1979, 1980, 1981). Daily stream discharge values for this same period were available from the USGS gaging station on Coyote Creek (USGS, 1981, 1983). Two years of data are used in this and all subsequent model runs to minimize the effects of intra-annual variations in climate and stream flow as well as to reduce the effect of individual model parameters on the overall results.

Parameter Values

The values of six user-specified parameters must be chosen to run the model. The parameters and their values are listed in Table 2. Optimization of the parameter values was initially done manually using knowledge of the physical characteristics of the basin and of the nature of its hydrologic response as displayed in plots of the meteorological and hydrological data series. The final parameter adjustments were made based on both visual assessments of plots of simulated and observed runoff, and evaluation of the results of regression analyses of simulated and observed runoff.

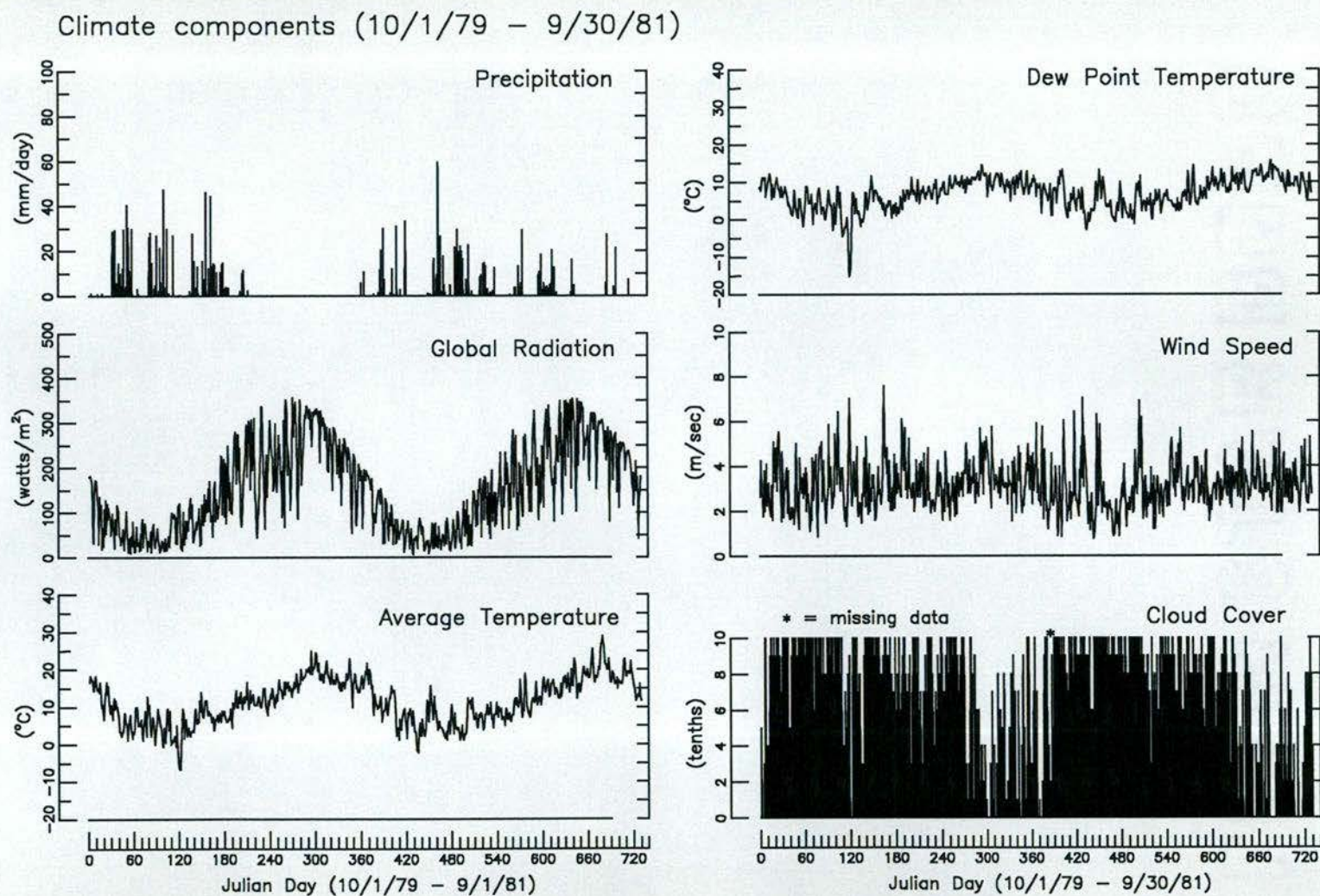


Figure 5. Meteorological input data for water years 1980 and 1981 (NCC, 1979, 1980, 1981).

Results of the Model Calibration

The model results for Coyote Creek using the final parameter values are displayed in Figure 6. For the first five graphs (Figure 6(a-e)) the horizontal axes display the julian day and the vertical axes are in units of mm or mm/day over the area of the watershed. The daily precipitation data for water years 1980 and 1981 are presented in Figure 6(a). Figure 6(b) compares the potential evapotranspiration data that were provided as input to the model and the actual evapotranspiration values calculated by the model. The strong seasonal contrasts in the study region between wet winters and dry summers are quite prominently displayed in the sinusoidal pattern of both series of data. The actual evapotranspiration curve shows good agreement with both the observed precipitation and potential evapotranspiration curves. In winter, when there is low incoming solar radiation (and hence, low potential evapotranspiration) and abundant precipitation, actual evapotranspiration can equal potential evapotranspiration. By summer, as incoming solar radiation increases and precipitation decreases, there is no longer sufficient available water for actual evapotranspiration to satisfy potential evapotranspiration and the actual evapotranspiration curve begins to drop below the potential evapotranspiration curve. One of the emergent properties of this rainfall-runoff model (i.e., a simulation result that was not explicitly coded for in the model) is its ability to simulate this summer moisture deficit.

Figure 7 compares the Coyote Creek observed runoff with the runoff simulated by the model. Overall, the model provides good simulation of the timing and size of individual runoff peaks, the hydrograph recession from those peaks, as well as agreement in larger scale seasonal variations of wet winters and dry summers. A regression analysis of simulated and observed runoff for this model run yielded an R^2 value of 79.8%. This measure, combined with a visual assessment of the fit of the two runoff curves (Figure 7)

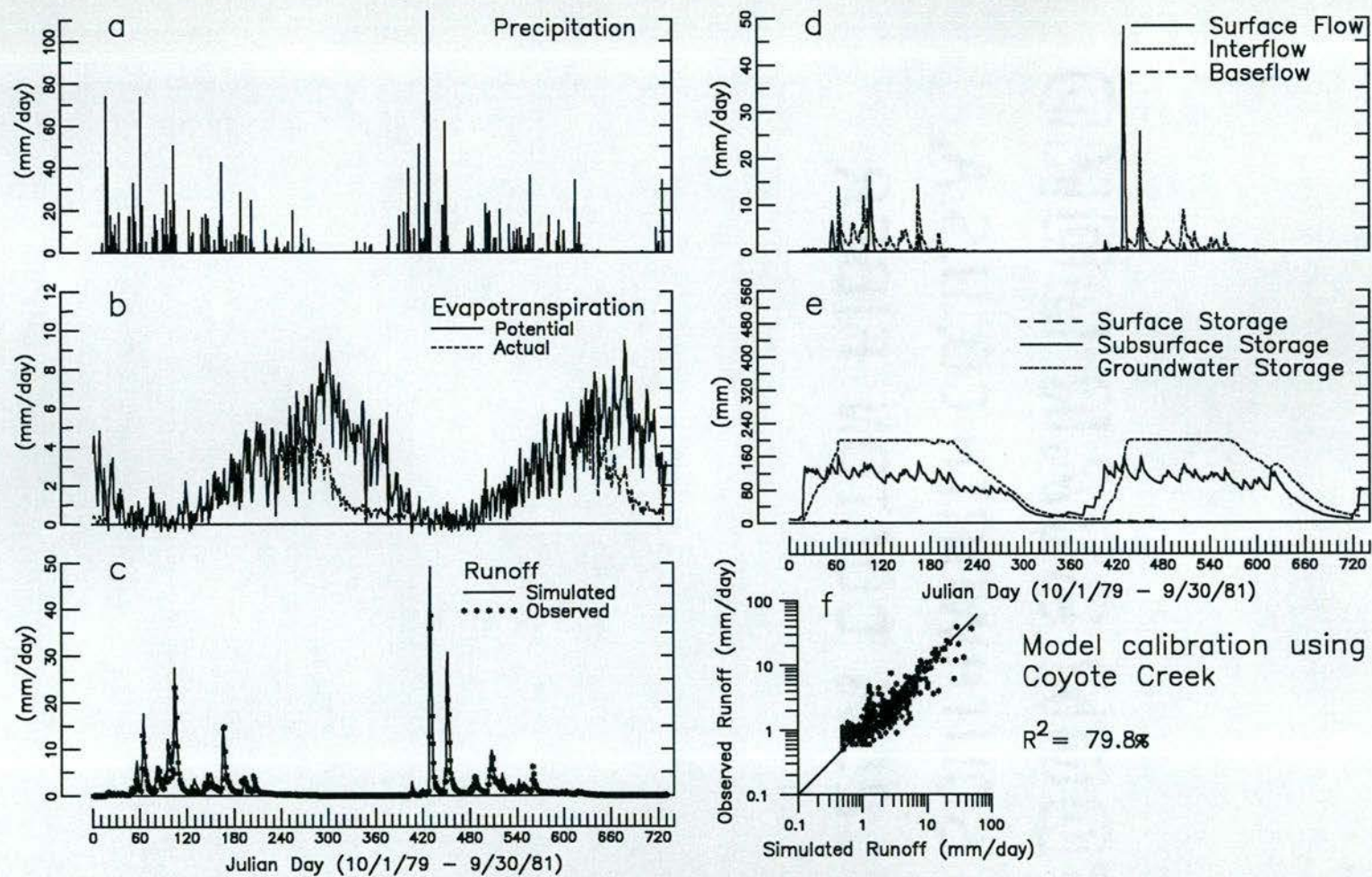


Figure 6. Results of the model calibration on the Coyote Creek watershed.

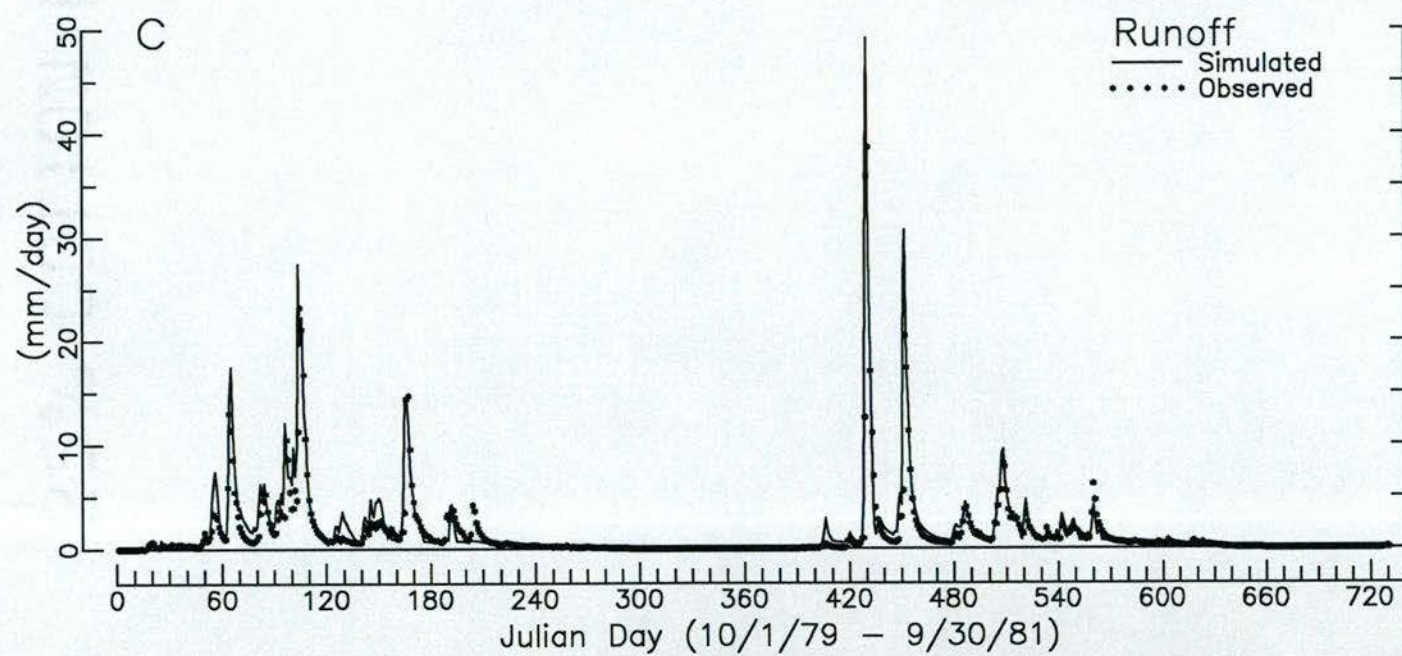


Figure 7. Simulated and observed runoff from the model calibration on the Coyote Creek watershed (from Figure 6(c)).

and the fairly tight fit of the simulated and observed values to the one-to-one line (Figure 6(f)), provided evidence of the model's satisfactory performance.

Figure 6(d) displays the three components of channel flow which are combined by the model to create total simulated runoff. Surface flow, composed of overland flow that reaches the channel, provides a large portion of the runoff during times when the model's storage reservoirs are near saturation. Interflow combines with surface flow to make up the bulk of the large flows and by itself forms most of the medium and low flows. Interflow's large volumes relative to the surface flow component accurately reflect the dominance of the subsurface flow regime for watersheds in this region (Booth, 1991; Satterlund and Adams, 1992). Baseflow volumes are never significant in the model output. As discussed earlier, the division of subsurface flow into interflow and baseflow is somewhat artificial. Both the baseflow and interflow components of the model output should be considered to compose the low discharge stream flows.

For large events that generate both surface flow and interflow, the interflow peaks created by the model lag slightly behind the surface flow peaks. This lag simulates the expected relationship of these flows; water that is delivered to the channel by overland flow moves much more quickly than water that must first infiltrate and then move through the soil to reach the channel.

Figure 6(e) shows the daily storage levels simulated by the model. Surface storage is the smallest of the three storage reservoirs and its volumes are barely visible in this figure. Surface storage can be quickly depleted by evapotranspiration, particularly when potential evapotranspiration is high.

Subsurface storage volumes represent the water content of the soil zone. Subsurface storage increases quickly at the beginning of the wet season though the very rapid rise at the beginning of the first water year may be an artifact of the initial conditions

in the model (Table 2). The many peaks in the subsurface storage curve reveal the model's sensitivity to individual runoff-generating precipitation events.

Groundwater storage may be considered to represent the elevation of the groundwater table. It rises gradually to a plateau during the wet season, which corresponds to the maximum parameter value for groundwater storage (GWMax), and then declines slowly throughout the summer dry season. The model does a good job of revealing the differences between subsurface storage and groundwater storage. The subsurface storage reservoir is much more sensitive than the groundwater reservoir to individual precipitation events. The subsurface also becomes saturated more rapidly at the beginning of the wet season and then dries more quickly during the summer.

A scatter plot of simulated and observed runoff (Figure 6(f)) indicates that the model has a slight tendency to overpredict, particularly at higher runoff levels. One possible explanation for this is the use of non-local meteorological data from the Willamette Valley as the model input data. This possibility is discussed in more detail in Appendix C.

Summary of the Model Calibration

The model calibration results showed good agreement between the simulated and observed runoff curves which was the primary criterion for calibration success. In addition, there were a number of other aspects of the model output that supported the calibration. These included the general agreement between the simulated data series and observed seasonal wet and dry cycles. Particularly important for the calibration were the emergent properties of the model's evapotranspiration and storage components. Actual evapotranspiration showed a declining trend through the summer dry period and the level of the groundwater storage lagged in a realistic fashion behind subsurface storage

throughout the year, even though there was nothing in the model code explicitly dictating this response.

Model Application to the Willow Creek Watershed

The Willow Creek watershed is a small rural basin that opens into the southern end of the Willamette Valley (Figure 1). Willow Creek itself is an intermittent stream that drains approximately 9.8 km^2 (3.8 mi^2) at the location of the gaging station on its main branch. Application of the rainfall-runoff model to the Willow Creek basin was necessary to calibrate the model before simulating the hydrologic effects of urbanization. It also provided the opportunity to test the model on a smaller basin using data from a different time period than was used for the model calibration on Coyote Creek.

Model Inputs

Meteorological Input Data for Willow Creek

Meteorological input data were collected from NCC monthly weather summaries for the Mahlon Sweet Field weather station (NCC, 1988, 1989, 1990). As can be seen in Figure 8, the pattern of the precipitation regime for water years 1989 and 1990 was distinctly different from the precipitation pattern of the two-year period used for the Coyote Creek calibration (Figure 5). This variation between the two records provided an opportunity to test the model's adaptability to different input data.

Hydrological Data for Willow Creek

A gaging station was installed on the main branch of Willow Creek approximately 700 m upstream of its confluence with Amazon Creek (Figure 1). Stream stage was

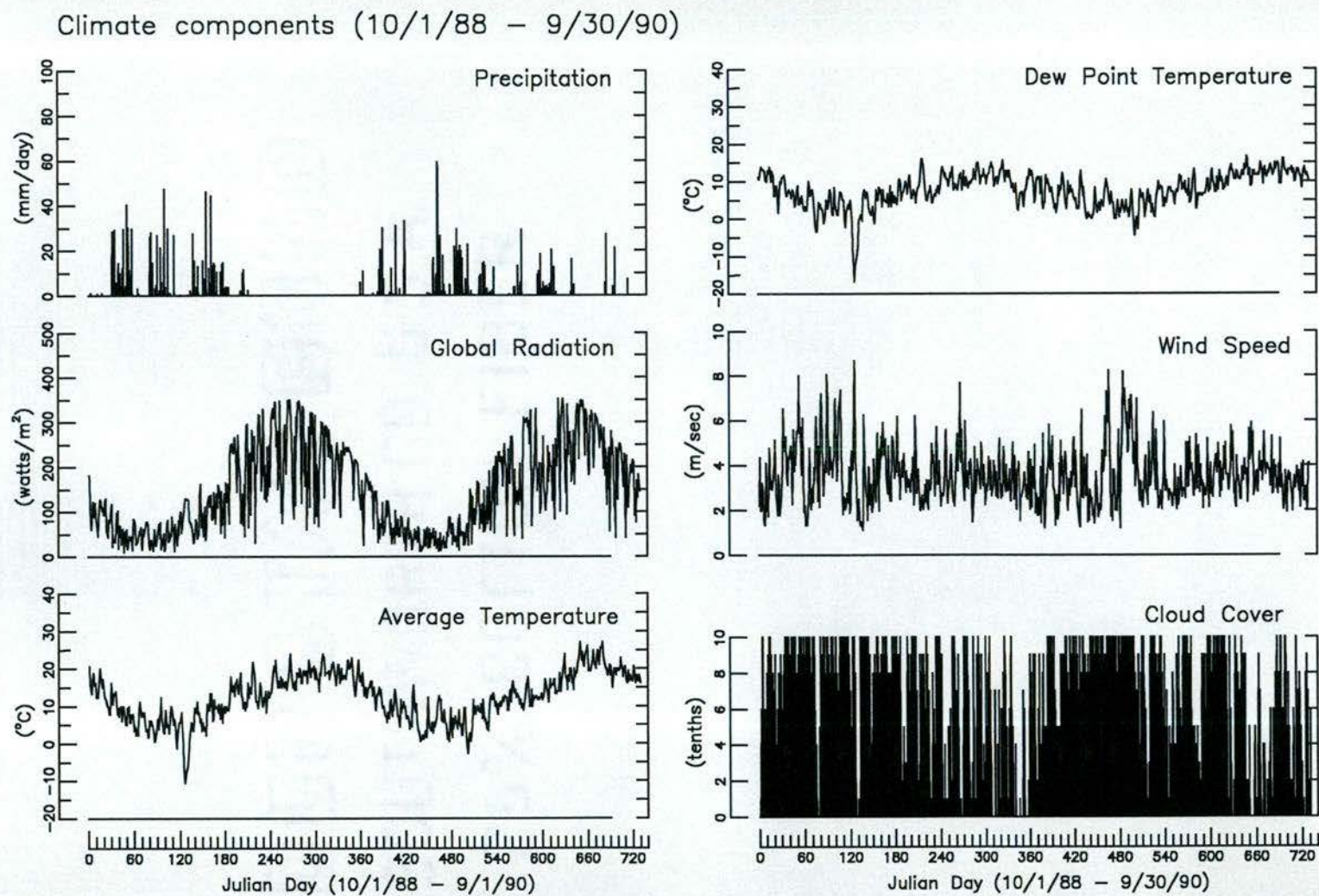


Figure 8. Meteorological input data for water years 1989 and 1990 (NCC, 1988, 1989, 1990).

automatically recorded at 15 minute intervals. Velocity measurements taken during various times of the wet season were used to construct a rating curve for the stream (Appendix D). Channel flow measurements were augmented by visual observations of stream flow, overland flow, and surface storage. Along this reach, and for an additional 200 m upstream of the gaging station, the stream channel has been ditched to increase its flood flow capacity. At the time of this study, grasses and emergent vegetation had recolonized the channel and sediments had formed a stair-step profile of small ponds and berms along this reach.

Parameter Values for Willow Creek

Sensitivity tests that varied the parameter values chosen during the Coyote Creek calibration suggested that these parameter values also produce the best model results for Willow Creek (Table 2). The parameters in the model reflect the physical characteristics of the surface topography and the subsurface matrix of the basin. Field observations, available data, and the close proximity of Willow Creek to Coyote Creek indicate that the two basins are physically similar, and this finding supported the use of the same parameter values in the model application to Willow Creek.

Results of the Model Application to Willow Creek

The timing of individual discharge peaks was well matched by the model as was the seasonal variation in runoff (Figure 9). The volume of runoff, however, was systematically overpredicted. This overprediction is easily observed in the plot comparing simulated and observed runoff (Figure 10) where the simulated runoff reaches higher values than the observed runoff data for the same precipitation events. Overprediction is also reflected by the large number of points lying below the one-to-one line of the plot of

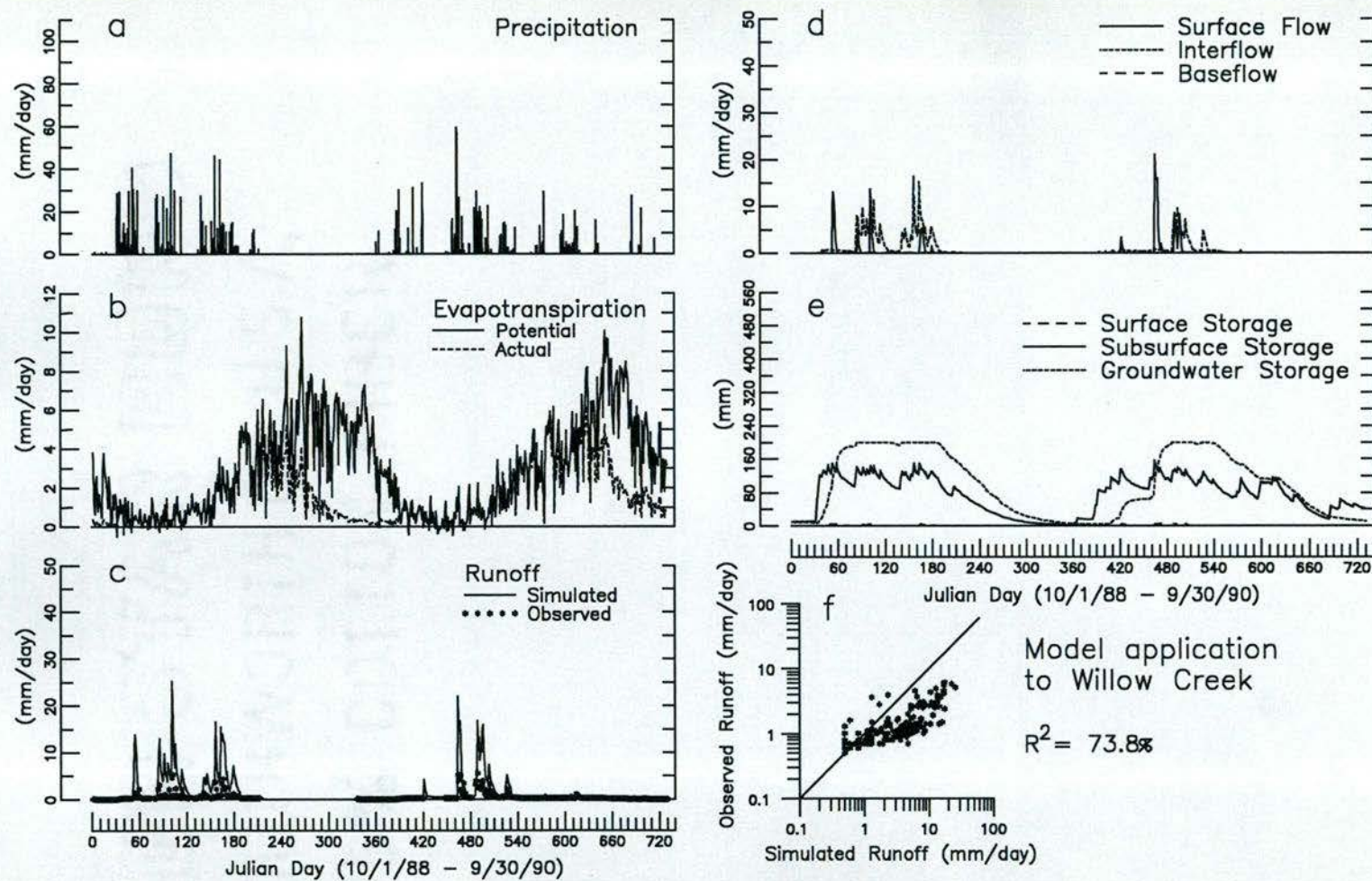


Figure 9. Results of the model application to the Willow Creek watershed.

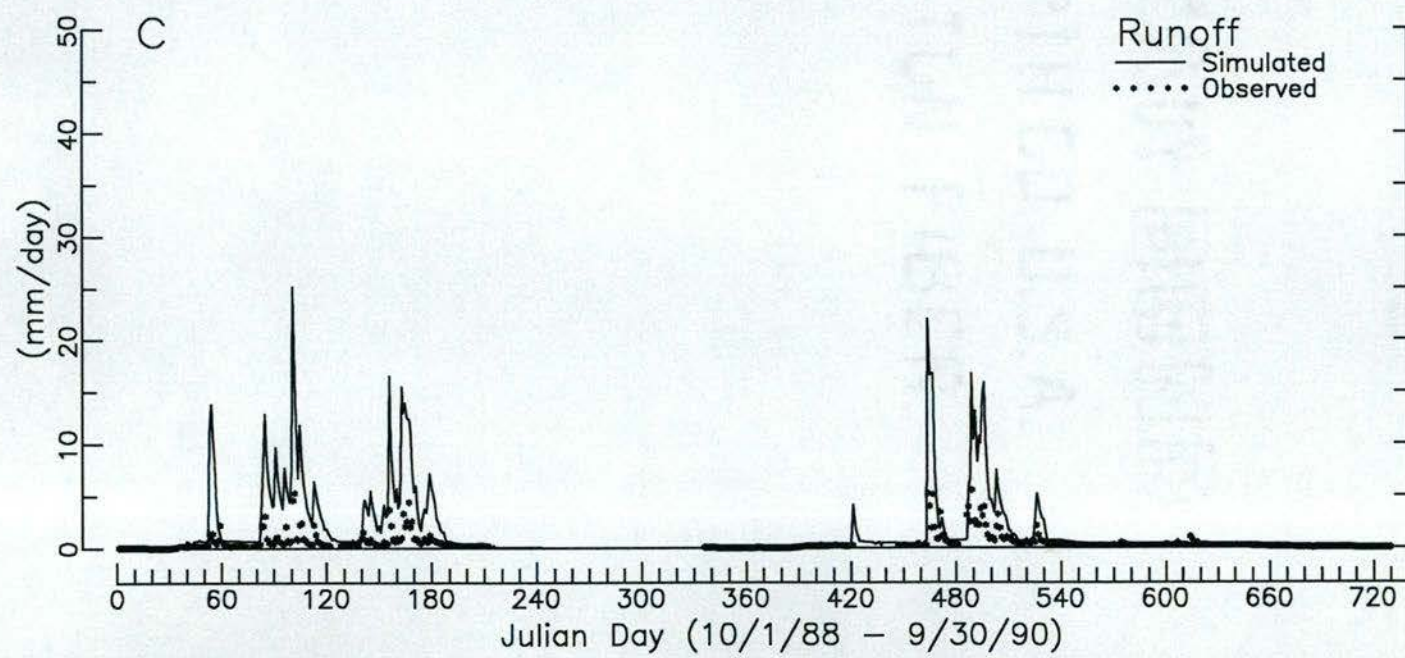


Figure 10. Simulated and observed runoff from the model application to the Willow Creek watershed (from Figure 9(c)).

simulated runoff and observed runoff (Figure 9(f)). The R^2 value for the regression analysis of simulated and observed runoff was 73.8%, which is significantly lower than the 79.8% from the Coyote Creek model calibration results discussed above.

Summary of the Model Application to Willow Creek

The less-good fit of the model was not expressed in the timing of the runoff peaks but in the volume of runoff simulated. This discrepancy between the simulated and observed runoff values was quite large; for some precipitation events the model simulated 2-3 times more runoff than was actually observed. There were two potential sources for this error in the simulated runoff: model inadequacy and data errors. The first possibility explored was that the assumptions made about the watershed, and upon which the conceptual framework and algorithms of the model were built, were all or in part incorrect. The model results suggested that the model expected more precipitation to reach the gaging station as runoff than was being measured there. Beaver ponds were known to exist in the basin, and further field work discovered a significant number of seasonal beaver ponds forming an extensive reservoir system. These ponds retain large quantities of water at certain times of the year which would decrease runoff from the basin. The model was therefore modified to account for the effects of the beaver ponds. The results from the application to Willow Creek of the modified model are presented in the next section.

The possibility of data error was also investigated. Evidence was found suggesting that the lee effect of the southern Willamette Valley hills suppresses local rainfall by up to 30% compared with measurements of the same precipitation events at the Mahlon Sweet Field station in the valley (OTAK, 1990a). If the observed discharge is the result of less precipitation than the model receives in its input data set, it is not surprising that the model

overpredicts runoff. The implications of this finding are discussed more fully in Appendix C.

The discovery of the beaver ponds in particular emphasizes the need for model calibration and the importance of using different basins in the model calibration process. If only data from Willow Creek had been used in building and running the model, attempts would have been made to reduce the simulated error by adjusting parameters and/or modifying the model functions. If these changes had reduced the error to an acceptable level there would have been no indication that additional fieldwork should be carried out and the conceptual flaw in the model structure, the lack of beaver ponds, would have remained.

Simulation of Beaver Ponds for the Willow Creek Watershed

A number of beaver dams exist along Willow Creek upstream from the point where stage measurements were collected for this study. These dams create seasonal ponds which fill in the winter and are often dry by the end of summer. The ponds form a significant storage reservoir within the Willow Creek basin and are an important component of the watershed's hydrology.

The storage volumes and rates of discharge of beaver ponds fluctuate as beavers modify existing dams, build new ones, and let others decay. Thus, at any given time, the response of Willow Creek to a precipitation event of a particular size may vary depending on the amount of empty storage available in the ponds and the current number and condition of dams. Modeling this temporal and spatial complexity in detail was beyond the scope of this project. An attempt was made, however, to assess the general significance of beaver ponds on the hydrology of the Willow Creek watershed by creating

a beaver pond subroutine for the rainfall-runoff model and observing its influence on the model results.

Changes to Model Structure

Beaver dams on Willow Creek have a number of effects on the watershed's hydrology. When the ponds are not full they retain stream flow, decreasing downstream flow volumes. Even when the ponds overflow their dams, the rate of discharge will be somewhat slower than unponded stream flow because the ponds detain the water moving through them. Where the beaver dams are permeable, pond storage will contribute to stream flows. Beaver ponds may contribute to subsurface and groundwater recharge and thus indirectly augment stream flows. The large surface area of the ponds will also add to the total evapotranspiration from the basin.

Research on beaver dams in Canada identified four general ways by which stream flow is routed past beaver dams: by flowing over the crest of the dam (overflow), or by flowing through the dam (gap flow, underflow and throughflow) (Woo and Waddington, 1990). Dams actively maintained by beavers were better at impounding water, and water moving past these dams tended to do so by flowing over the tops of the dams when the ponds were full (overflow). As dams decayed, gaps allowed water to move through the dams (gap flow and underflow). The oldest dams tended to have the least structural integrity and were relatively porous, allowing water to flow through them (throughflow). Woo and Waddington also found that of the four dam types, an underflow dam was best able to attenuate peak storm flow because the underflow gap restricted the volume of discharge from the pond to the stream.

A simple beaver pond subroutine was added to the rainfall-runoff model to simulate the effect of pond storage on stream flow (Figure 2). The subroutine represents

the aggregate response of all the beaver ponds in the watershed by simulating one large pond. A parameter, RunoffMin, sets the minimum discharge of water from the simulated pond to the channel. This parameter is meant to represent water that flows through porous dams to the channel below, and water from the beaver ponds that infiltrates through the pond banks into subsurface storage and then moves back into the channel as baseflow further downstream. If the amount of runoff calculated by the model for a particular day exceeds RunoffMin and the simulated pond is not yet full, then 75% of the difference between Runoff and RunoffMin is added to pond storage,

$$\text{ResStore} = \text{ResStore} + (.75 * (\text{Runoff} - \text{RunoffMin})),$$

and the remaining 25% is combined with RunoffMin to form the total runoff for that day by the equation

$$\text{Runoff} = \text{RunoffMin} + (.25 * (\text{Runoff} - \text{RunoffMin})).$$

A user-specified parameter, ResStoreMax, is used to define maximum pond storage capacity. If this capacity is exceeded, the excess water is routed directly into the channel, thereby representing water flowing over the top of beaver dams.

Model Inputs

Meteorological and Hydrological Input Data

Meteorological input data were collected from NCC monthly weather summaries for the Mahlon Sweet Field weather station (NCC, 1988, 1989, 1990). Both the meteorologic and hydrologic inputs were the same as those used in the model application to Willow Creek.

Parameter Values for Beaver Pond Simulation

The values for the user-specified parameters used in the initial application of the model to Willow Creek were not changed. RunoffMin and ResStoreMax were the two new parameters added to the model with the beaver pond subroutine (Table 2). RunoffMin was given a value of 0.2 mm/day because this was the level of sustained summer low flows in the observed runoff data for Willow Creek. ResStoreMax was set at 430 mm; this value was chosen by observing the effects of different values of ResStoreMax on the model output and choosing a value that optimized the model results.

Results of the Beaver Pond Simulation

Including the beaver pond subroutine in the model reduced the volume of runoff simulated by the model which in turn created a better fit between simulated and observed runoff (Figures 11 and 12). This increased fit of volume was accomplished while maintaining the agreement in the timing of runoff peaks. The 1-to-1 plot in Figure 11(f) displays a tighter clustering of points showing the extent to which overprediction has been reduced. The R^2 value for this model run was 74.3% as compared to 73.8% for the application of the model without beaver ponds to Willow Creek. Total evapotranspiration increased with the addition of the beaver ponds; the increase is particularly obvious during the end of the dry season when the water stored in the ponds was used to satisfy potential evapotranspiration.

Beaver ponds increase the amount of available storage in a basin by ponding water. One of the effects of beaver ponds on runoff, therefore, should be to increase the time between the beginning of the wet season, when storage reservoirs in the basin are filling and the stream is not responding to individual precipitation events, and that point in time when the various storage components are sufficiently full that storm peaks can be

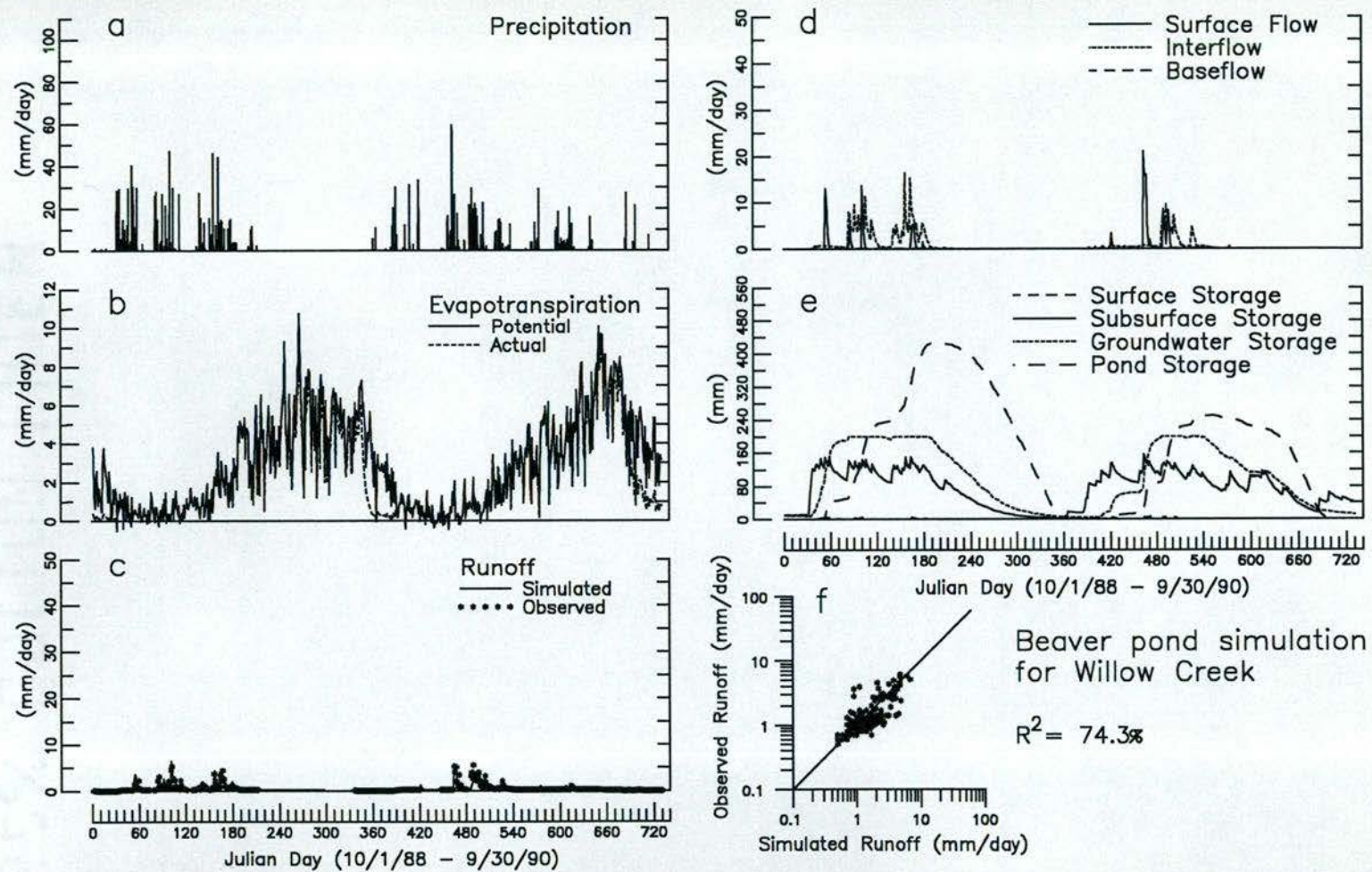


Figure 11. Results of the beaver pond simulation for the Willow Creek watershed.

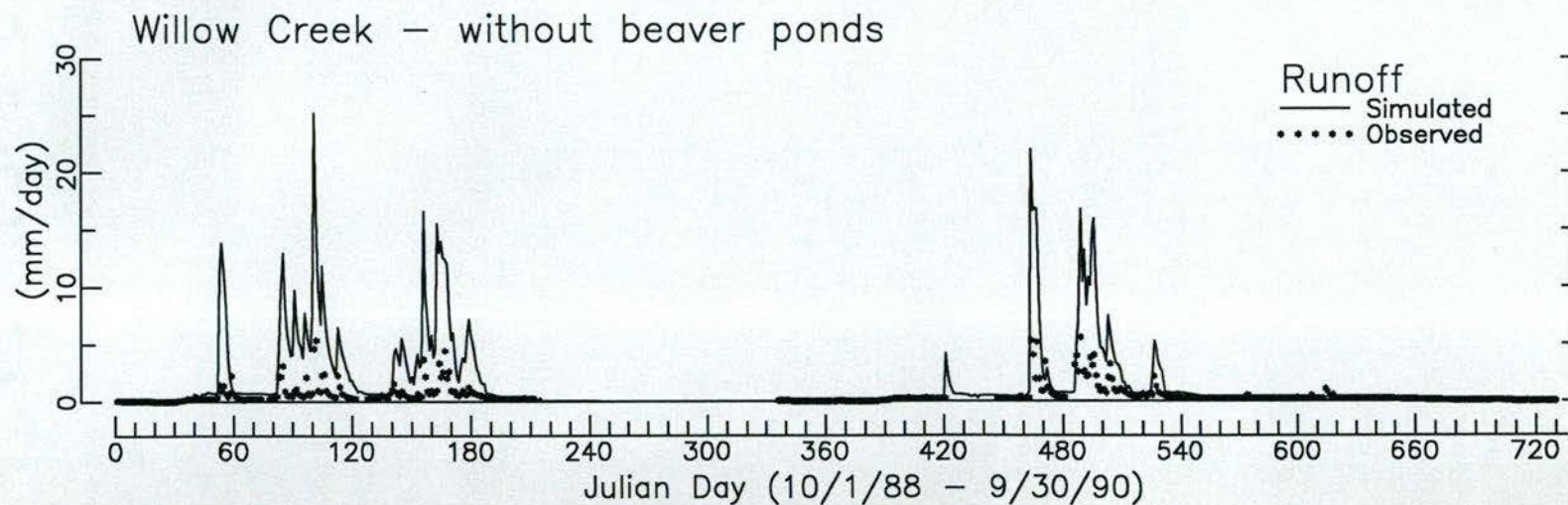
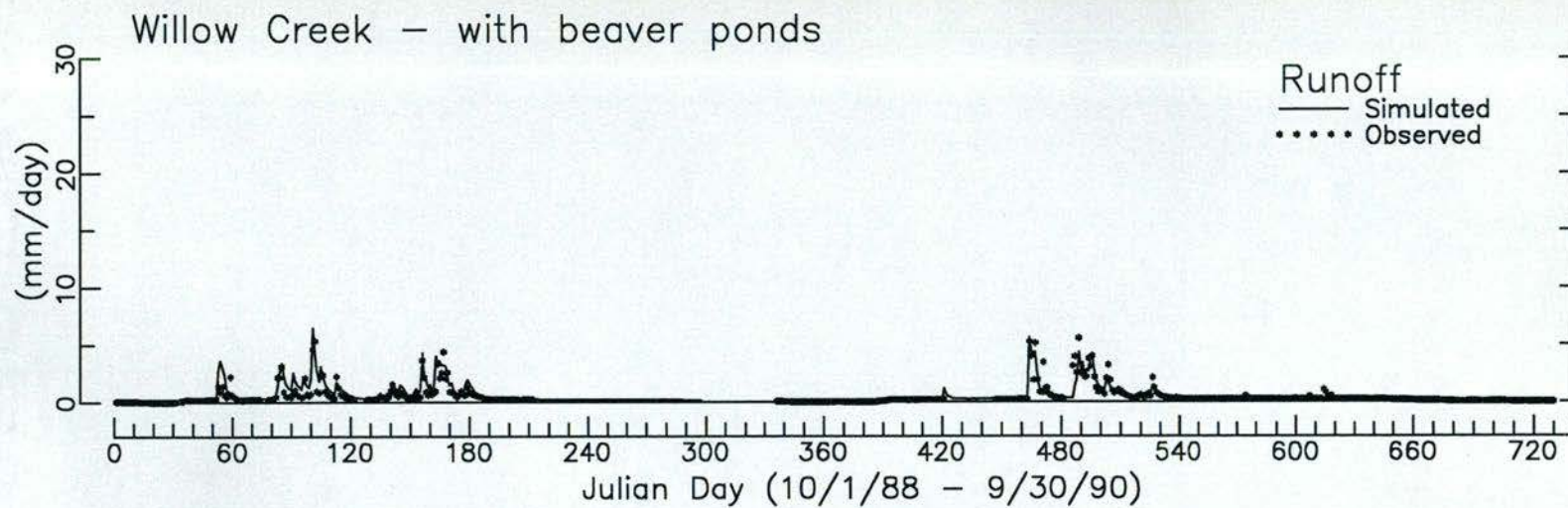


Figure 12. Willow Creek simulated and observed runoff from model runs with and without the beaver pond subroutine (from Figures 11(c) and 9(c)).

observed in the plot of runoff for the basin. Similarly, the presence of beaver ponds should damp out runoff peaks at the end of the wet season. In Figure 12, the model with beaver ponds does create a better match between the simulated and observed runoff curves during these times.

The model results also revealed a significant flaw in the beaver pond subroutine; the beaver pond storage volume simulated by the model never reaches the value of ResStoreMax (Figure 11(e)). Thus the model's simulated beaver pond never "overflows" into the stream channel. This contradicts field observations at Willow Creek of beaver ponds overflowing their dams during the wet season. The ResStoreMax parameter value that produced the best model results was 430 mm of water per watershed area which is equal to a total volume of water of approximately 4,214,000 m³. The total volume of storage in the Willow Creek beaver ponds has not been measured; however, three beaver ponds in the basin have been surveyed. Their volumes when full to dam height were calculated using the average area method which yielded values of 300 m³ (10,625 ft³), 517 m³ (18,306 ft³), and 474 m³ (16,772 ft³) for a total storage volume of 1,291 m³ for all three (J. B. Fisher and S. Shafer, unpublished data). Additional fieldwork is needed to determine the approximate volume of water contained by all the beaver ponds in the basin but it is likely that the actual reservoir storage volume will be much less than the current value of ResStoreMax. These preliminary field measurements raise the question of whether the peak flow reductions observed in the model results can be attributed to beaver ponds, or simply reflect the use of an unrealistic pond storage parameter.

Summary of Beaver Pond Simulation

The beaver pond subroutine succeeded in reducing a large part of the overprediction by the model and produced a better fit between the model's simulated and

observed runoff. The results imply that beaver ponds may be a significant component of Willow Creek's hydrology. Conclusions about the particular hydrologic effects of the beaver ponds, however, can not be drawn from the model results because the beaver pond subroutine was too simple to successfully model beaver pond flows and storages.

Model Calibration of the Urbanization Subroutine on the Amazon Creek Watershed

One of the most common types of landuse change affecting hydrologic systems is the urbanization of watersheds. Construction of buildings and roads increase a watershed's impermeable area, and the accompanying infrastructure, such as storm sewers and drainage ditches, alter natural flow pathways. Surface impermeability and new flow dynamics increase both the volume and speed at which water leaves a watershed (Booth, 1990, 1991).

Part of the Willow Creek basin lies within the urban growth boundary of Eugene, Oregon (WEWSAS, 1991). This area includes a remnant of wetland prairie which is a part of The Nature Conservancy's Willow Creek Preserve. Future urbanization in the watershed may affect the basin's hydrology in ways that will have negative effects on the wetland. A goal of this study, therefore, was to simulate the effects of urbanization on the rainfall-runoff relationship of the Willow Creek basin. To do this, an urbanization subroutine was added to the model structure and this modified model was then calibrated using data from an urbanized watershed, Amazon Creek.

Model Structure Modification for Urbanization

Amazon Creek is a small (55.2 km², 21.3 mi²), partially urbanized watershed which contains the Willow Creek basin (Figure 1). It was used to test the ability of the model's urbanization subroutine to simulate runoff under urbanized conditions. The

subroutine uses the percentage of impermeable area in the basin as the primary indicator of urbanization because of the direct effect impermeable areas have on a basin's hydrology. Impermeable areas are simulated using a user-specified parameter, ImpermeableProp, to set the percentage of the total estimated impermeable area for the basin. Precipitation is multiplied by this parameter to determine the amount of precipitation that will become urban runoff. This amount is then subtracted from precipitation and added directly to the surface flow component of total runoff. Routing the water through the model in this way simulates the fast delivery of water that falls on pavement, roofs, etc., and is channeled by ditches and storm sewers directly into a stream (Figure 2).

Model Inputs

Meteorological and Hydrological Data

Daily meteorological input data from water years 1980 and 1981 were collected from NCC weather summaries for the Mahlon Sweet Field station (Figure 5) (NCC, 1979, 1980, 1981). Daily stream discharge values for this period were obtained from the USGS gaging station on Amazon Creek (USGS, 1981, 1983).

Parameter Values

The same parameter values used for the Coyote Creek model calibration produced the best results for the Amazon Creek calibration (Table 2). This may reflect the general physical similarities of the two basins. The new urbanization subroutine parameter, ImpermeableProp, was given a value of 0.2 based on estimates of impermeable area in the basin (OTAK, 1990b).

Results of the Urbanization Subroutine Calibration

The model results of the urbanization subroutine calibration are displayed in Figure 13. There is good agreement in the timing of individual peaks although the model still shows a tendency to overpredict (Figures 13(f) and 14). The R^2 value for the regression analysis of simulated and observed runoff is 79.6%. This is sufficiently close to the 79.8% from the Coyote Creek calibration results to consider the calibration of the urbanization subroutine as successful as the initial calibration of the model.

By comparing the observed runoff data of Amazon Creek (Figure 13(c)) with the observed runoff data of Coyote Creek (Figure 6(c)) one can see the effect of urbanization on a watershed's rainfall-runoff relationship. The model runs for both basins used the same precipitation series of input data, water years 1980 and 1981, and yet many more runoff peaks are present in the observed Amazon Creek runoff. This increased sensitivity to individual precipitation events is consistent with the hydrology of urbanized basins (Booth, 1991). The success of the urbanization subroutine is reflected in its ability to simulate these more frequent runoff events found in the Amazon Creek observed runoff data.

Summary of Urbanization Calibration

The model with the urbanization subroutine was able to satisfactorily simulate the rainfall-runoff relationship in the urbanized Amazon Creek basin. Of particular importance was the ability of the model to simulate the increased sensitivity under urbanized conditions of stream flow to precipitation events. Increased model sensitivity was accomplished while maintaining both the match of timing and frequency of discharge peaks of simulated and observed runoff and the overall fit to seasonal trends.

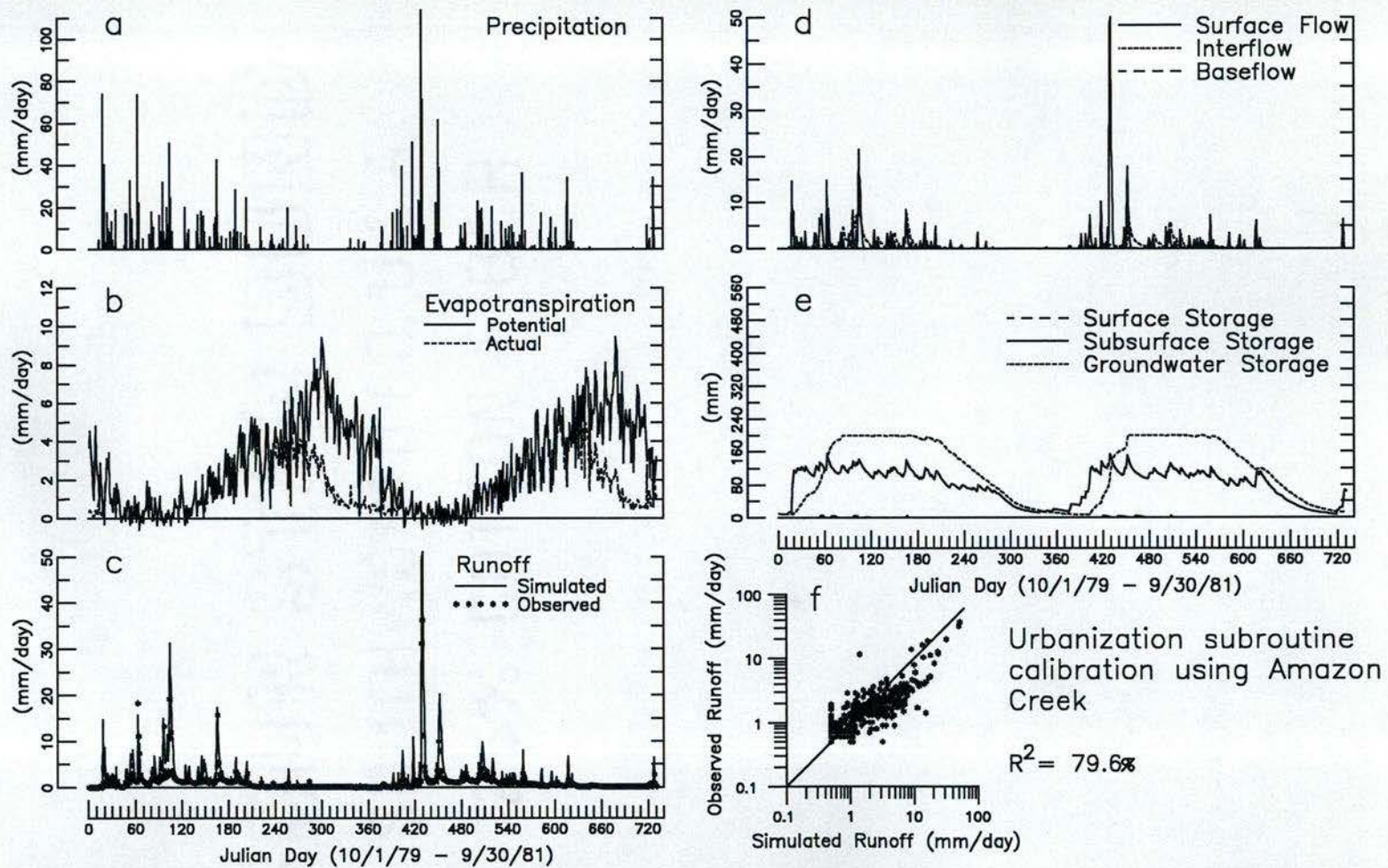


Figure 13. Results of the urbanization subroutine calibration on the Amazon Creek watershed.

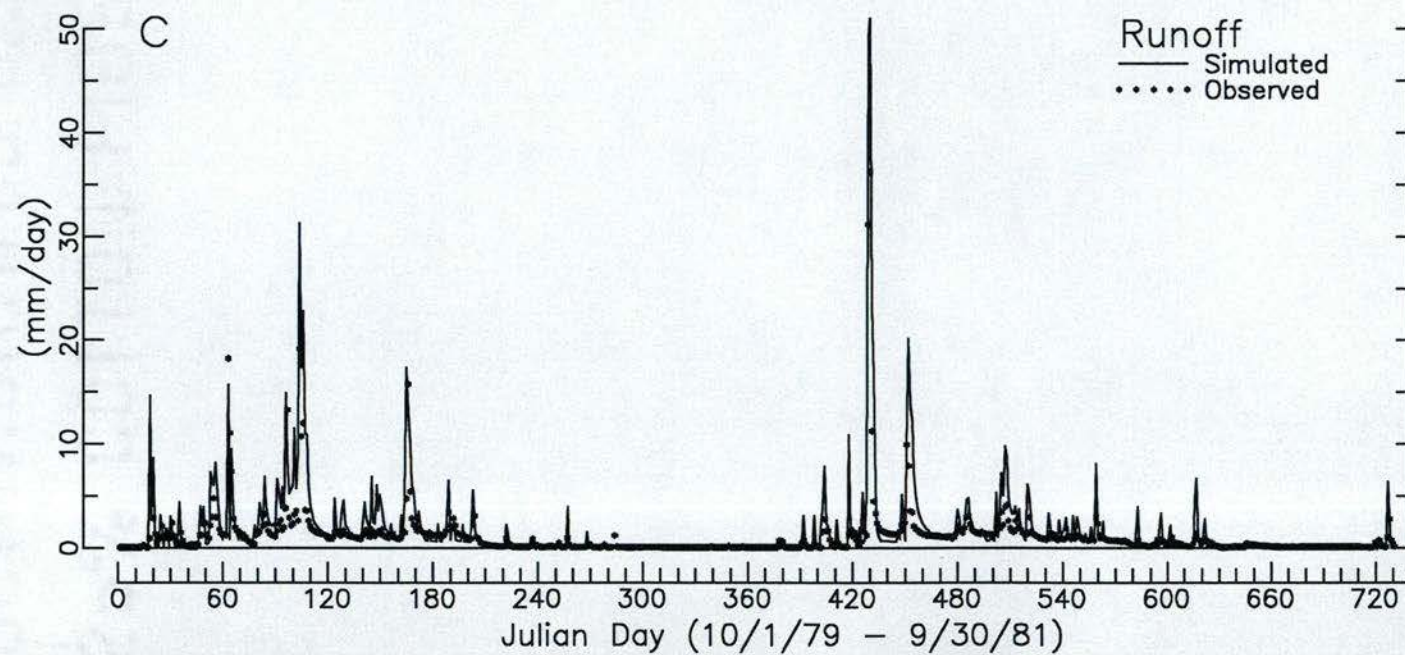


Figure 14. Simulated and observed runoff from the urbanization subroutine calibration on the Amazon Creek watershed (from Figure 13(c)).

Simulation of Urbanization of the Willow Creek Watershed

The Nature Conservancy Willow Creek Preserve lies within the urban growth boundary of Eugene, Oregon. Concern exists, as mentioned earlier, that urbanization in this basin might alter the local hydrology to such an extent that the Preserve's wetland prairie community would be negatively affected. The urbanization of the watershed was simulated in an attempt to discover the effect of urbanization on the rainfall-runoff relationship at Willow Creek.

The urban development predicted for the Willow Creek basin by Eugene's 1986 metropolitan plan could create an effective impervious area of approximately 20% (OTAK, 1990b). The effect of 20% estimated impermeable area for the watershed was therefore simulated using the urbanization subroutine calibrated on the Amazon Creek watershed.

Model Structure

The model schematic for this simulation consists of the rainfall-runoff model with both the beaver pond subroutine and the urban runoff subroutine discussed in the previous section (Figure 2). In this simulation, all the runoff from impermeable areas is routed through the beaver ponds.

Model Inputs

Meteorological and Hydrological Input Data

Meteorological input data were collected from NCC monthly weather summaries for the Mahlon Sweet Field station (NCC, 1988, 1989, 1990). The hydrologic inputs were the same as those used in the model application to Willow Creek (Figure 8).

Parameter Values

The impermeable area parameter was set at 0.2 to match the estimated effective impermeable area predicted for the basin under future urbanization (OTAK, 1990b). The remaining parameter values are the same for the Willow Creek urbanization simulation as were used for the beaver pond simulations (Table 2).

Results of the Urbanization Simulation

The urbanization simulation results are displayed in Figures 15 and 16. Simulated runoff series are compared in Figure 17 from model runs with and without impermeable area. As was observed in the model results from Amazon Creek, one of the major effects of urbanization on Willow Creek runoff is to increase the number and size of runoff peaks. Of particular note are the changes at the beginning and end of the wet season. Whereas under non-urbanized conditions (0% impermeable area) these periods show a very constant low level of runoff, in the urbanization simulation they contain numerous runoff peaks. The additional peaks imply that under urbanized conditions precipitation that was previously stored in the basin will be channeled out of it.

If we examine a simple water budget for the Willow Creek basin,

$$\Delta \text{Storage} = \text{Precipitation} - \text{Evapotranspiration} - \text{Runoff},$$

we find that for the two-year study period there is an overall simulated change in total storage of +62.1 mm for Willow Creek with beaver ponds, and that this value drops to +49.6 when the urbanization subroutine is added. This is a decrease of approximately 20% and represents water lost from the basin under the simulated urban landuse conditions.

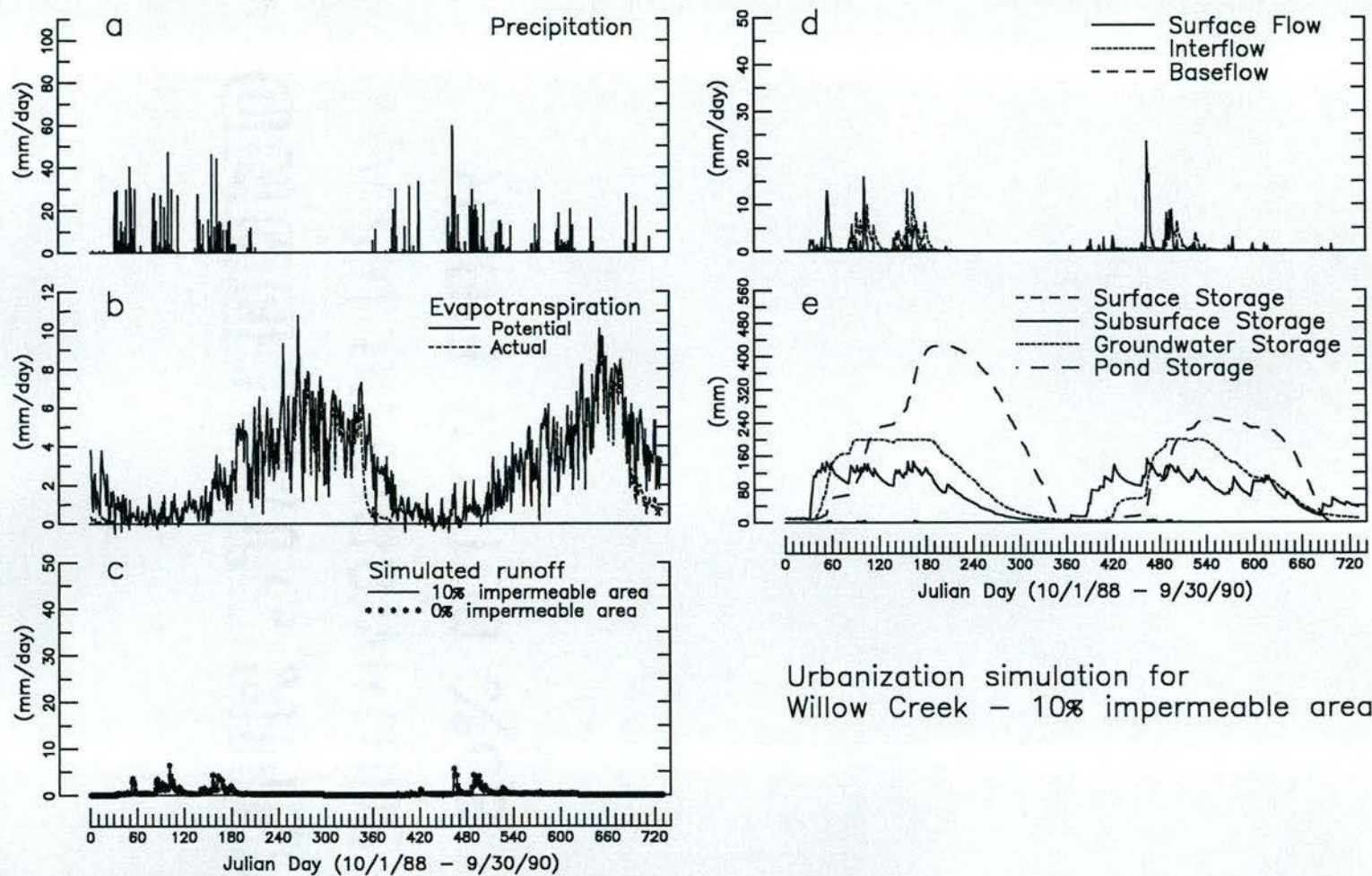
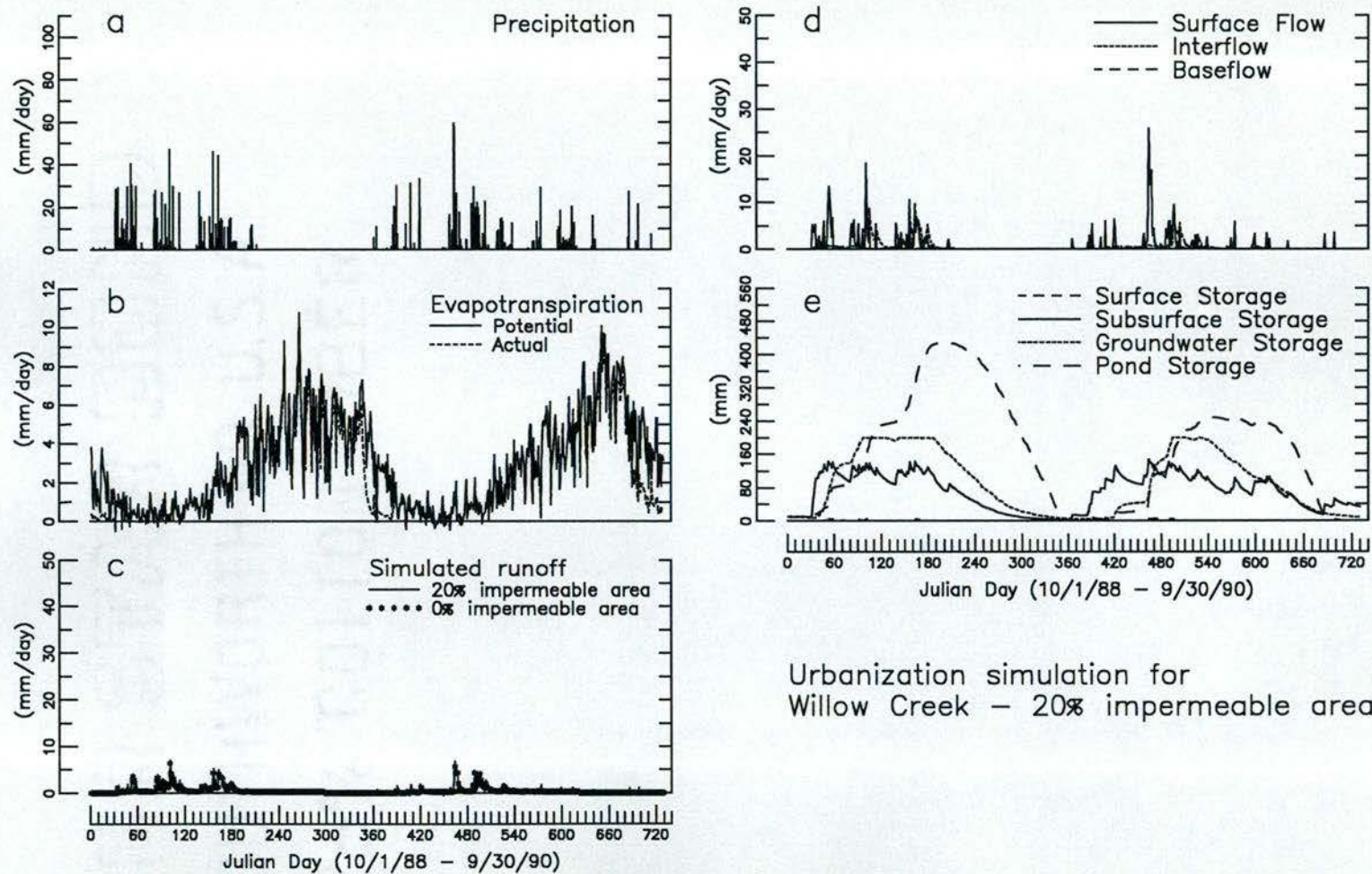


Figure 15. Results of the simulated urbanization of the Willow Creek watershed assuming 10% impermeable area. Both the beaver pond and urbanization subroutines were used during this model run.



Urbanization simulation for
Willow Creek - 20% impermeable area

Figure 16. Results of the simulated urbanization of the Willow Creek watershed assuming 20% impermeable area. Both the beaver pond and urbanization subroutines were used during this model run.

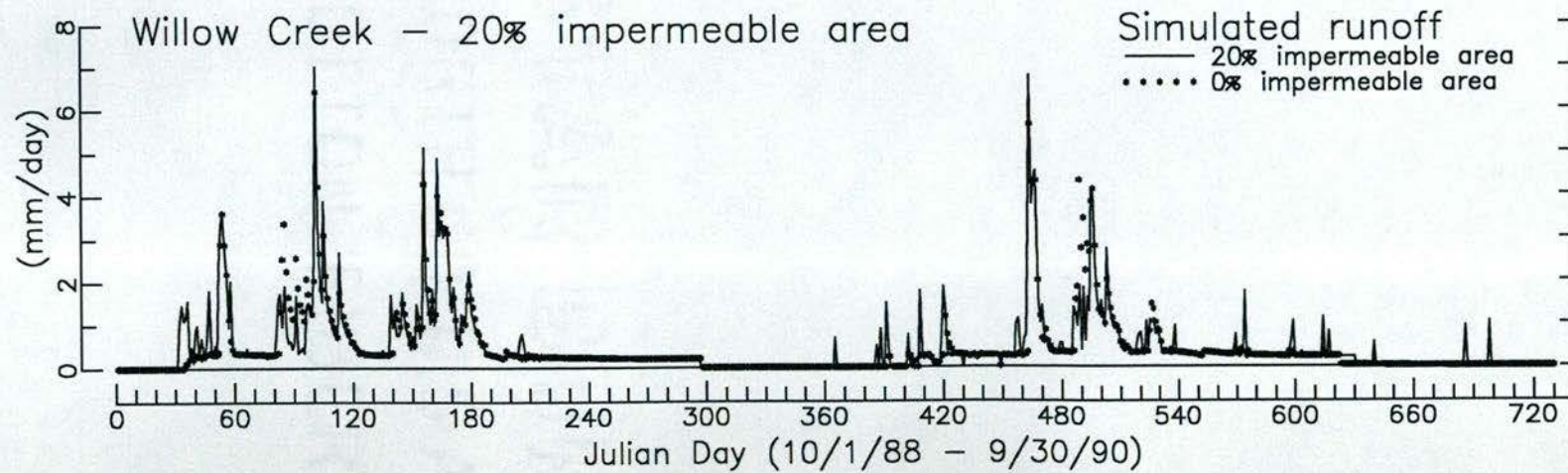
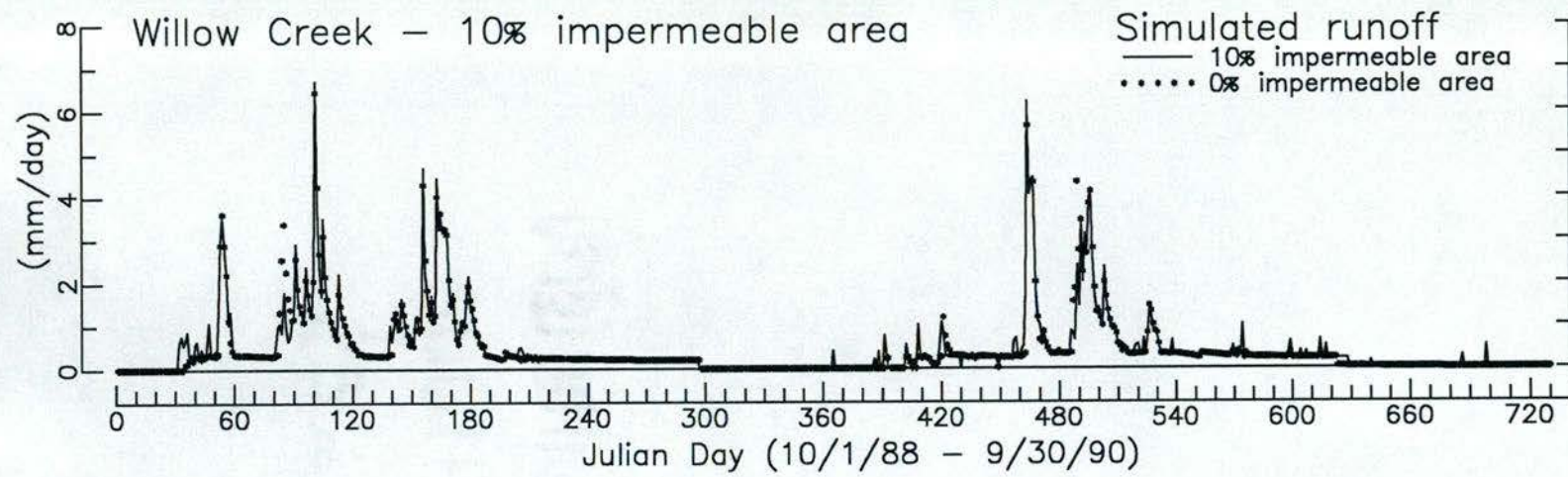


Figure 17. Simulated runoff from Willow Creek under urbanization scenarios of 10% and 20% impermeable area.

The urbanization subroutine assumes that all urban runoff is routed to the Willow Creek channel. If under urbanized conditions some or all of the urban runoff was routed out of the basin via storm sewers, the resulting runoff peaks would be smaller. The urbanization subroutine also assumes that all urban runoff moves through the beaver ponds. If urban runoff were to enter the channel below the beaver ponds it would augment the model's simulated runoff peaks. This can be seen in Figure 18 which presents model results from an urbanization simulation for the Willow Creek basin without beaver ponds. Figure 19 compares simulated urbanized runoff from model runs with and without beaver ponds.

Summary of Urbanization Simulation

The model results indicate that the effects of additional urbanization in the Willow Creek watershed would significantly increase runoff, and decrease the amount of water retained in the basin. These results correspond with what is known from the literature about the hydrology of urbanized basins (Booth, 1990).

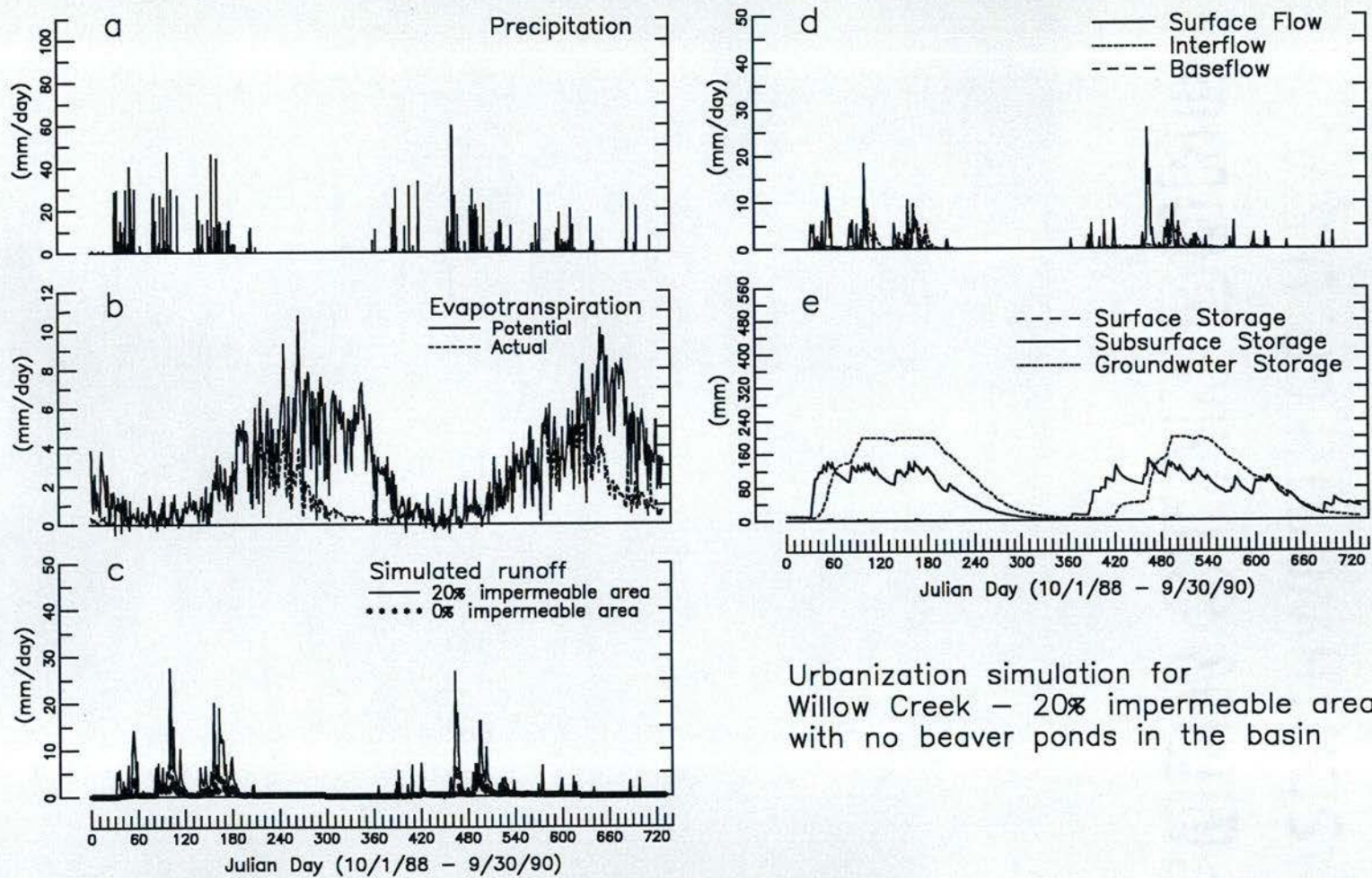


Figure 18. Results of the urbanization simulation for Willow Creek with 20% impermeable area and no beaver ponds in the basin.

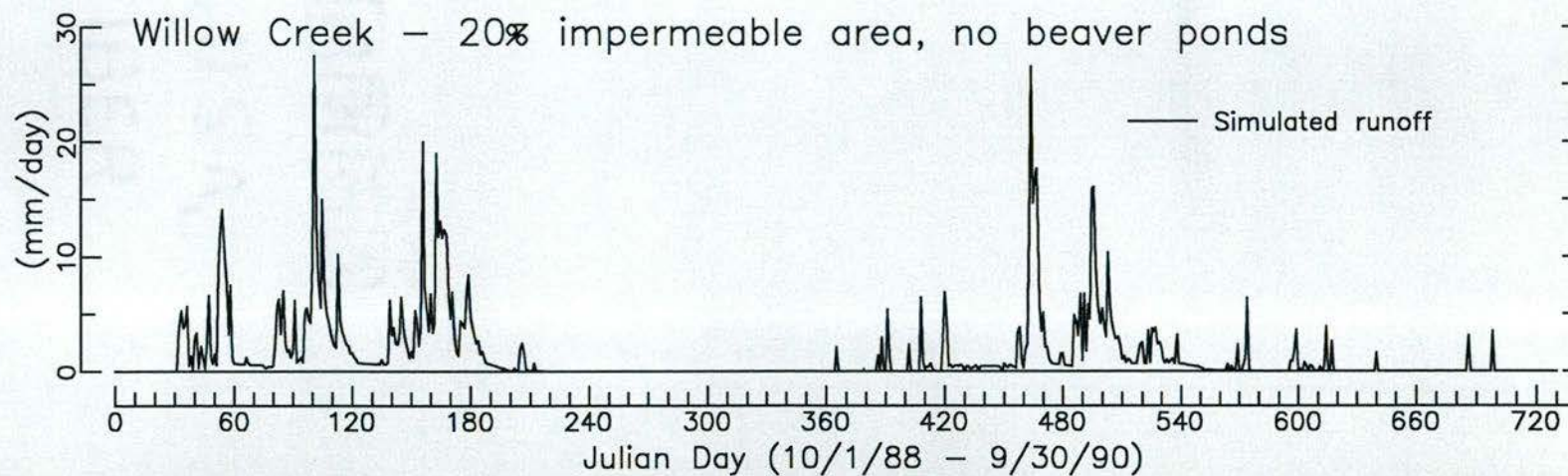
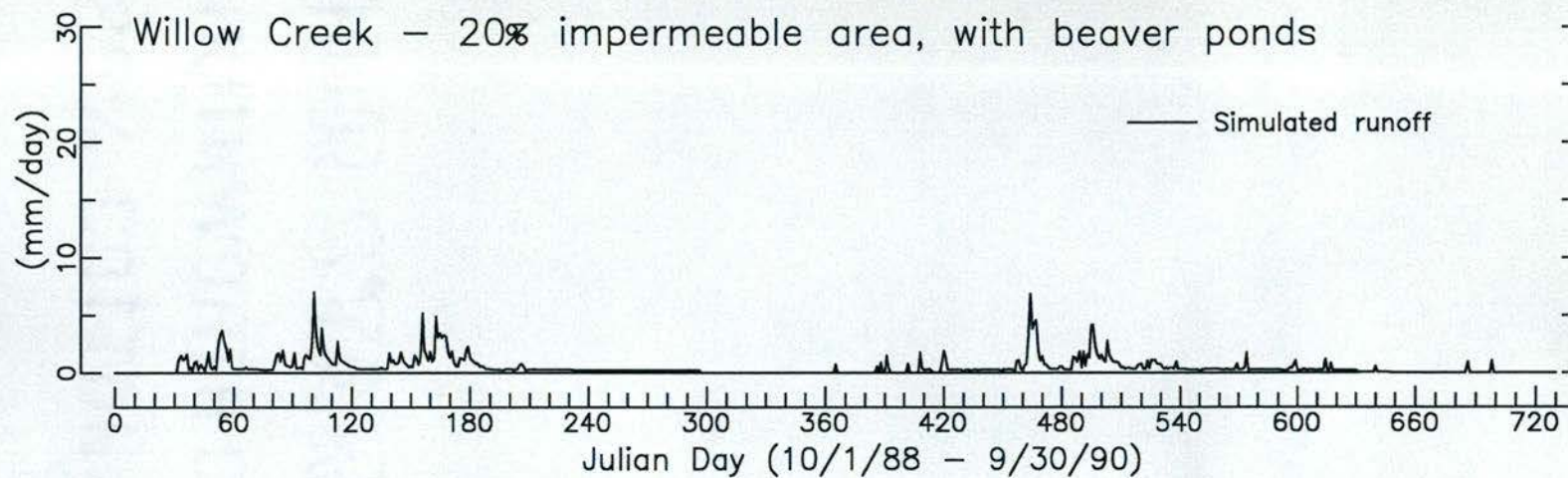


Figure 19. Simulated runoff for Willow Creek from model runs simulating urbanization with and without beaver ponds in the basin.

CHAPTER V

DISCUSSION

Performance of the Rainfall-Runoff Model

The rainfall-runoff model used in this study proved to be a useful tool for exploring the hydrologic regime of small basins. The model was able to adequately simulate the runoff from the three study basins which varied in both their size and landuse characteristics. In all model runs, the response of the model's flows and storages to individual precipitation events was good. The model simulation results consistently reproduced the seasonal wet-dry cycles of the study region and the timing of peak flows. The model was less accurate at simulating volumes of flow for individual precipitation events. The objective of the modeling effort, however, was to establish the relationship between rainfall and runoff and then simulate the magnitude and direction of change in runoff, not to predict actual flow volumes.

By revealing a discrepancy between simulated and observed runoff during the initial model application to Willow Creek, the rainfall-runoff model proved its value as a conceptual tool for testing assumptions about the physical world. In this case, my original assumption that beaver ponds were insignificant components of the hydrologic cycle of the Willow Creek basin--components that did not need to be explicitly modeled--was proven wrong. The model was also used to simulate changes to the rainfall-runoff relationship under different landuse conditions. It was successful at simulating the hydrologic effects of urbanization on the Amazon Creek basin, which in turn supported the use of the model in projecting the hydrologic response of the Willow Creek basin to future urbanization.

Model Limitations

Though more complex than McCuen and Snyder's original model, this model still uses a number of assumptions to simplify the hydrologic processes occurring in a watershed. Many important physical aspects of the hydrologic cycle, such as interception, channel roughness, variations in topographic slope, and changes in seasonal vegetation cover, are ignored. Others, such as the effect of soil type on infiltration rates, are considered to be homogeneous across the entire basin. The choice of which hydrologic components to simulate in the model and which to leave out was based on subjective decisions concerning which components were needed to best resolve the questions motivating this study. These simplifications limit the model's predictive ability and must be kept in mind when interpreting the model results.

The Effects of Beaver Ponds on Watershed Hydrology

The effects of beaver activities on watershed hydrologic flows and storages are not well understood (Woo and Waddington, 1990); very few field studies have addressed the specific hydrologic effects of beaver ponds and beaver dams, or the hydrologic changes which might occur as beaver alter riparian vegetation. Naiman *et al.* (1988) attribute this lack of research to the decimation of beaver populations in the last few centuries throughout much of their historical range. Estimates of beaver populations in North America prior to European settlement vary from 60-400 million (Seton, 1929: 447). Trapping for the fur trade led to extermination of beaver in many areas, though habitat loss to agriculture and urbanization was also a factor contributing to beaver population declines. Only during the latter part of this century have trapping pressures decreased, allowing beaver populations to stabilize and grow in certain regions. Estimates of current

numbers range from 6-12 million individuals (Naiman *et al.*, 1988) which is still far below historic levels.

It is during this recent era of depressed beaver populations that the science of hydrology has rapidly developed. Many of the field studies that have helped form our understanding of natural hydrologic systems have been carried out in watersheds where beaver were once dominant but have been reduced in numbers or removed (Naiman *et al.*, 1988). As a result, our knowledge of the hydrologic effects of beaver still comes largely from anecdotal stories and observations of the changes that occur when beaver reoccupy stream systems. Clearly, because of the historical decimation of beaver populations, we do not recognize that many of our "natural" stream systems may once have had a very different hydrologic character as a result of beaver activities; these streams should be considered significantly disturbed in the human-induced absence of beaver (Naiman and Melillo, 1984; Naiman *et al.*, 1988).

Studies that have discussed the hydrologic effects of beaver ponds indicate that beaver significantly change the hydrologic nature of stream reaches (Naiman *et al.*, 1988; Woo and Waddington, 1990). It is estimated that where healthy beaver populations occur they may modify up to 50% of the length of 2nd-4th order streams (Naiman and Melillo, 1984). In addition the literature suggests that beaver ponds:

1. Decrease stream flow velocities by ponding water (Naiman *et al.*, 1986) and may reduce peak storm flows (Woo and Waddington, 1990);
2. Allow sediments to settle out of the water column, thereby retaining the sediments behind beaver dams and decreasing the sediment concentration of stream flow downstream of the dams (Allred, 1980; Naiman *et al.*, 1986);

3. Decrease the stream gradient by creating a stair-step channel profile (Naiman et al., 1988);
4. May contribute water to soil moisture and groundwater storage reservoirs (DeBano and Heede, 1987; Naiman et al., 1988; Woo and Waddington, 1990);
5. Increase evaporation from a basin by increasing the surface area of ponded water (DeBano and Heede, 1987; Woo and Waddington, 1990); and
6. May change the overall annual flow regime of a stream, primarily by contributing to stream low flows (Stabler, 1985; Naiman et al., 1988; Woo and Waddington, 1990).

All of these effects will vary significantly from site to site depending on the physical characteristics of the basin (e.g., local climate and hydrologic regimes, topography, and soil type) and the character of the beaver dams (size, shape, structural integrity, etc.).

One of the challenges for understanding beaver-dominated hydrologic systems is that the effects of beaver activities are spatially and temporally dynamic (Naiman et al., 1988). The total amount of beaver pond storage in a particular basin will change through time as beaver build new dams, maintain old ones, and cease to use others. The decay and failure of dams and sedimentation of ponds over time will affect the flow and storage of water. Fluctuations in beaver populations in the basin will alter the rate of their activities. Effectively modeling such a system is a task that requires site-specific fieldwork to establish an understanding of the basic beaver pond flows and storages. An attempt at such a study would be appropriate on a basin as small as Willow Creek where the effects of beaver ponds seem to create a clear "beaver signal" in the hydrologic system. For larger basins, beaver will have less of an effect on hydrology at a watershed scale but

beaver ponds will still be significant hydrologic factors in riparian areas, and research on their local hydrologic effects should also be encouraged.

Another compelling reason for additional work on the hydrologic effects of beaver ponds is the frequency with which beaver are referred to as natural agents of riparian restoration (Leidholt-Bruner *et al.*, 1992). Many of the hydrologic effects of beaver ponds, such as sediment retention, are perceived as beneficial controls on the negative effects of logging, grazing, urbanization, and other disturbances that destabilize riparian systems. To date, however, only a handful of studies address the restorative qualities of beaver ponds and the conditions under which they may be most effective. More studies are needed to explore the role of beaver as important components of riparian systems and to support the use of beaver in riparian restoration efforts. Willow Creek provides a good opportunity for future study because initial baseline data exist on the hydrologic regime of the system and the basin is small enough that all its beaver ponds could be effectively monitored.

The Effects of Beaver Activities on the Willow Creek Watershed

The rainfall-runoff model used in this study was not explicitly designed to measure the effects of beaver ponds on stream hydrology. A beaver pond subroutine was added to the model only after the discovery of multiple large beaver ponds in the basin. The model results, nevertheless, imply that the hydrologic effects of beaver ponds are significant for Willow Creek. These results are combined in the following section with information drawn from the literature on the hydrologic effects of beaver activities in order to discuss the potential hydrologic effects of beaver activities in the Willow Creek watershed.

Reduction of Peak Storm Flows

The management of peak storm flows is the focus of flood control efforts in urbanized areas. The primary motivation for the ditching of portions of Willow Creek has been to increase the channel's flood flow capacity in order to reduce the potential for flooding. With the possibility for future development in the Willow Creek basin, and, thus, the increased potential for flood damage, detention ponds have been suggested as a means of reducing peak storm flows (OTAK, 1987). The peak flow reduction effect of both artificially constructed detention ponds and beaver ponds has been questioned in the literature (Booth, 1991; Beedle, 1992). Booth (1991) notes that if detention ponds are full at the beginning of a storm event, their ability to reduce peak flows will be limited. Beedle (1992) used the modified Puls method of reservoir flood routing to model the effect of full beaver ponds on peak storm flows. He predicted that an individual beaver pond only slightly attenuated peak flows while a series of five large beaver ponds could reduce the peak storm flow of a two-year precipitation event by up to 14.0%. The effect of the ponds decreased as the size of the modeled storm event increased; the same five ponds reduced peak flow by only 3.9 % for a fifty-year precipitation event.

Beedle's model (Beedle, 1992) assumes that the water level in beaver ponds never drops below the level of the dam during the wet season and thus his modeled ponds produced insignificant reductions in peak flow volumes. Field observations indicate that full ponds are not the rule at Willow Creek; between precipitation events the ponds drain through and around the beaver dams so that even during the wet season there may be available pond storage in the watershed to reduce the peak flows of individual precipitation events. The Willow Creek beaver ponds should also affect peak storm flows during full-pond conditions (Figure 12), though it appears from Beedle's results that these reductions would be minimal; a decrease in peak flow volume of only a few percent would

be expected depending on the size of the precipitation event and the time of year it occurred.

Additional peak flow reductions may be possible due to the intermittent nature of the Willow Creek stream system which allows the beaver ponds to dry during the summer. This creates a large volume of available pond storage at both the leading and trailing edges of the wet season. In the runoff record for Willow Creek, runoff levels remain constant and do not respond to the initial precipitation events at the beginning and the very end of the wet season (Figure 10). This pattern implies that at these times there is storage capacity available in the various storages in the basin, including beaver ponds. The exact volume of beaver pond storage in the basin is not known, but if the beaver ponds were removed we would expect to see a somewhat earlier response by runoff to autumn precipitation events, as well as a stronger runoff response to late spring rainfall. More fieldwork is needed to determine the magnitude and timing of peak flow reduction attributable to the beaver ponds.

Contributions to Soil Moisture and Groundwater Levels

Beaver ponds inundate land creating a large surface area over which water can infiltrate into the soil (Naiman *et al.*, 1988). This additional water increases soil moisture and groundwater levels which in turn may contribute to stream flow downstream. At Willow Creek, these contributions could help to increase and extend stream flow, particularly during the summer when many reaches of the stream are dry.

The elevated water surface in beaver ponds also reduces the flow gradient between the groundwater table and the pond so that less water drains from the local groundwater to the channel. This maintains higher substrate moisture levels which allow saturated substrate conditions to be attained more quickly during the wet season and sustained

longer into the dry season. In this way the beaver ponds also contribute to stream low flows simply by keeping water stored in the subsurface near ponded reaches for a longer period of time than would occur along stream reaches with no ponds.

A series of shallow-well transects across both ponded and unponded reaches of Willow Creek to monitor groundwater levels would help determine the areal extent and the duration of the effect the ponds have on subsurface and groundwater moisture levels. Care should be taken in choosing the placement of wells. Two previous groundwater monitoring attempts have encountered problems due to the strong shrink-swell capacity of the clayey soil in the lower part of the basin which makes it difficult to effectively seal well casings. Sites on different soils may produce better results.

Channel Incision

Channel incision is the erosional deepening of a stream channel, often in response to a particular disturbance in the channel system (Booth, 1990). A common example of an incision-initiating event is the increase in peak storm flow volumes resulting from urbanization in a basin. Incision directly increases the sediment yield of a stream as channel bed and banks are eroded. As incision continues, the gradient of a stream increases, raising the erosive energy of the stream flow, and incision may progress both upstream and downstream of the initial disequilibrium point. If a stream receives discharge from groundwater, the level of the local groundwater table in the vicinity of the channel will slope down to meet the incised level of the stream. This will drain areas of saturated soil near the channel which in turn may affect the composition of riparian vegetation.

The lower portions of both main channels of Willow Creek are incised. The west branch has been ditched for flood control purposes. The east branch is also incised,

though it is not clear whether this is the direct result of ditching or is incision in response to changes elsewhere in the stream system. The incision and the migration of headcuts in the channel indicate that stream flow is not currently in equilibrium with the channel gradient. The current rate of incision could be estimated by establishing a series of channel measurement points throughout the basin.

The erosive power of stream flow increases with both stream gradient and discharge levels (Satterlund and Adams, 1992). By slowing flow rates, beaver ponds decrease the erosivity of the stream flow within ponded reaches along Willow Creek (Naiman *et al.*, 1986). Lower flow velocities allow sediments to settle out in the ponds which raises the level of the stream bed. As the channel aggrades the stream gradient decreases which also reduces flow velocity.

Though beaver ponds may limit erosion along unponded stream reaches, they may also contribute to erosion at other points in the channel. Unponded reaches below the beaver ponds will receive water that has traveled through the ponds and dropped some of its sediment load. This water will have unsatisfied sediment carrying capacity and under the right conditions may cause erosion of the stream channel downstream of beaver dams. In the event of dam failure, severe erosion may occur downstream as a result of the large amount of water released from a pond.

Retention of Sediment

By ponding water, beaver ponds allow sediments to settle out of the water column. Naiman *et al.* (1986) found a positive relationship between the surface area of a pond or meadow created by beaver dams and the amount of sediment retained. They reported that a dam as small as 4-18 m³ could retain as much as 2,000-6,500 m³ of sediment. The amount of sediment held is dependent on a number of factors including topography of the

basin, stream order, and the effectiveness of the dam. As was mentioned earlier, sediment retention in ponds will help to reduce incision processes along ponded reaches by reducing the stream gradient. The dams, however, may also prevent sediment from moving downstream, creating sediment-starved channel reaches below beaver ponds and reducing the rate at which the channel beds of these reaches can aggrade (Clifton, 1987).

DeBano and Hansen (1989) found that sediments deposited behind artificial channel structures could store large amounts of water. The sediments slowly drained providing water necessary to extend the duration of stream flow. Sediments stored behind beaver dams should have a similar effect on stream flow along reaches of Willow Creek.

Coarse Woody Debris Contribution to the Channel

Coarse woody debris in a channel helps to increase channel roughness; the additional friction the stream flow encounters dissipates the shear stress of the flow on channel sediments which reduces erosion of the channel banks and bed (Beschta, 1979; Harmon *et al.*, 1986; DeBano and Heede, 1987). Woody debris, if large enough and positioned correctly, can also retain sediment, causing the channel to aggrade. If enough sediment is retained, longitudinal steps may form in the stream profile, decreasing the stream gradient and thereby reducing flow velocity (Harmon *et al.*, 1986). Finally, woody debris can provide both food and habitat for stream organisms and will contribute as it decays to nutrient cycling within the stream system (Naiman *et al.*, 1986).

Woody debris naturally enters stream channels by the senescence of vegetation and from canopy gap formation processes (e.g., windthrow). Beaver activities also introduce woody debris into stream channels in the form of building materials for dams and lodges, food caches, and trees and shrubs that are felled by the beaver or that are drowned by the ponds (Naiman *et al.*, 1986). The contributions of woody debris by beavers may be

especially significant for those reaches of Willow Creek where the woody riparian vegetation has been removed, limiting introduction of wood to the stream.

Effects of Beaver on Wetland Prairie Vegetation

The direct effects of the beaver ponds on the wetland prairie community at Willow Creek will be restricted to the riparian areas. Certainly long-term inundation by the beaver ponds would ultimately destroy prairie habitat. This is unlikely to affect the current extent of the prairie, however, as the beaver ponds are generally restricted to the confines of the incised stream channels. The dams creating the ponds are built from bank to bank and below bank height so that ponds overflow their dams and contribute water downstream before they overflow their banks. If stream incision is sufficiently reversed the flooding from beaver ponds may become more extensive in the future. The general benefits to the wetland that might result from the contribution of the beaver ponds to the maintenance of saturated conditions within the basin have already been discussed.

The Effects of Urbanization on Watershed Hydrology

Urbanization and its accompanying infrastructure radically alter a basin's hydrology. As cities expand, many small basins may be completely urbanized. Efforts to preserve urban green spaces and natural areas notwithstanding, the effects of urbanization on natural systems are devastating. The destruction of natural habitat by urbanization is obvious. The effect of urbanization on the hydrologic system of a region may be less evident but is equally as severe, affecting every component of the hydrologic cycle.

Potential Effects of Urbanization on the Willow Creek Watershed

Impermeable Area

The most direct effect of urbanization on a hydrologic system is to increase the impermeable area of a basin. Roads, parking lots, buildings, etc., seal the ground surface, preventing precipitation from infiltrating. Water that collects on these impervious areas is often rapidly routed via storm sewers and roadside ditches to the nearest stream channel. This increases the volume and rate of peak storm flows which increases the erosivity of the stream flow.

Discussions of the hydrologic effects of urbanization often focus on the "flashier" response of an urbanized basin to an individual precipitation event as more water reaches the channel sooner than would naturally occur (Booth, 1991). Urbanization, however, may also decrease stream flows. By preventing infiltration and removing water quickly, total contributions by precipitation to subsurface and groundwater storage in the basin decline. As infiltration is suppressed, the groundwater table can drop; this in turn may diminish the subsurface contributions to interflow and baseflow, decreasing the low flows of a stream (Ferguson, 1990; Ferguson and Suckling, 1990). Because Willow Creek is already dry along certain channel reaches during the summer, urbanization, in addition to decreasing low stream flows, would likely decrease the total length of time the stream flows during the year.

Decreased Infiltration

The observed stream stage for Willow Creek rises in response to the initial autumn rains and then maintains a fairly constant level until later in the season when stream runoff begins to respond to individual precipitation events. This runoff plateau occurs when the

soil is becoming saturated, the subsurface reservoirs are recharging, and the beaver ponds are filling after the summer dry season. In the urbanization simulation for Willow Creek, there is an increase in the number of runoff peaks that are present during this recharge period. The same pattern appears in the late spring after the winter rains have ceased. These peaks represent water that would be lost from the basin under urbanized conditions. Prairie wetlands are maintained by saturated soil conditions during particular times of the year. By channeling water more quickly out of the basin, urbanization could delay the time of soil saturation at the beginning of the wet season as well as shortening the length of the saturation period.

Drainage Networks

Urbanization is frequently accompanied by a network of storm sewers and drainage ditches which provide flood protection by quickly routing water from impermeable areas to stream channels. Their use has a number of consequences for a basin's hydrology. First, water is routed to a stream channel faster than it would be under natural conditions. This increases the amount of water in a storm flow peak and the speed with which it moves through the basin. Changes to channel morphology may occur as the increased flow volumes and velocities raise the erosivity of the stream flow. Both channel incision and channel expansion are common channel responses to urbanization; the extent of either response will be controlled by the physical characteristics of the basin and the magnitude of change in the flow regime resulting from urbanization (Booth, 1990).

Drainage networks may also route water into a different channel than the channel in which it would naturally flow. New routing of water disrupts channel processes in both the channel which receives additional water and in the channel which is denied flow.

Annual water budgets for entire watersheds may change if water is routed out of one basin and into another.

Natural channels in and near urban areas may be ditched and lined to decrease channel roughness and increase their flow capacity. These actions destroy the natural channel and the riparian system it supports. Ditching artificially deepens channels, lowering the bed level and increasing the stream gradient, which can initiate channel incision and expansion in unlined channels. Ditching also tends to straighten channels which also raises the channel gradient. The lower reach of Willow Creek has been re-routed from its natural channel into an unlined ditch which runs from the northern edge of the Willow Creek Preserve to Amazon Creek. The channel is periodically re-excavated to remove accumulations of sediment and vegetation. This artificial incision creates a gradient imbalance between the ditch and may contribute to channel incision within the preserve.

Evapotranspiration

Evapotranspiration rates have been shown to increase in urbanized settings where the air is advectively heated by surrounding surfaces (Suckling, 1980). This removes water from a basin that might otherwise have contributed to watershed flows and storages (Ferguson and Suckling, 1990). Evapotranspiration from advective heating can be a significant source of water loss for some basins.

Overland Flow

Overland flow is runoff that flows over the land surface. It is produced when precipitation exceeds available surface storage or it appears where subsurface flow paths intercept the surface. Overland flow may be critical to the maintenance of the Willow

Creek wetland prairie because it fills surface storage reservoirs, helping to maintain standing water conditions in the basin. Standing water, in turn, creates anaerobic conditions that promote hydrophytic wetland plants by excluding their non-hydrophytic competitors. Water flowing overland from upland areas of the basin supplements standing water from precipitation in the microdepressions of the lower basin where the wetland community exists. This helps sustain saturated substrate conditions between precipitation events.

Field observations at Willow Creek indicate that overland flow in the basin can persist for days after precipitation has ended. Because the basin is still largely rural, the water can drain from the upper slopes of the basin and collect at lower elevations. Urbanization will introduce more roads and drainage ditches into the Willow Creek basin which will interrupt and re-route the current overland flow system. An important question for The Nature Conservancy, therefore, is whether the Willow Creek wetland prairie could be sustained by precipitation alone without contributions to saturated conditions from overland flow.

CHAPTER VI

CONCLUSION

This study presented and calibrated a rainfall-runoff model appropriate for use on small western Oregon watersheds. The model was successfully applied to three watersheds and proved to be effective at simulating the relative magnitudes of hydrologic flows and storages in small basins. This rainfall-runoff model could be considered for use in hydrologic studies of small basins in the Willamette Valley region, particularly where issues of broad-scale hydrologic change are to be addressed. In doing so, it must be remembered that modifying the model structure and parameters to reflect the particular characteristics of a basin's hydrologic system, as was done in this study by creating a beaver pond subroutine, will yield more specific results.

As beaver populations recover from past exploitation, beaver are reasserting their dominance over many hydrologic systems. Although the effects of beaver ponds were not explicitly measured in this study, the model results raise some important questions about their effects on hydrologic systems. The results imply that for a basin as small as Willow Creek beaver ponds may be significant storage reservoirs affecting peak storm flows, particularly at the beginning and end of the wet season. From a review of the literature, it also appears that beaver ponds can play a critical role in stabilizing the channel system and controlling the effects of urbanization and agriculture.

This study has provided the basic data for understanding the current hydrologic conditions that exist in the Willow Creek basin, and a model with which to simulate the effects on the hydrologic system of future landuse change within that basin. The results of the urbanization simulations for Willow Creek should be considered indicative of the

magnitude of change that would occur with future development of the watershed. The model results support previous findings that urbanization, particularly in small basins, increases the volume and rate of peak storm flows. Increased flow volumes may disrupt and destroy riparian and channel systems and alter the hydrologic regime of a watershed. These findings argue strongly for a conservative approach to urban development in the Willow Creek basin in order to maintain the current hydrologic conditions supporting the basin's wetland prairie community.

APPENDIX A

EVAPOTRANSPIRATION MODEL

Daily potential evapotranspiration values are used in the rainfall-runoff model as the maximum amount of actual evapotranspiration that is allowed for any individual day. The potential evapotranspiration series data were calculated by applying the Penman equation to local meteorological observations from the Mahlon Sweet Field station. The model for calculating evapotranspiration was developed by P. Bartlein (unpublished) from work by Brutsaert (1982), Brutsaert and Stricker (1979), and Morton (1983) to estimate regional actual evapotranspiration. Within the program, the Penman equation is used to calculate potential evapotranspiration. The input data for this program consists of average daily temperature ($^{\circ}\text{F}$), average daily dewpoint temperature ($^{\circ}\text{F}$), average daily windspeed (miles per hour), cloud cover (tenths), global radiation (W/m^2), and albedo, which was given a constant daily value of 0.2 (Satterlund and Adams, 1992: 113). The algorithm is written in QuickBasic.

Evapotranspiration Model Code

```

DECLARE SUB DataInput ()
DECLARE SUB Equations ()
DEFINT A-Z

DIM SHARED ndays
'ndays = 731 for Coyote Creek and Amazon Creek data; 730 for Willow Creek data
ndays = 730
DIM SHARED nobs
nobs = 730

```

DIM SHARED Id\$(nobs)
 DIM SHARED Temp!(nobs)
 DIM SHARED AveTemp!(nobs)
 DIM SHARED Dew!(nobs)
 DIM SHARED DewPt!(nobs)
 DIM SHARED W!(nobs)
 DIM SHARED Wind!(nobs)
 DIM SHARED C!(nobs)
 DIM SHARED Cloud!(nobs)
 DIM SHARED Glob!(nobs)
 DIM SHARED GlobRad!(nobs)
 DIM SHARED Albedo!(nobs)

DIM SHARED AveKelv!(nobs)
 DIM SHARED KUp!(nobs)
 DIM SHARED NetK!(nobs)
 DIM SHARED LongWaveUp!(nobs)
 DIM SHARED LDCLR!(nobs)
 DIM SHARED LongWaveDown!(nobs)
 DIM SHARED NetLong!(nobs)
 DIM SHARED Q!(nobs)
 DIM SHARED V!(nobs)
 DIM SHARED VA!(nobs)
 DIM SHARED Delta!(nobs)
 DIM SHARED QNE!(nobs)
 DIM SHARED F!(nobs)
 DIM SHARED C2!(nobs)
 DIM SHARED EA!(nobs)
 DIM SHARED EADV!(nobs)
 DIM SHARED C1!(nobs)
 DIM SHARED ERAD!(nobs)
 DIM SHARED EP!(nobs)
 DIM SHARED EPE!(nobs)
 DIM SHARED EVAP!(nobs)

' Dimension parameter variables

DIM SHARED Ems!
 DIM SHARED Sigma!
 DIM SHARED Gamma!
 DIM SHARED Alpha!
 DIM SHARED LHeat!

```

' Get input data
  CALL DataInput

' Set parameter values
Ems! = .975
Sigma! = 5.6697E-08
Gamma! = .67
Alpha! = 1.26
LHeat! = 28.4028

' Calculate evaporation
  CALL Equations
END

SUB DataInput
OPEN "wcclimat.dat" FOR INPUT AS #1
OPEN "cl8890me.dat" FOR OUTPUT AS #2

FOR i = 1 TO ndays
  INPUT #1, Id$(i), Temp!(i), Dew!(i), W!(i), C!(i), Glob!(i), Albedo!(i)

  ' Converts Fahrenheit to Celsius
  AveTemp!(i) = (5! / 9!) * (Temp!(i) - 32!)
  DewPt!(i) = (5! / 9!) * (Dew!(i) - 32!)

  ' Convert Kj/m2 to Watts/m2
  GlobRad!(i) = Glob!(i) * .011574

  ' Converts mph to m/sec
  Wind!(i) = W!(i) * .44704

  ' Converts Cloudcover to tenths
  Cloud!(i) = C!(i) * .1
NEXT i
END SUB

SUB Equations
OPEN "willevap.dat" FOR OUTPUT AS #3
OPEN "rad8890.dat" FOR OUTPUT AS #4

FOR i = 1 TO ndays
  'AveKelv -- Air temperature in degrees Kelvin (K)
  AveKelv!(i) = AveTemp!(i) + 273.16

  'KUp -- Reflected shortwave radiation (w)(m**-2)
  KUp!(i) = Albedo!(i) * GlobRad!(i)

```

```

'NetK -- Net shortwave radiation (w)(m**-2)
  NetK!(i) = GlobRad!(i) - KUp!(i)
'LongWaveUp -- Longwave radiation emitted by surface (w)(m**-2)
  LongWaveUp!(i) = Ems! * Sigma! * (AveKelv!(i) ^ 4!)
'LDCLR -- Idso-Jackson clear-sky lw radation (w)(m**-2)
  LDCLR!(i) = Sigma! * (AveKelv!(i) ^ 4!) * (1! - .261 / EXP(.000777 *
    (273.16 - AveKelv!(i)) * (273.16 - AveKelv!(i))))
'LongWaveDown -- Cloudy-sky longwave down (Bolz Eqn) (w)(m**-2)
  LongWaveDown!(i) = LDCLR!(i) * (1! + ((.2 * (Cloud!(i) ^ 2))))
'NetLong -- Net longwave radiation (w)(m**-2)
  NetLong!(i) = LongWaveDown!(i) - LongWaveUp!(i)
'Q -- Net radiation
  Q!(i) = NetK!(i) + NetLong!(i)
'V -- Saturation vapor pressure at air temperature
  V!(i) = .611 * EXP((17.27 * (AveTemp!(i))) / ((AveTemp!(i) + 237.3)))
'VA -- Air vapor pressure
  VA!(i) = .611 * EXP((17.27 * DewPt!(i)) / (DewPt!(i) + 237.3))
'DELTA -- Slope of vapor pressure versus temperature curve
  Delta!(i) = (10! * 17.27 * 237.3 * V!(i)) / ((AveTemp!(i) + 237.3) ^ 2)
'QNE -- Q expressed as Equiv. Vaporization Rate (mm)(d**-1)
  QNE!(i) = Q!(i) / LHeat!
'F -- Penman's wind function (mm)(d**-1)(KPA**-1)
  F!(i) = 2.6 * (1! + .54 * Wind!(i))
'C2 -- multiplier
  C2!(i) = Gamma! / (Delta!(i) + Gamma!)
'EA -- "Drying power" of the wind (mm)(d**-1)
  EA!(i) = F!(i) * (V!(i) - VA!(i))
'EADV -- Large-scale advective term in Penman eqn. (mm)(d**-1)
  EADV!(i) = C2!(i) * EA!(i)
'C1 -- multiplier
  C1!(i) = Delta!(i) / (Delta!(i) + Gamma!)
'ERAD -- radiative forcing term in Penman eqn. (mm)(d**-1)
  ERAD!(i) = C1!(i) * QNE!(i)
'EP -- potential evapotranspiration (Penman) (mm)(d**-1)
  EP!(i) = ERAD!(i) + EADV!(i)
'EPE -- Potential equilibrium evapotranspiration (Priestley-Taylor)
  EPE!(i) = Alpha! * ERAD!(i)
'EVAP -- Regional evaporation (mm)(d**-1)
  EVAP!(i) = (2! * EPE!(i)) - EP!(i)
NEXT i
END SUB

```

APPENDIX B

RAINFALL-RUNOFF MODEL

The rainfall-runoff model used in this study was based on a textbook model created by McCuen and Snyder (1986). The model code was translated from a FORTRAN algorithm into QuickBasic and then modified as needed. In order to track changes to the model's storages and flows some of the variables are given suffixes of W(etting) or D(rying) to indicate whether the storage is in a wetting or drying stage, followed by numbers to track the variables through the model code (e.g., GWStoreW, GWStoreD1, GWStoreD2, etc.).

Rainfall-Runoff Model Code

```
DEFINT J-N
DEFDBL A-I, O-Z
```

```
DECLARE SUB ParameterInput ()
DECLARE SUB DataOutput ()
DECLARE SUB Userfunc ()
DECLARE SUB DataInput ()
DECLARE SUB pause ()
DECLARE SUB UnitHydro ()
```

```
DECLARE FUNCTION GWD (GWS, GWSM)
DECLARE FUNCTION HYDRO (j)
DECLARE FUNCTION INFIL (SUBFLOW, SubSurfStoreMax)
DECLARE FUNCTION PERC (SUBFLOW, SubSurfStoreMax)
DECLARE FUNCTION SubSurfETCO (SUBFLOW, SubSurfStoreMax)
```

```
DIM SHARED ndays
DIM SHARED nobs
DIM SHARED convert
```

ndays = 731

nobs = 731

DIM SHARED id\$(nobs)
DIM SHARED discharge(nobs)
DIM SHARED PrecipIn(nobs)
DIM SHARED Precip(nobs)
DIM SHARED OverlandFlow(nobs)
DIM SHARED PotEvap(nobs)
DIM SHARED TotalET(nobs)
DIM SHARED Store(nobs)
DIM SHARED SurfStore(nobs)
DIM SHARED SubSurfStore(nobs)
DIM SHARED GWStore(nobs)
DIM SHARED SurfFlow(nobs)
DIM SHARED Interflow(nobs)
DIM SHARED Baseflow(nobs)
DIM SHARED Runoff(nobs)
DIM SHARED ObsRunoff(nobs)
DIM SHARED diff(nobs)
DIM SHARED ResStore(nobs)
DIM SHARED ResEvap(nobs)

DIM SHARED TPrecip
DIM SHARED Precip2
DIM SHARED Infiltration
DIM SHARED InfilProp
DIM SHARED ImpermeableProp
DIM SHARED SurfStoreW
DIM SHARED SurfStoreD1
DIM SHARED SurfStoreD2
DIM SHARED SubSurfRecharge
DIM SHARED SubSurfStoreW
DIM SHARED SubSurfStoreD1
DIM SHARED SubSurfStoreD2
DIM SHARED SubSurfStoreD3
DIM SHARED GWRecharge
DIM SHARED GWStoreW
DIM SHARED GWStoreD1
DIM SHARED GWStoreD2
DIM SHARED GWStoreD3
DIM SHARED GWDDProp

```

DIM SHARED GWExcess
DIM SHARED PercProp
DIM SHARED Deficit
DIM SHARED PotEvapD0
DIM SHARED PotEvapD1
DIM SHARED PotEvapD2
DIM SHARED PotEvapD3
DIM SHARED PotEvapD4
DIM SHARED SurfETCoeff
DIM SHARED SurfET
DIM SHARED SubSurfETCoeff
DIM SHARED SubSurfET
DIM SHARED GWETCoeff
DIM SHARED GWET
DIM SHARED ResStoreMax
DIM SHARED ResStoreMax1
DIM SHARED ResStoreMax2
DIM SHARED DeltaS

```

```

DIM SHARED UHShape
DIM SHARED SurfStoreMax
DIM SHARED SubSurfStoreMax
DIM SHARED GWCap
DIM SHARED GWDMax
DIM SHARED PropIntF
DIM SHARED UHCoeff(4)
DIM SHARED RunoffMin

```

```

' Get input data
  CALL DataInput

```

```

' Set parameter values
  CALL ParameterInput

```

```

' Call Userfunc
  CALL Userfunc

```

```

' Plot Data
  INPUT " Plot data (y or n): ", ans$
  IF UCASE$(ans$) = "Y" THEN CALL DataOutput
END

```

SUB DataInput

PRINT "Which watershed (Willow, Amazon, Coyote) would you like"

PRINT "to run the model for?"

INPUT watershed\$

IF UCASE\$(watershed\$) = "WILLOW" THEN

OPEN "willow3.dat" FOR INPUT AS #1

OPEN "willevap.dat" FOR INPUT AS #3

convert = .24525

ndays = 730

ELSEIF UCASE\$(watershed\$) = "AMAZON" THEN

OPEN "amazon.dat" FOR INPUT AS #1

OPEN "dalyevap.dat" FOR INPUT AS #3

convert = .044348

ndays = 731

ELSEIF UCASE\$(watershed\$) = "COYOTE" THEN

OPEN "coyote.dat" FOR INPUT AS #1

OPEN "dalyevap.dat" FOR INPUT AS #3

convert = .009933

ndays = 731

nobs = 731

END IF

TPrecipIn = 0: TDischarge = 0: TPrecip = 0: TObsRunoff = 0: TPotEvap = 0:

FOR j = 1 TO ndays

INPUT #1, id\$(j), PrecipIn(j), discharge(j)

IF discharge(j) <> 9999 THEN

TPrecipIn = TPrecipIn + PrecipIn(j)

TDischarge = TDischarge + discharge(j)

Precip(j) = 25.4 * PrecipIn(j)

ObsRunoff(j) = convert * discharge(j)

TPrecip = TPrecip + Precip(j)

TObsRunoff = TObsRunoff + ObsRunoff(j)

ELSE

ObsRunoff(j) = 9999

END IF

INPUT #3, PotEvap(j)

TPotEvap = TPotEvap + PotEvap(j)

IF j = 366 THEN

PRINT USING "#####.##"; j, TPrecipIn; TDischarge; TPrecip; TObsRunoff;
TPotEvap

```

    CALL pause
  END IF
NEXT j
PRINT "Total Precip (inches):    "; USING "#####.#"; TPrecipIn
PRINT "Total Discharge (cu ft/sec): "; USING "#####.#"; TDischarge
PRINT "Total Precip (mm):        "; USING "#####.#"; TPrecip
PRINT "Total Discharge (mm):     "; USING "#####.#"; TObsRunoff
PRINT "Total PotEvap (mm):      "; USING "#####.#"; TPotEvap
CALL pause
CLOSE #1
CLOSE #3
END SUB

```

```

SUB DataOutput
  PRINT "  Writing output files..."
  OPEN "evap.dat" FOR OUTPUT AS #2
  ETTTotal = 0
  FOR j = 1 TO ndays
    ETTTotal = ETTTotal + TotalET(j)
    PRINT #2, USING "####"; j;
    PRINT #2, USING "#####.#####"; PotEvap(j); TotalET(j)
    IF j = 366 THEN
      PRINT "366 ETTTotal ="; ETTTotal
      CALL pause
    END IF
  NEXT j
  CLOSE #2
  PRINT "Total Evap (mm):          "; USING "#####.#"; ETTTotal

  OPEN "ppt.dat" FOR OUTPUT AS #2
  FOR j = 1 TO ndays
    PRINT #2, USING "####"; j;
    PRINT #2, USING "#####.#####"; Precip(j);
    PRINT #2, "    0.0"
  NEXT j
  CLOSE #2

  OPEN "ro.dat" FOR OUTPUT AS #2
  OPEN "obsro.dat" FOR OUTPUT AS #22
  ROTotal = 0!
  FOR j = 1 TO ndays
    IF ObsRunoff(j) <> 9999 THEN

```

```

    ROTotal = ROTotal + Runoff(j)
    PRINT #2, USING "####"; j;
    PRINT #2, USING "#####.#####"; Runoff(j)
    PRINT #22, USING "####"; j;
    PRINT #22, USING "#####.#####"; ObsRunoff(j)
ELSE
    PRINT #2, USING "####"; j;
    PRINT #2, USING "#####.#####"; Runoff(j)
END IF
IF j = 366 THEN
    PRINT "366 ROTotal="; ROTotal
    CALL pause
END IF
NEXT j
CLOSE #2
CLOSE #22
PRINT "Total Runoff (mm):      "; USING "#####.##"; ROTotal
DeltaS = TPrecip - ETTotal - ROTotal
PRINT "Delta S"; DeltaS
CALL pause

OPEN "comp.dat" FOR OUTPUT AS #2
FOR j = 1 TO ndays
    PRINT #2, USING "####"; j;
    PRINT #2, USING "#####.#####"; SurfFlow(j); Interflow(j); Baseflow(j)
NEXT j
CLOSE #2

OPEN "store.dat" FOR OUTPUT AS #2
FOR j = 1 TO ndays
    PRINT #2, USING "####"; j;
    PRINT #2, USING "#####.#####"; SurfStore(j); SubSurfStore(j); GWStore(j);
                                                ResStore(j)
NEXT j
CLOSE #2

OPEN "difflog.dat" FOR OUTPUT AS #2
OPEN "regress.mtw" FOR OUTPUT AS #12
FOR j = 1 TO ndays
    IF ObsRunoff(j) <> 9999 THEN
        PRINT #2, USING "####"; j;
        PRINT #2, USING "#####.##"; (Runoff(j) + .5); (ObsRunoff(j) + .5); diff(j)
    
```

```

    PRINT #12, USING "#####.##"; Runoff(j); ObsRunoff(j)
  END IF
NEXT j
CLOSE #2
CLOSE #12

```

```

OPEN "text.plt" FOR OUTPUT AS #2
xpos = 7.2: ypos = 2.3
PRINT #2, "SS" + " DEFAULT.SYM"
PRINT ""
PRINT "Enter title annotations. (Press enter twice to stop.):"
DO
  LINE INPUT text$
  textlength = LEN(text$)
  IF textlength > 2 THEN
    PRINT #2, "PS";
    PRINT #2, USING "##.###"; xpos; ypos;
    PRINT #2, " 0.125 0.000 ";
    PRINT #2, CHR$(34) + text$ + CHR$(34)
  END IF
  ypos = ypos - .2
LOOP WHILE textlength > 2
PRINT #2, "PS";
PRINT #2, USING "##.###"; xpos; ypos;
PRINT #2, " 0.100 0.000 "; CHR$(34);
PRINT #2, "R"; CHR$(34)
xpos2 = xpos + .095
ypos2 = ypos + .08
PRINT #2, "PS";
PRINT #2, USING "##.###"; xpos2; ypos2;
PRINT #2, " 0.086 0.000 "; CHR$(34) + "2" + CHR$(34)
PRINT "enter r-squared value: "
LINE INPUT text$
xpos3 = xpos + .19
PRINT #2, "PS";
PRINT #2, USING "##.###"; xpos3; ypos;
PRINT #2, " 0.100 0.000 "; CHR$(34);
PRINT #2, "=" + text$ + CHR$(34)
PRINT #2, "PS";
PRINT #2, USING "##.###"; xpos; ypos;
PRINT #2, " 0.100 0.000 "; CHR$(34) + " " + CHR$(34)
ypos = ypos - .15

```

```
CLOSE #2
END SUB
```

```
FUNCTION GWD (GWS, GWSM)
  ratio = (GWS / GWSM) ^ 2
  SELECT CASE ratio
    CASE IS < .5
      GWD = .5 * ratio
    CASE IS >= .5
      GWD = (ratio * 1.5) - .5
  END SELECT
END FUNCTION
```

```
FUNCTION HYDRO (j)
  IF j < 4 THEN
    steps = j
  ELSE
    steps = 4
  END IF
  H = 0
  FOR k = 1 TO steps
    H = H + (UHCoeff(k) * OverlandFlow(j - k + 1))
  NEXT k
  HYDRO = H
END FUNCTION
```

```
FUNCTION INFIL (Store, StoreMax)
  ratio = (Store / StoreMax)
  SELECT CASE ratio
    CASE IS < .65
      INFIL = 1
    CASE .65 TO .85
      INFIL = 1 - (.25 + 13 * (ratio - .5) / 7)
    CASE IS > .85
      INFIL = 1 - (.9 + (ratio - .85) / 1.5)
  END SELECT
END FUNCTION
```

```
SUB ParameterInput
  CLS
  PRINT "Enter Parameter Values:"
```

```

INPUT " Unit hydrograph shape parameter (UHShape): ", UHShape
INPUT " Surface storage capacity (SurfStoreMax): ", SurfStoreMax
INPUT " Interflow proportion (PropIntF): ", PropIntF
INPUT " Subsurface storage saturation (SubSurfStoreMax): ", SubSurfStoreMax
INPUT " Groundwater capacity (GWCap): ", GWCap
INPUT " Groundwater discharge maximum (GWDMax): ", GWDMax
INPUT " Reservoir storage maximum (ResStoreMax): ", ResStoreMax
INPUT " Minimum flow from beaver ponds (RunoffMin): ", RunoffMin
INPUT " Impermeable area proportion (ImpermeableProp): ", ImpermeableProp
END SUB

```

```

SUB pause
  WHILE INKEY$ = "": WEND
END SUB

```

```

FUNCTION PERC (Store, StoreMax)
  ratio = ((Store / StoreMax) - .4)
  IF ratio < 0 THEN ratio = 0
  ratio = ratio ^ 2
  SELECT CASE ratio
    CASE IS < .5
      PERC = .5 * ratio
    CASE .5 TO .85
      PERC = .25 + (13 * (ratio - .5) / 7)
    CASE IS > .85
      PERC = .9 + ((ratio - .85) / 1.5)
  END SELECT
END FUNCTION

```

```

FUNCTION SubSurfETCO (Store, StoreMax)
  ratio = (Store / StoreMax)
  SELECT CASE ratio
    CASE IS < .5
      SubSurfETCO = .5 * ratio
    CASE IS >= .5
      SubSurfETCO = (ratio * 1.5) - .5
  END SELECT
END FUNCTION

```

```

SUB UnitHydro
  UHCoeff(1) = 1
  UHCoeff(2) = UHShape

```

```

UHCoeff(3) = UHShape ^ 2
UHCoeff(4) = UHShape ^ 3
sum = 0
FOR k = 1 TO 4
    sum = sum + UHCoeff(k)
NEXT k
FOR k = 1 TO 4
    UHCoeff(k) = UHCoeff(k) / sum
NEXT k
END SUB

SUB Userfunc STATIC
CALL UnitHydro
FOR j = 1 TO ndays
' Infiltration
    InfilProp = INFIL(SubSurfStoreD3, SubSurfStoreMax)
    Precip2 = Precip(j) - (ImpermeableProp * Precip(j))
    Infiltration = InfilProp * Precip2

' Surface storage addition
    SurfStoreW = ((1! - InfilProp) * Precip2) + SurfStoreD2

' Surface storage after precipitation
    IF SurfStoreW > SurfStoreMax THEN
        OverlandFlow(j) = SurfStoreW - SurfStoreMax
        SurfStoreD1 = SurfStoreMax
    ELSE
        OverlandFlow(j) = 0!
        SurfStoreD1 = SurfStoreW
    END IF

' Surface flow
    SurfFlowW1 = HYDRO(j)
    SurfFlowW1 = SurfFlowW1 + (ImpermeableProp * Precip(j))

' Subsurface storage addition
    SubSurfStoreW = SubSurfStoreD3 + Infiltration

' Interflow
    IF (SubSurfStoreW / SubSurfStoreMax) <= .4 THEN
        InterflowW1 = 0!
        SubSurfStoreD1 = SubSurfStoreW
    
```

```

ELSE
    InterflowW1 = PropIntF * SubSurfStoreW
    SubSurfStoreD1 = SubSurfStoreW - InterflowW1
END IF

' Percolation to groundwater
PercProp = PERC(SubSurfStoreD1, SubSurfStoreMax)

' Groundwater recharge
GWRecharge = SubSurfStoreD1 * PercProp
SubSurfStoreD2 = SubSurfStoreD1 - GWRecharge

' Groundwater storage
GWStoreW = GWStoreD3 + GWRecharge

' Excess groundwater
IF GWStoreW > GWCap THEN
    GWExcess = GWStoreW - GWCap
    GWStoreD1 = GWCap
ELSE
    GWExcess = 0!
    GWStoreD1 = GWStoreW
END IF

' Update Interflow
InterflowW2 = InterflowW1 + GWExcess

' Evapotranspiration from surface storage
PotEvapD0 = PotEvap(j)
IF PotEvapD0 <= SurfStoreD1 THEN
    SurfET = PotEvapD0
    SurfStoreD2 = SurfStoreD1 - SurfET
    PotEvapD1 = PotEvapD0 - SurfET
ELSE
    SurfET = SurfStoreD1
    SurfStoreD2 = SurfStoreD1 - SurfET
    PotEvapD1 = PotEvapD0 - SurfET
END IF
IF PotEvapD1 < 0! THEN PotEvapD1 = 0!
SurfStore(j) = SurfStoreD2

```

' Subsurface evapotranspiration

SubSurfETCoeff = SubSurfStoreD2 / SubSurfStoreMax

IF PotEvapD1 * SubSurfETCoeff < SubSurfStoreD2 THEN

SubSurfET = PotEvapD1 * SubSurfETCoeff

SubSurfStoreD3 = SubSurfStoreD2 - SubSurfET

PotEvapD2 = PotEvapD1 - SubSurfET

ELSE

SubSurfET = SubSurfStoreD2

SubSurfStoreD3 = SubSurfStoreD2 - SubSurfET

PotEvapD2 = PotEvapD1 - SubSurfET

END IF

IF PotEvapD2 < 0! THEN PotEvapD2 = 0!

SubSurfStore(j) = SubSurfStoreD3

' Groundwater evapotranspiration

GWETCoeff = GWStoreD1 / GWCap

IF PotEvapD2 * GWETCoeff <= GWStoreD1 THEN

GWET = PotEvapD2 * GWETCoeff

GWStoreD2 = GWStoreD1 - GWET

PotEvapD3 = PotEvapD2 - GWET

ELSE

GWET = GWStoreD1

GWStoreD2 = GWStoreD1 - GWET

PotEvapD3 = PotEvapD2 - GWET

END IF

' Evapotranspiration from surface flow and interflow

IF PotEvapD3 >= (SurfFlowW1 + InterflowW2) THEN

FlowET = SurfFlowW1 + InterflowW2

SurfFlowW2 = 0!

InterflowW3 = 0!

PotEvapD4 = PotEvapD3 - (SurfFlow1 + InterflowW2)

ELSE

FlowET = PotEvapD3

FLOW = SurfFlowW1 + InterflowW2

SurfFlowW2 = SurfFlowW1 - ((SurfFlowW1 / FLOW) * FlowET)

InterflowW3 = InterflowW2 - ((InterflowW2 / FLOW) * FlowET)

PotEvapD4 = 0

END IF

' Total evapotranspiration

TotalET(j) = TotalET(j) + SurfET + SubSurfET + GWET + FlowET

```

' Baseflow
  GWDDProp = GWD(GWStoreD2, GWCap)
  IF (GWDDProp * GWDDMax) > GWStoreD2 THEN
    Baseflow(j) = GWStoreD2
    GWStoreD3 = 0!
  ELSE
    Baseflow(j) = GWDDProp * GWDDMax
    GWStoreD3 = GWStoreD2 - Baseflow(j)
  END IF
  GWStore(j) = GWStoreD3

' Total storage
  Store(j) = SurfStore(j) + SubSurfStore(j) + GWStore(j)

' Total runoff
  SurfFlow(j) = SurfFlowW2
  Interflow(j) = InterflowW3
  Runoff(j) = SurfFlow(j) + Interflow(j) + Baseflow(j)

Reservoir function
  ResStore(j) = ResStore(j) + ResStore(j - 1)
  IF ResStore(j) > ResStoreMax THEN
    Runoff(j) = Runoff(j) + (ResStore(j) - ResStoreMax)
    ResStore(j) = ResStoreMax
  END IF

  IF ResStoreMax <> 0 THEN
    IF ResStore(j) < ResStoreMax AND Runoff(j) > RunoffMin THEN
      IF .75 * (Runoff(j) - RunoffMin) < (ResStoreMax - ResStore(j)) THEN
        ResStore(j) = ResStore(j) + (.75 * (Runoff(j) - RunoffMin))
        Runoff(j) = RunoffMin + (.25 * (Runoff(j) - RunoffMin))
      ELSE
        IF .75 * (Runoff(j) - RunoffMin) >= (ResStoreMax - ResStore(j)) THEN
          ResStore(j) = ResStoreMax
          Runoff(j) = Runoff(j) - (ResStoreMax - ResStore(j))
        END IF
      END IF
    END IF
  ELSE
    IF ResStore(j) >= .5 * ResStoreMax THEN
      Runoff(j) = Runoff(j) + RunoffMin
      ResStore(j) = ResStore(j) - RunoffMin
    END IF
  END IF

```

```
END IF
IF PotEvapD4 > 0 AND (PotEvapD4 * .85) < (ResStore(j) * .2) THEN
  ResStore(j) = ResStore(j) - (PotEvapD4 * .85)
  ResEvap(j) = (PotEvapD4 * .85)
ELSE
  IF PotEvapD4 > 0 AND (PotEvapD4 * .85) > (ResStore(j) * .2) THEN
    ResEvap(j) = ResStore(j) * .2
    ResStore(j) = ResStore(j) - (ResStore(j) * .2)
  END IF
END IF
TotalET(j) = TotalET(j) + ResEvap(j)
END IF

' Observed minus simulated runoff
diff(j) = Runoff(j) - ObsRunoff(j)

NEXT j
END SUB
```

APPENDIX C

EFFECT OF METEOROLOGICAL INPUTS ON MODEL FIT

The meteorological data used in the model runs was collected at the Mahlon Sweet Field weather station, approximately 9.5 km (5.9 mi) north-northwest of the Willow Creek gaging station and approximately 28 km (17.4 mi) from the southernmost end of the Coyote Creek basin. This station was chosen because it was the closest continuous meteorological collection site in the area. All three study basins, however, straddle the transition zone between the southern end of the Willamette Valley and the Coast Range hills. Precipitation measurements from within the city of Eugene, Oregon, and from a tipping bucket raingage at the Willow Creek gaging station, recorded approximately 20-30% less precipitation than the Mahlon Sweet Field station for the same precipitation events (OTAK, 1990a; S. Shafer, unpublished data). It has been suggested that this indicates the presence of a local rainshadow on the lee slopes of the southern Willamette Valley hills (OTAK, 1990a) or perhaps a regional rainshadow caused by the crest of the Oregon Coast Range. If either rainshadow exists, using the Mahlon Sweet Field station precipitation data in the rainfall-runoff model will inevitably lead to overprediction of runoff by the model and the use of unrealistic model parameters in order to bring simulated and observed discharge values into agreement.

An attempt was made to use the precipitation measured at Willow Creek in the input data set. Using the observed precipitation creates a better model fit for individual peak runoff volumes but the model can not accommodate the gaps in the Willow Creek record; as a result, the overall agreement between simulated and observed runoff for the entire two-year study period is poor. A regression analysis of Willow Creek precipitation

and Mahlon Sweet Field precipitation did not reveal a significant relationship, preventing the use of the Mahlon Sweet Field precipitation record to estimate the precipitation volumes for the gaps in the Willow Creek record. A network of precipitation gages has been proposed for the Eugene area (OTAK, 1990a). This should help determine the extent of the lee slope effect and provide better data for hydrologic modeling.

The potential of systemic overprediction from the use of the Mahlon Sweet Field precipitation does not invalidate the model results presented in this study. The Amazon Creek and Coyote Creek model calibrations produced good results that were similar to each other and very different from the initial Willow Creek results even though all three relied on Mahlon Sweet Field data. Therefore, the conclusion that beaver ponds create a significant hydrologic difference between these two basins and Willow Creek is still valid.

APPENDIX D

DEVELOPING A RATING CURVE FOR WILLOW CREEK

A rating curve was needed to convert stage measurements from the Willow Creek gaging station into discharge rates. Velocity readings were taken at various times during the two-year study period at the gaging station channel cross-section using the six-tenths depth method (Rantz, 1982). The linear relationship between stage and discharge developed from these measurements is shown in Figure 20 by curve Q1. This curve is unsatisfactory, however, because it calculates 0.0 cfs flow in the channel below a stage of 0.55 m (1.8 ft). The velocity meter could not record velocities at this stage but often flow could be visually observed. A linear relationship between the lowest recorded flow at 0.55 m (1.8 ft) and 0.0 cfs flow at 0.0 m stage was used to extend the low flow end of the rating curve.

A graph of stream stage and time reveals a distinct plateau at the beginning of the wet season during which stream stage remains relatively constant even though precipitation events continue. Then, at a particular point in the record, the stream stage responds to precipitation events. This plateau is distinct at the beginning of both water years and suggests the effect of a channel constraint on stream flow. A survey of the channel thalweg indicated that a series of small depressions or "bathtubs" had formed in the channel bed (Figure 21). The elevation of a berm (bathtub lip) upstream of the gaging station corresponded to the stage height of a prominent bench in the stage time series record. To accommodate this physical constraint within the rating curve three non-linear equations were developed and tested (Figure 20). Of these, the piece-wise linear equation (line Q3) was chosen because it provided the best qualitative fit with the observed

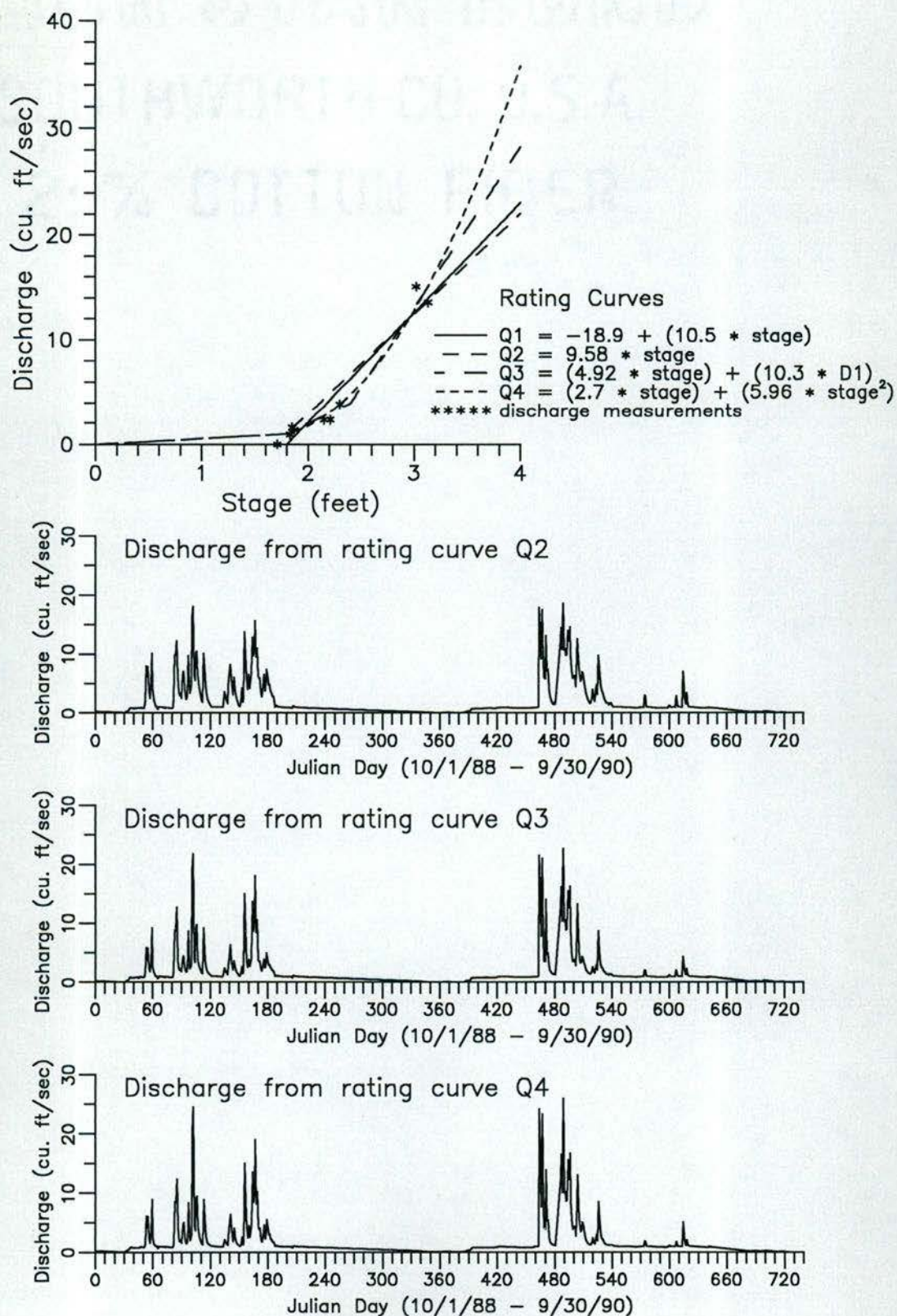


Figure 20. Non-linear rating curves for Willow Creek and the discharge calculated by three of the curves.

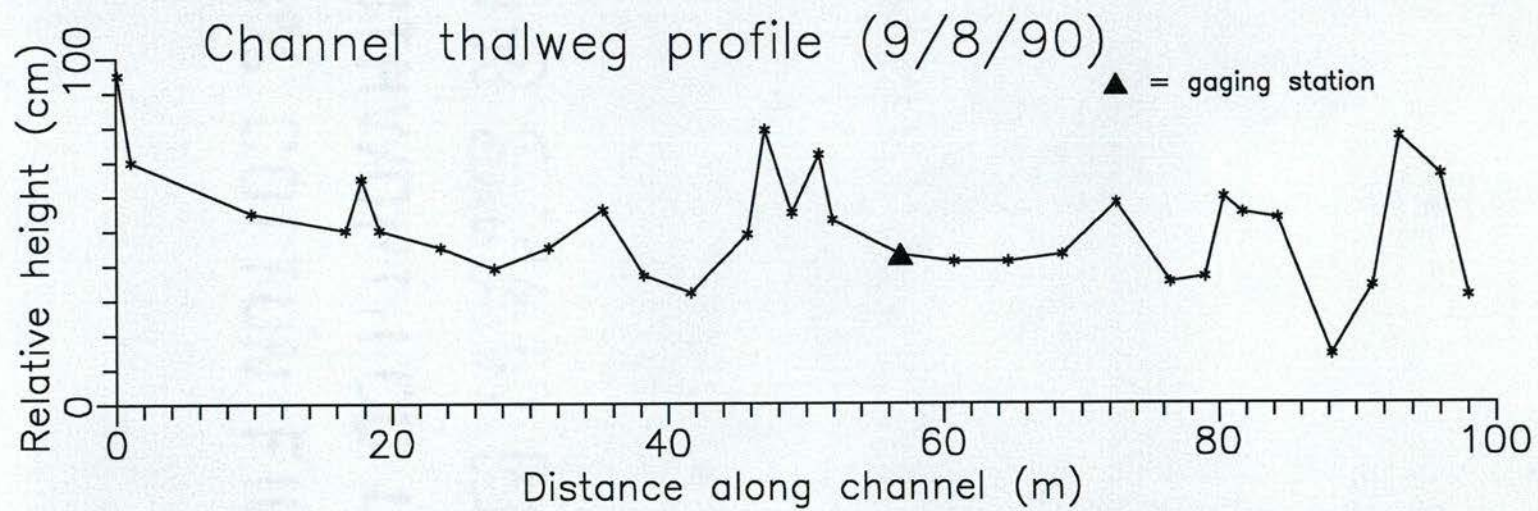


Figure 21. Profile of the Willow Creek channel thalweg. The vertical scale is greatly exaggerated in this figure.

discharge measurements. The relatively low flows at high stage levels may reflect flood waters from Amazon Creek backing up into the Willow Creek channel.

The beaver ponds may also affect the stage-discharge relationship, particularly at the beginning of the wet season when the ponds are low or dry. Much of the runoff at this time will fulfill pond storage and a strong response by stream stage to precipitation will not be observed until all the major storage reservoirs in the basin have been filled.

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