# Guidelines for Continuous Simulation of Streamflow in Johnson County, Kansas, with HEC-HMS

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# ABSTRACT

Continuous simulation of streamflow is useful for predicting the streamflow impacts of land-use changes and stormwater management practices. This report provides guidance for continuous simulation of streamflow in Johnson County with the HEC-HMS Hydrologic Modeling System of the U. S. Army Corps of Engineers. The general soil-moisture accounting (SMA) model in HEC-HMS is simplified for Johnson County applications by omitting the groundwater layers and by treating all precipitation as rainfall. The simplified SMA model is calibrated through test simulations using local precipitation data for the period 1997-2006. The model is calibrated to yield a mean annual runoff of approximately 10 inches from pervious surfaces. An analysis of USGS streamflow gaging records indicate that a mean annual runoff of 10 inches is typical for rural areas in Johnson County.

Potential infiltration rates can be input as monthly average values or computed from net radiation and temperature data by the Priestly-Taylor method. We recommend the monthly-average method at present. The implementation of the Priestly-Taylor evapotranspiration method in HEC-HMS Version 3.4 is poorly documented. The required radiation input is not incident solar radiation, as stated in the program and user's manual, but rather net radiation. An appendix to this report provides a procedure for calculation of daily net radiation from solar radiation, temperature and humidity data.

Three examples demonstrate practical applications of the recommended continuous-simulation procedures for Johnson County. The first two examples investigate the impacts of land development practices on runoff volumes and rates. The final example investigates the suitability of HEC-HMS for continuous simulation of streamflow in a complex watershed with numerous subbasins and channel reaches.

# ACKNOWLEDGMENTS

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

A comprehensive stormwater management program has three major concerns: (1) prevention or mitigation of flood damage, (2) preservation or restoration of stream stability, and (3) preservation or restoration of stream ecology. The recent county-wide watershed studies have focused on flooding. Future efforts are likely to focus on stream stability and stream ecology.

Studies of flooding, stream stability and stream ecology require different types of hydrologic information. Flood studies require hydrographs for hypothetical events with specific return periods, generated with single-event hydrologic models. Studies of stream stability and ecology require examination of the entire spectrum of streamflows, as represented by the flow-duration curve (discharge versus percent of time exceeded). A continuous-simulation hydrologic model is the appropriate tool for such studies. This type of hydrologic model generates a continuous record of streamflow from records of precipitation and other climatic variables. Continuous-simulation models account for hydrologic processes that are neglected in single-event flood models. These processes include evapotranspiration, canopy interception, depression storage, percolation, shallow subsurface flow and snowmelt.

Continuous simulation of streamflow is useful for predicting the impacts of land-use changes and stormwater management practices on stream stability and ecology. The shear stress-duration curves needed for stream stability studies are readily generated from simulated streamflow records. The hydrologic impacts of various stormwater best management practices (BMPs) and low-impact development (LID) practices can be assessed by continuous simulation.

## 1.2 HEC-HMS

The two major streamflow simulation programs used by civil engineers are HEC Hydrologic Modeling System (HEC-HMS) of the U.S. Army Corps of Engineers and the Storm Water Management Model (SWMM) of the U. S. Environmental Protection Agency. Although HEC-HMS and SWMM were originally developed for single-event simulation, both programs now include continuous-simulation capabilities. HEC-HMS is preferable to SMWW for continuous simulation of streamflow in Johnson County. HEC-HMS has three major advantages over SWMM for Johnson County:

1. The single-event hydrologic models from the recent county-wide watershed studies were developed with the HEC-1 Flood Hydrograph Package of the U. S. Army Corps of Engineers. HEC-HMS is the successor program to HEC-1. HEC-HMS and HEC-1 use most of the same hydrologic and hydraulic methods, and HEC-HMS can import HEC-1 data files and create equivalent HEC-HMS models. SWMM is incompatible with HEC-1 because the two programs use substantially different hydrologic methods.

2. HEC-HMS uses the same unit-hydrograph methods as HEC-1. Considerable research has already been done on calibration of unit-hydrograph models for Johnson County watersheds. SWMM does not use unit-hydrograph methods.

3. HEC-HMS accounts for evapotranspiration (ET) directly, and SWMM does not. In SWMM, potential infiltration rates can be input as monthly average values or computed from net radiation and temperature data by the Priestly-Taylor method. The actual ET rate is the product of the potential rate, a crop coefficient and a water-stress coefficient. In SWMM, the recovery of infiltration capacity between rainfall events (which results from evapotranspiration and percolation) occurs at a user-specified rate, which does not vary seasonally and is independent of weather and soil-moisture conditions.

### 1.3 Overview of Report

This report provides guidance for continuous simulation of streamflow in Johnson County with HEC-HMS. Chapter 2 examines the hydrologic characteristics of USGS-gaged streams in Johnson County. Chapter 3 explains how HEC-HMS models the relevant hydrologic processes in continuous simulation mode. Chapter 4 develops the subbasin runoff component of a continuous streamflow model for Johnson County. This model is calibrated through test simulations with a decade of local meteorological data. Chapter 5 demonstrates some practical applications of continuous simulation by the recommended methods. Appendix A presents a procedure for calculation of daily net radiation, a required input to the continuous simulation model. A digital appendix provides a decade of meteorological time-series data for continuous simulation of streamflow in Johnson County.

# CHAPTER 2

# CHARACTERISTICS OF STREAMFLOW IN JOHNSON COUNTY

Examination of the U. S. Geological Survey's streamflow data for Johnson County provides some insights into typical streamflow characteristics, which are useful for model calibration. The USGS currently measures streamflows at the nine locations listed in Table 2-1. Drainage areas at these gages range from 7.9 to 76 square miles, and the watershed conditions range from rural to urban. Two stations have record lengths over 30 years, two have 13-year records, and the other five have fewer than five years of record.

Table 2-1 USGS streamflow-gaging stations in Johnson County

| Station number | Station name | Drainage area (mi$^2$) | Start of daily record |
|---|---|---|---|
| 6892360 | Kill Creek at 95th Street near DeSoto | 53.4 | 3/27/2003 |
| 6892495 | Cedar Creek near DeSoto | 58.4 | 10/1/2002 |
| 6892513 | Mill Creek at Johnson Drive, Shawnee | 58.1 | 10/1/2002 |
| 6893080 | Blue River near Stanley | 46 | 9/20/1974 |
| 6893100 | Blue River at Kenneth Road, Overland Park | 76 | 4/16/2003 |
| 6893300 | Indian Creek at Overland Park | 26.6 | 3/7/1963 |
| 6893390 | Indian Creek at State Line Road, Leawood | 64.17 | 4/22/2003 |
| 6914950 | Big Bull Creek near Edgerton | 28.7 | 7/7/1993 |
| 6914990 | Little Bull Creek near Spring Hill | 7.86 | 10/1/1993 |
| 6892000* | Stranger Creek near Tonganoxie | 406 | 4/21/1929 |

*Leavenworth County, included for comparison

Table 2-2 lists some key streamflow statistics for these nine stations. The statistics are the mean annual runoff depth (mean annual streamflow volume divided by drainage area), the corresponding mean discharge, and the discharges exceeded 10%, 50% and 90% of the time. The discharge statistics are normalized by drainage area (in cfs/mi$^2$). Statistics for Stranger Creek near Tonganoxie, in neighboring Leavenworth County, are included for comparison.

The differences in the streamflow statistics for the ten gages reflect differences in watershed conditions, record lengths and other factors. The Little Bull Creek, Big Bull Creek, Kill Creek and Stranger Creek watersheds are almost entirely rural at present. The Cedar Creek and Blue River watersheds are mostly rural, the Mill Creek watershed is mostly urban, and the Indian Creek watershed is almost entirely urban. The watersheds of the Indian Creek gage at Overland Park (Marty Street) and the Blue River gage near Stanley have experienced considerable urbanization since the gages were installed in 1967 and 1974.

Table 2-2 Streamflow statistics for USGS gaging stations in Johnson County

| Station name | Water-years of record | Mean annual runoff (in.) | Discharge ($cfs/mi^2$) | | | |
|---|---|---|---|---|---|---|
| | | | Mean | 10% exceeds | 50% exceeds | 90% exceeds |
| Kill Cr. at 95th St. | 3 | 7.60 | 0.560 | 0.768 | 0.122 | 0.026 |
| Cedar Cr. near DeSoto | 4 | 7.98 | 0.588 | 0.822 | 0.188 | 0.057 |
| Mill Cr. at Johnson Dr. | 4 | 10.43 | 0.769 | 1.153 | 0.241 | 0.077 |
| Blue R. near Stanley | 32 | 10.38 | 0.765 | 1.174 | 0.107 | 0.002 |
| Blue R. at Kenneth Rd. | 3 | 10.72 | 0.790 | 1.158 | 0.171 | 0.029 |
| Indian Cr. at Overland Park** | 43 | 18.25 | 1.344 | 2.180 | 0.526 | 0.060 |
| Indian Cr. at State Line Rd.** | 3 | 19.11 | 1.408 | 2.228 | 0.499 | 0.327 |
| Big Bull Cr. near Edgerton | 13 | 9.77 | 0.720 | 0.767 | 0.087 | 0.017 |
| Little Bull Cr. near Spring Hill | 13 | 13.88 | 1.023 | 1.221 | 0.178 | 0.042 |
| Stranger Cr. near Tonganoxie* | 77 | 8.21 | 0.605 | 1.045 | 0.099 | 0.005 |

*Leavenworth County, included for comparison
**Streamflow augmented by WWTP effluent

Statistics computed from a few years of data do not provide reliable estimates of the longer-term statistics because streamflow conditions vary greatly from year to year, as Figure 2-1 shows for the Blue River gage near Stanley. Annual runoff is much more variable than annual precipitation, and cannot be estimated reliably from annual precipitation alone, as Figure 2-2 shows. The gages on Kill Creek, Cedar Creek, Mill Creek, Blue River at Kenneth, and Indian Creek at State Line have fewer than 5 years of record. These records are too short to provide reliable estimates of the longer-term streamflow statistics for these gages.

The mean runoff depths and normalized streamflows are much higher for the Indian Creek gages than the other gages because Indian Creek conveys a large quantity of treated wastewater as well as runoff from rainfall. Johnson County Wastewater (JCW) provided five years of influent data for the two wastewater treatment plants that discharge into Indian Creek. For the five-year period 2002-2006, the inflow to the JCW's Middle Basin treatment plant, upstream of the USGS gage at Marty Street (0683300, Indian Creek at Overland Park), was 9.92 million gallons per day (mgd). None of this water originated as precipitation over the watershed, and nearly all of it was discharged into Indian Creek after treatment. A wastewater effluent discharge of 9.9 mgd (15.3 cfs) would augment the annual streamflow by 11,100 acre-feet, which is equivalent to 7.8 inches of runoff from the 26.6-$mi^2$ watershed of the USGS gage at Marty Street. The average flow of wastewater effluent from the Middle Basin treatment plant over the stream gage's 43-year period of record (1964-2006) would have been somewhat less than the average for 2002-2006. A reasonable estimate of the average effluent flow for 1964-2006 would be 80% of the average for 2002-2006. This average effluent flow would be equivalent to 6.26 inches of runoff from the watershed. Subtracting the estimated wastewater effluent from the measured streamflow at the gage reduces the mean annual runoff from 18.25 inches to 12.0 inches.

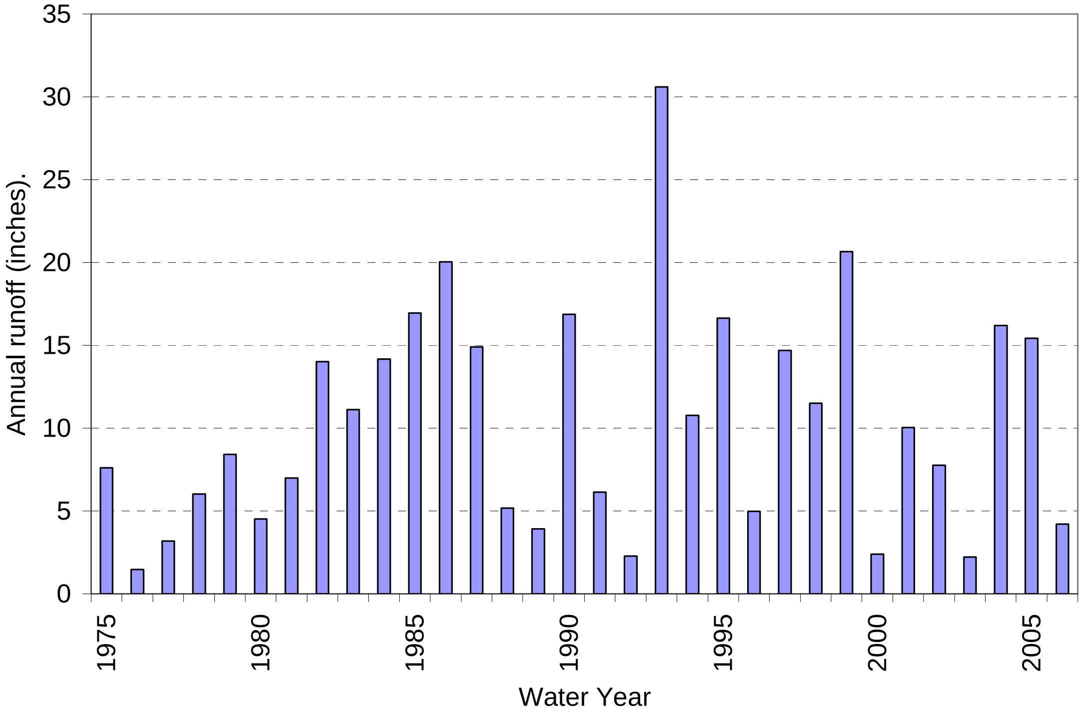


Figure 2-1 Annual runoff depths for Blue River near Stanley, WY 1975-2006

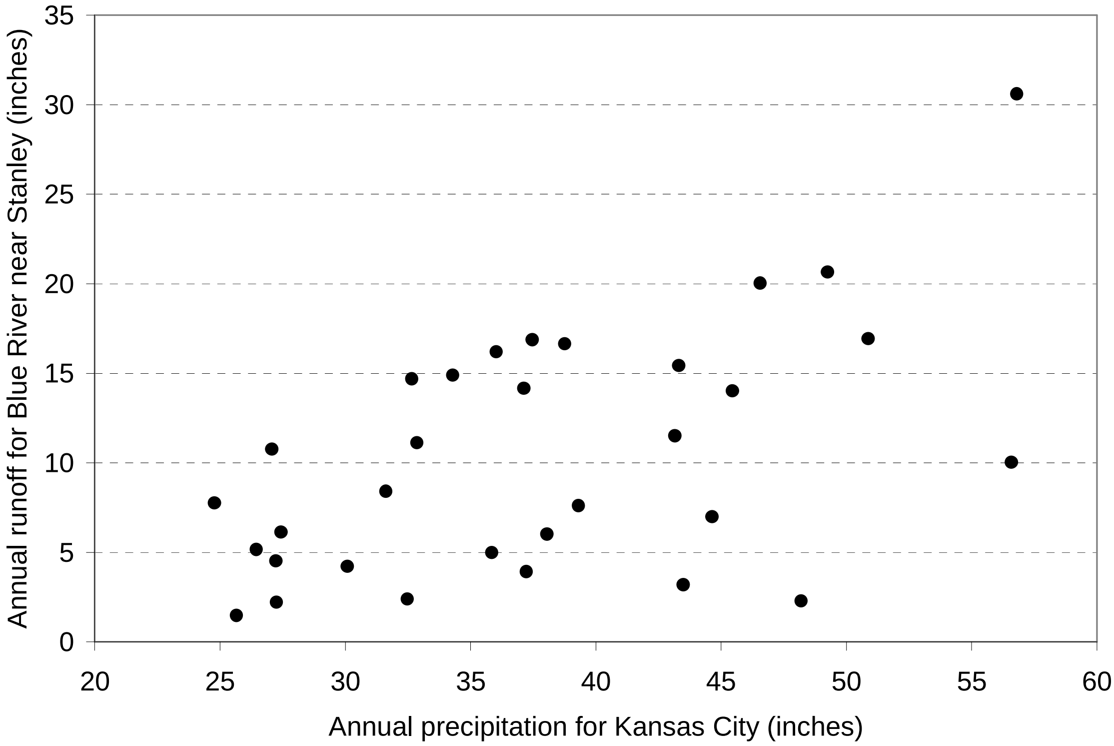


Figure 2-2 Annual runoff vs. precipitation for Blue River near Stanley, WY 1975-2006

The data in Table 2-2 indicate that a long-term mean annual runoff of 10 inches is typical for rural watersheds in Johnson County. The mean annual precipitation for Johnson County is approximately 39 inches per year (Rasmussen and Perry, 2000). Therefore, in rural areas of Johnson County, streamflow accounts for approximately one-fourth of precipitation over the long term, and evapotranspiration accounts for the other three-fourths.

Most streamflow in Johnson County originates as direct runoff from rainfall, and recedes quickly after rainfall ceases. Base flows (dry-weather flows) resulting from groundwater drainage are quite small. The data in Table 2-2 indicate that discharges in a rural streams are typically below 1.0 cfs/mi$^2$ approximately 90% of the time. Discharges in this range have negligible erosion potential. Streamflows resulting from snowmelt are generally small and do not contribute to stream instability.

The entire spectrum of streamflows at a given location can be represented by a flow-duration curve: a plot of discharge versus the percentage of time that the discharge is exceeded. Figure 2.3 shows a flow-duration for Big Bull Creek near Edgerton, developed from hourly streamflow data for the period 2002-2006. This flow-duration curve covers only flows exceeded 10% or less of the time. The flows that occur the other 90% of the time are negligible by comparison. This pattern is typical for Johnson County streams.

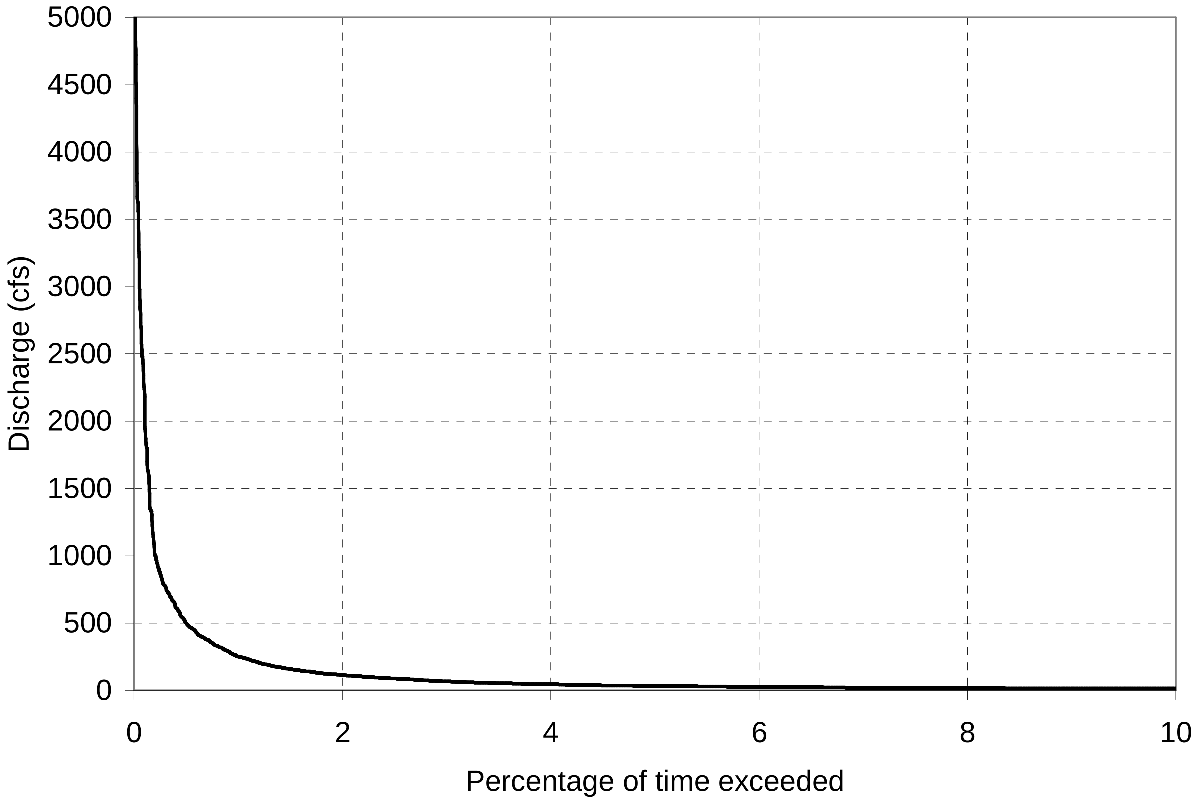


Figure 2-3. Flow-duration curve for Big Bull Creek near Edgerton, WY 2002-06, hourly data

# CHAPTER 3

# CONTINUOUS SIMULATION OF STREAMFLOW WITH HEC-HMS

## 3.1 HEC-HMS Overview

HEC-HMS basin models for single-event and continuous simulation differ only at the subbasin level. Surface runoff and groundwater flow are computed with a soil-moisture accounting (SMA) model rather than a simple loss model. The SMA model accounts for evapotranspiration and percolation between rainfall events as well as infiltration and other losses during rainfall events. Modeling of snowpack accumulation and snowmelt is optional. HEC-HMS generates a continuous streamflow record for the subbasin from the direct-runoff and baseflow records by the same methods used in single-event simulation. Direct runoff is transformed to streamflow by a user-selected transform method. The transform options include several unit-hydrograph methods, the Clark time-area method and a kinematic wave method. Downstream processes such as channel routing and reservoir routing are handled the same for continuous simulation as for single-event simulation.

## 3.2 Soil-Moisture Accounting

Figure 3-1 shows the conceptual design of the soil-moisture accounting module. Water is stored on the canopy, in surface depressions, in the soil profile, and in two groundwater layers. Canopy storage is considered an initial loss that must be satisfied before any precipitation reaches the soil surface. Infiltration is deducted from the precipitation that exceeds the canopy storage capacity. Precipitation that cannot be infiltrated is allocated to depression storage. Overflow from depression storage becomes surface runoff (direct runoff, future streamflow). Canopy interception is computed identically for the pervious and impervious parts of the subbasin. No infiltration or depression-storage losses are deducted from precipitation onto impervious surfaces. All impervious surfaces are assumed to be “directly connected”; i.e., runoff from impervious surfaces has no second chance to infiltrate. Water is removed from canopy storage by evaporation. Water is removed from depression storage by evaporation and infiltration.

The maximum rate at which water can be absorbed into the soil at a particular instant is termed the potential infiltration rate. The potential infiltration rate varies with the water content of the soil. The soil-moisture accounting module assumes that the potential infiltration rate decreases linearly with increasing water content as shown in Figure 3-2. The actual infiltration rate is the lesser of the potential infiltration rate and the rate at which precipitation reaches the soil surface.

Soil-moisture storage is partitioned into two zones: an upper zone and a tension zone. Water is removed from the upper zone by evapotranspiration (ET) and by percolation (gravity drainage) to the upper groundwater layer. Water is removed from the tension zone by ET but not by percolation. ET is extracted from the tension zone only when the upper-zone storage is depleted. The rate of percolation between two adjacent layers depends on a user-specified maximum rate and the degrees of saturation of the two layers.

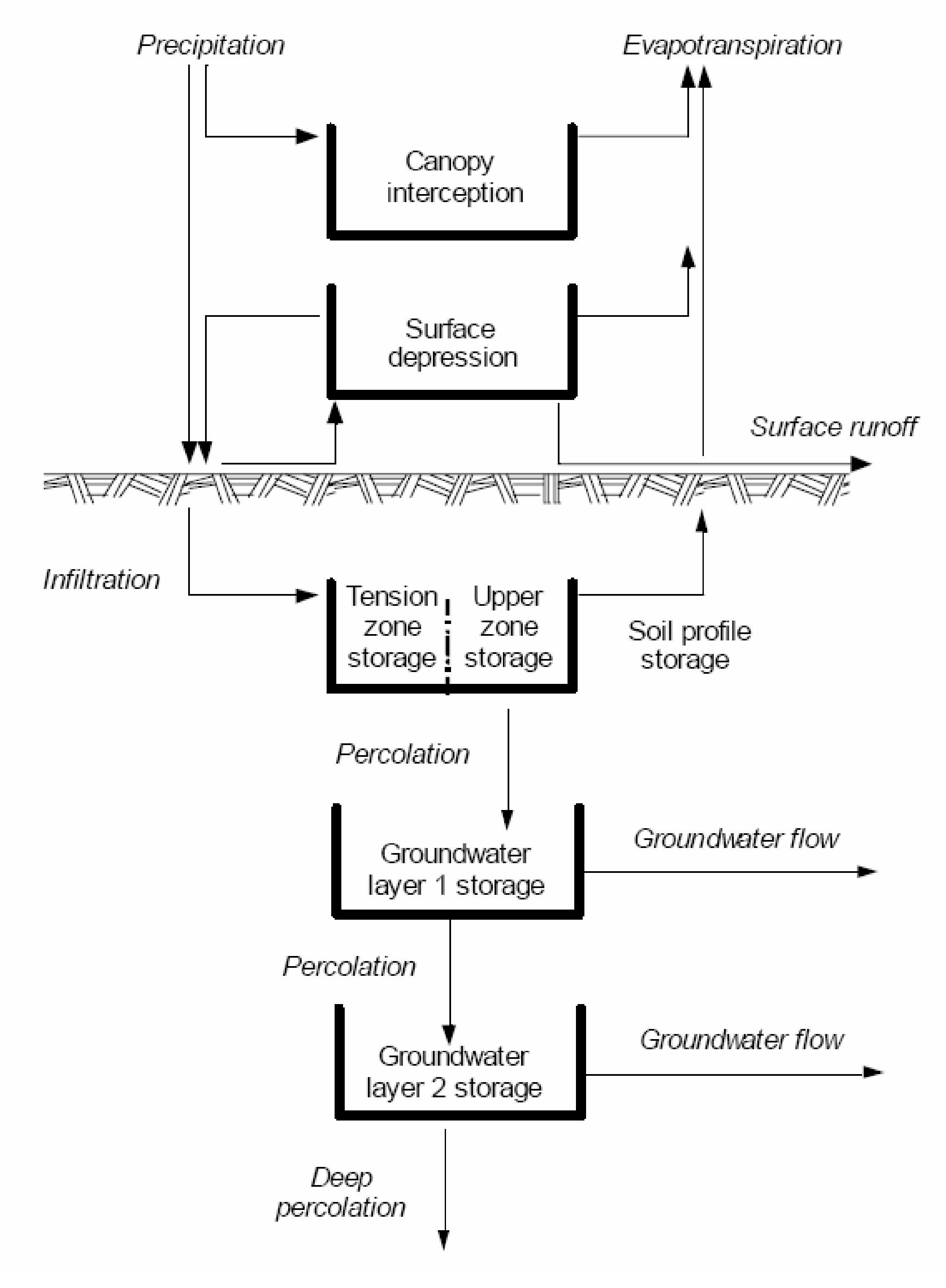


Figure 3-1. Schematic diagram of HEC-HMS soil-moisture accounting module

The two groundwater layers are optional. The upper groundwater layer can be used to account for shallow subsurface flow processes such as drainage of saturated hill slopes. The lower groundwater layer can represent a more extensive aquifer that is hydraulically connected to the stream. Lateral outflow from the groundwater layers can be routed to the stream as baseflow.

The rate of evapotranspiration depends on weather conditions, vegetative cover conditions, and the amounts of water stored on the canopy, in surface depressions and in the soil. Potential evapotranspiration is defined as the evapotranspiration that would occur with specified weather and vegetative cover conditions and unlimited soil moisture. The user can input monthly-average values of potential ET, or the program can compute potential ET from user-input net radiation and temperature data by the Priestly-Taylor method.

HEC-HMS assumes zero ET during periods of rainfall. At all other times, the evaporative demand is met first from canopy storage, then from surface storage, and finally from the upper-zone soil storage. The rate of evapotranspiration from the soil is the product of the potential ET rate and a water-stress coefficient. The water-stress coefficient is related to the water content of the tension zone, expressed as a percentage of capacity, as shown in Figure 3-3. When the water content of the tension zone exceeds 60% of capacity, ET is not limited by water availability. HEC-HMS assumes zero ET during periods of rainfall.

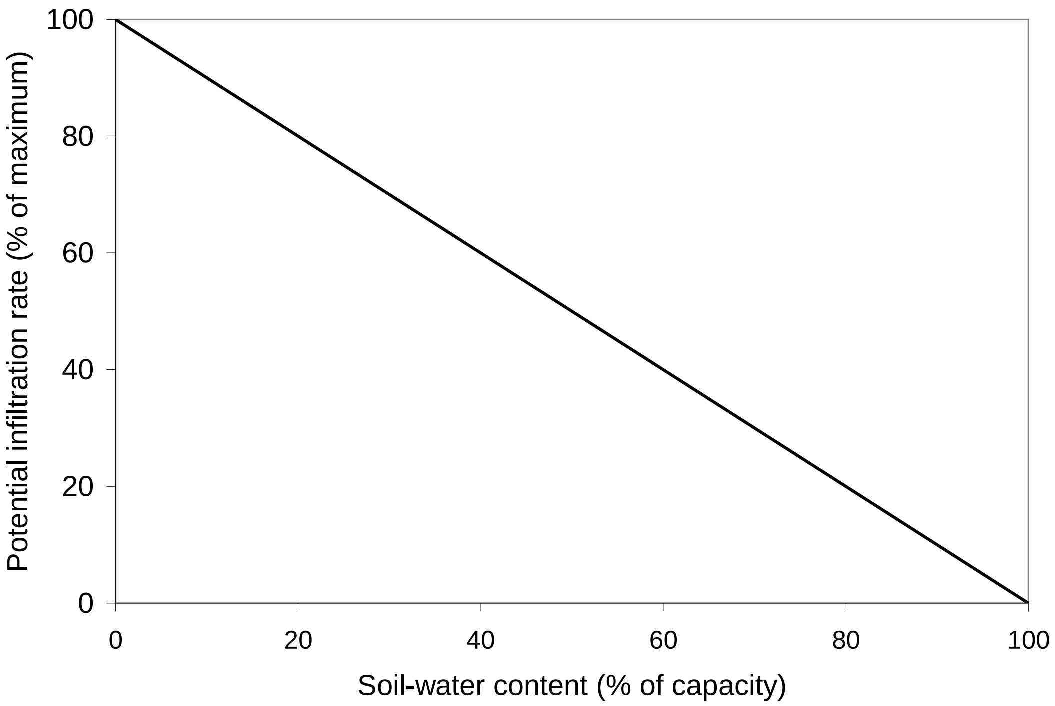


Figure 3-2. Relationship for potential infiltration rate in SMA module

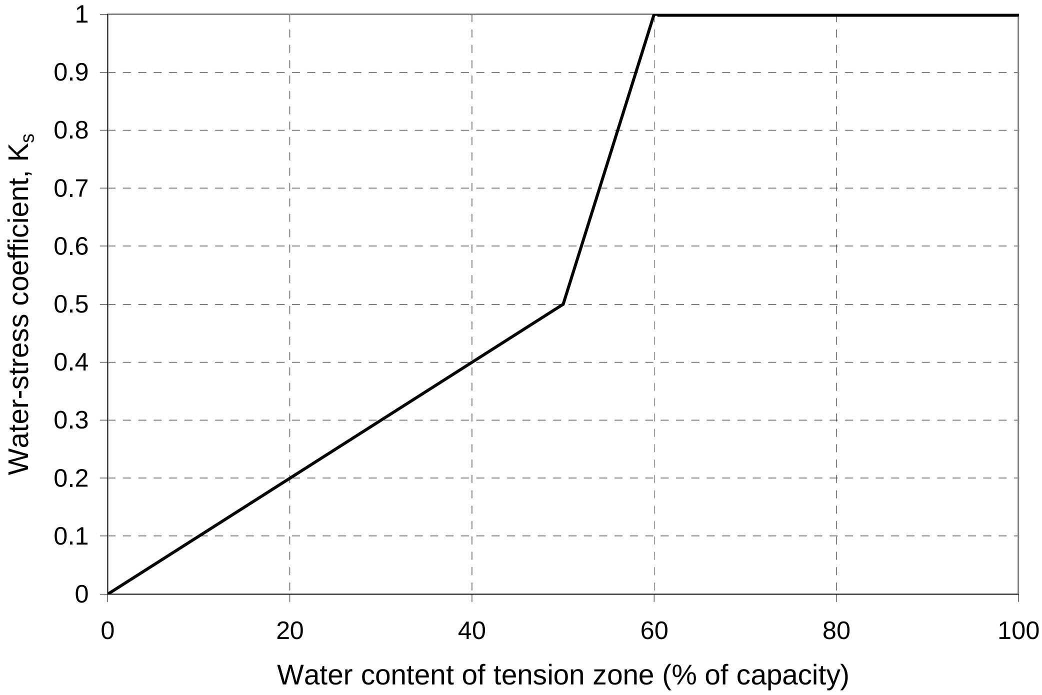


Figure 3-3. Relationship for water-stress coefficient in SMA module

Twelve parameters and five initial conditions are required to characterize the canopy, surface, soil and groundwater storage units. The twelve parameters are:

Canopy storage (inches)
Surface storage (inches)
Maximum infiltration rate (inches per hour)
Impervious surface area (%)
Total soil storage (inches)
Soil tension storage (inches)
Groundwater layer 1 storage (inches)
Groundwater layer 1 maximum percolation rate (inches per hour)
Groundwater layer 1 storage coefficient (hours)
Groundwater layer 2 storage (inches)
Groundwater layer 2 maximum percolation rate (inches per hour)
Groundwater layer 2 storage coefficient (hours)

The five initial conditions are:

Canopy storage initially filled (%)
Surface storage initially filled (%)
Soil storage initially filled (%)
Groundwater layer 1 storage initially filled (%)
Groundwater layer 2 storage initially filled (%)

### 3.3 Potential Evapotranspiration

Potential infiltration rates can be input as monthly average values or computed from net radiation and temperature data by the Priestly-Taylor method. We recommend the monthly-average method at present. The Priestly-Taylor method was added to HEC-HMS with the release of Version 3.0 in December 2005. The method is poorly documented in HEC-HMS Versions 3.0 through 3.4. The program and User's Manual misstate the input requirements for the method, and the Technical Reference Manual, published in December 2002, does not include it. An explanation of the Priestly-Taylor method and a correct statement of the input requirements are provided below.

The Priestly-Taylor equation yields an estimate of the reference evapotranspiration rate, defined as the ET rate for a hypothetical grass reference crop with specific characteristics and abundant water (Allen et al., 1998). The reference ET rate depends only on meteorological conditions: primarily solar radiation, air temperature, humidity and wind speed. To obtain the potential ET rate for a particular type and condition of vegetation, the reference ET rate is multiplied by a crop coefficient that accounts for the vegetation type and condition. The recommended value of the crop coefficient for established cool-season turf grass, the most common vegetative cover in the developed portions of Johnson County, is 0.95 (Allen et al., 1998).

The Priestly-Taylor equation for reference ET is (Priestly and Taylor, 1972):

$$ET_o = \frac{C}{L_e \rho} \cdot \frac{\Delta}{\Delta + \Gamma}\left(R_n - G\right)$$

in which

$ET_o$ = potential ET
$C$ = dryness coefficient (dimensionless constant)
$L_e$ = latent heat of vaporization
$\rho$ = density of water
$\Delta$ = slope of saturation vapor pressure versus temperature curve (function of temperature)
$\Gamma$ = psychrometric constant
$R_n$ = net radiation
$G$ = heat loss to the ground

The recommended value of the dryness coefficient for non-arid climates is 1.26 (Priestly and Taylor, 1972; Shuttleworth, 1993). The heat loss (or gain) to the ground is usually small in comparison to net radiation on a daily basis, and averages to zero over the long term. HEC-HMS neglects the heat loss to the ground.

Net radiation, $R_n$, is the difference between the net incoming shortwave radiation, $R_{ns}$, and the net outgoing longwave radiation, $R_{nl}$:

$$R_n = R_{ns} - R_{nl}$$

The net shortwave radiation is the portion of the incident solar radiation not reflected by the surface. The reflected fraction of incident solar radiation is termed the albedo, α. Incident shortwave radiation, net shortwave radiation and albedo are related as follows:

$$R_{ns} = (1 - \alpha)\, R_s$$

The accepted value of albedo for the hypothetical grass reference crop is 0.23 (Allen et al., 1998). Daily incident solar radiation depends mainly on latitude, time of year (Julian date) and cloud cover. The net outgoing longwave radiation is the difference between the longwave radiation emitted and the longwave radiation absorbed by the surface. On a daily basis, the net outgoing longwave radiation depends mainly on temperature, humidity and cloud cover. Appendix A presents the relationships for calculation of daily net radiation from solar radiation and weather data by the United Nations Food and Agriculture Organization's recommended method (Allen, et al., 1998).

The correct inputs to the Priestly-Taylor potential evapotranspiration routine in HEC-HMS are a dryness coefficient and time-series data for net radiation, temperature and the crop coefficient. The HEC-HMS program and User's Manual mistakenly state that the required radiation input is solar radiation rather than net radiation. Our tests showed that the program uses the "solar" radiation time-series data as <u>net</u> radiation the Priestly-Taylor equation. Therefore, <u>net radiation time-series data should be input in place of solar radiation data.</u>

### 3.4 Time-Series Output for Subbasins

HEC-HMS provides complete time-series output for the following hydrologic processes and storage units for each subbasin:

- Outflow (total streamflow)
- Potential ET
- Canopy overflow
- Canopy ET
- Canopy storage
- Surface ET
- Surface storage
- Incremental precipitation
- Soil storage
- Soil percolation
- Soil ET
- Soil saturation fraction
- Groundwater layer 1 storage
- Groundwater layer 1 lateral flow
- Groundwater layer 1 percolation
- Groundwater layer 2 storage
- Groundwater layer 2 lateral flow
- Groundwater layer 2 percolation
- Excess precipitation
- Precipitation loss
- Direct runoff
- Baseflow

# CHAPTER 4

# A CONTINUOUS HYDROLOGIC MODEL FOR JOHNSON COUNTY

## 4.1 Model Framework

The continuous simulation capabilities in HEC-HMS, as described in Chapter 3, are quite general and adaptable to a wide range of hydrologic settings. However, a watershed model that incorporated all of these capabilities would be difficult to calibrate due to an excessive number of uncertain inputs. A model intended for a certain range of conditions can be simplified and thereby improved by neglecting components and processes that have little effect on streamflow under these conditions.

This chapter develops the subbasin runoff component of a continuous streamflow model for Johnson County. This model is calibrated through test simulations using local precipitation data for the period 1997-2006. Potential ET is determined from user-input monthly average values. are computed by the Priestly-Taylor radiation-based method. The model is calibrated by adjusting the values of key inputs to obtain a target value of mean annual runoff for undeveloped conditions.

The number of inputs that must be estimated or calibrated is reduced to a workable number by not modeling two processes that have little effect on streamflow characteristics:

- Snowpack accumulation and snowmelt are not modeled. All precipitation is considered to be rainfall.

- The groundwater layers are omitted from the SMA model. Percolation and groundwater drainage (baseflow) are not modeled. Water is removed from soil storage only by evapotranspiration.

Omitting the groundwater layers reduces the number of SMA model parameters from twelve to six, and the number of initial conditions from five to three.

Subbasin runoff is transformed to streamflow by the NRCS unit-hydrograph method and channel routing is performed by the Muskingum-Cunge method, as in the county-wide watershed studies.

## 4.2 Precipitation Data

Continuous simulation of streamflow requires a continuous record of precipitation with an appropriate time interval. Precipitation records for the tests of the Johnson County subbasin model were developed from data recorded at ALERT gage 1100, Overland Park City Hall. The gage data were converted from the original fixed-depth-interval format to the required fixed-time-interval format with a computer program written for this task. We generated records of incremental precipitation for the decade 1997-2006 with time intervals of 5 minutes, 15 minutes and 1 hour. These precipitation datasets are provided in a digital appendix to this report.

Gage 1100 recorded a total of 382 inches of precipitation over this decade, for a mean annual precipitation of 38.2 inches, a typical long-term mean for gages in the Kansas City area. Table 4-1 provides monthly and annual precipitation totals and summary statistics. The record exhibits large year-to-year variability in monthly and annual precipitation totals, as is typical for the Central Plains. Figure 4-1 shows the variability of the annual precipitation over this decade.

Table 4-1. Precipitation at ALERT gage 1100, Overland Park City Hall, 1997-2006

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ann |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1997 | 1.14 | 3.58 | 0.98 | 3.70 | 4.61 | 2.83 | 1.38 | 3.70 | 3.03 | 3.78 | 0.16 | 0.00 | 28.89 |
| 1998 | 0.00 | 0.59 | 3.86 | 2.72 | 1.50 | 8.74 | 7.07 | 2.43 | 10.46 | 9.40 | 5.32 | 1.18 | 53.27 |
| 1999 | 1.58 | 0.87 | 0.98 | 6.89 | 5.59 | 7.80 | 0.39 | 2.91 | 5.39 | 0.55 | 0.94 | 1.97 | 35.86 |
| 2000 | 0.16 | 2.09 | 2.05 | 0.91 | 3.62 | 7.40 | 6.76 | 2.06 | 3.15 | 4.57 | 2.05 | 0.55 | 35.37 |
| 2001 | 0.51 | 4.60 | 2.36 | 1.85 | 3.39 | 9.14 | 3.11 | 4.80 | 3.74 | 3.03 | 0.67 | 0.67 | 37.87 |
| 2002 | 2.17 | 0.98 | 1.10 | 5.51 | 6.57 | 2.36 | 1.46 | 2.05 | 1.14 | 3.98 | 0.35 | 0.00 | 27.67 |
| 2003 | 0.24 | 1.26 | 1.85 | 4.22 | 2.31 | 5.24 | 0.71 | 10.14 | 2.46 | 0.87 | 1.14 | 3.11 | 33.55 |
| 2004 | 1.03 | 1.61 | 7.91 | 2.53 | 6.57 | 5.75 | 7.60 | 7.21 | 2.16 | 2.78 | 4.15 | 0.75 | 50.05 |
| 2005 | 3.54 | 2.80 | 1.30 | 1.65 | 3.86 | 9.45 | 2.72 | 11.34 | 5.04 | 2.76 | 0.91 | 1.10 | 46.47 |
| 2006 | 0.83 | 0.00 | 1.69 | 2.05 | 1.65 | 3.70 | 4.80 | 7.83 | 1.97 | 4.53 | 1.69 | 2.20 | 32.94 |
| | | | | | | | | | | | | | |
| Min | 0.00 | 0.00 | 0.98 | 0.91 | 1.50 | 2.36 | 0.39 | 2.05 | 1.14 | 0.55 | 0.16 | 0.00 | 27.67 |
| Max | 3.54 | 4.60 | 7.91 | 6.89 | 6.57 | 9.45 | 7.60 | 11.34 | 10.46 | 9.40 | 5.32 | 3.11 | 53.27 |
| Avg | 1.12 | 1.84 | 2.41 | 3.20 | 3.97 | 6.24 | 3.60 | 5.45 | 3.85 | 3.63 | 1.74 | 1.15 | 38.19 |
| S.D. | 1.08 | 1.44 | 2.12 | 1.88 | 1.86 | 2.65 | 2.76 | 3.46 | 2.67 | 2.45 | 1.70 | 1.00 | 8.80 |

S.D. = standard deviation

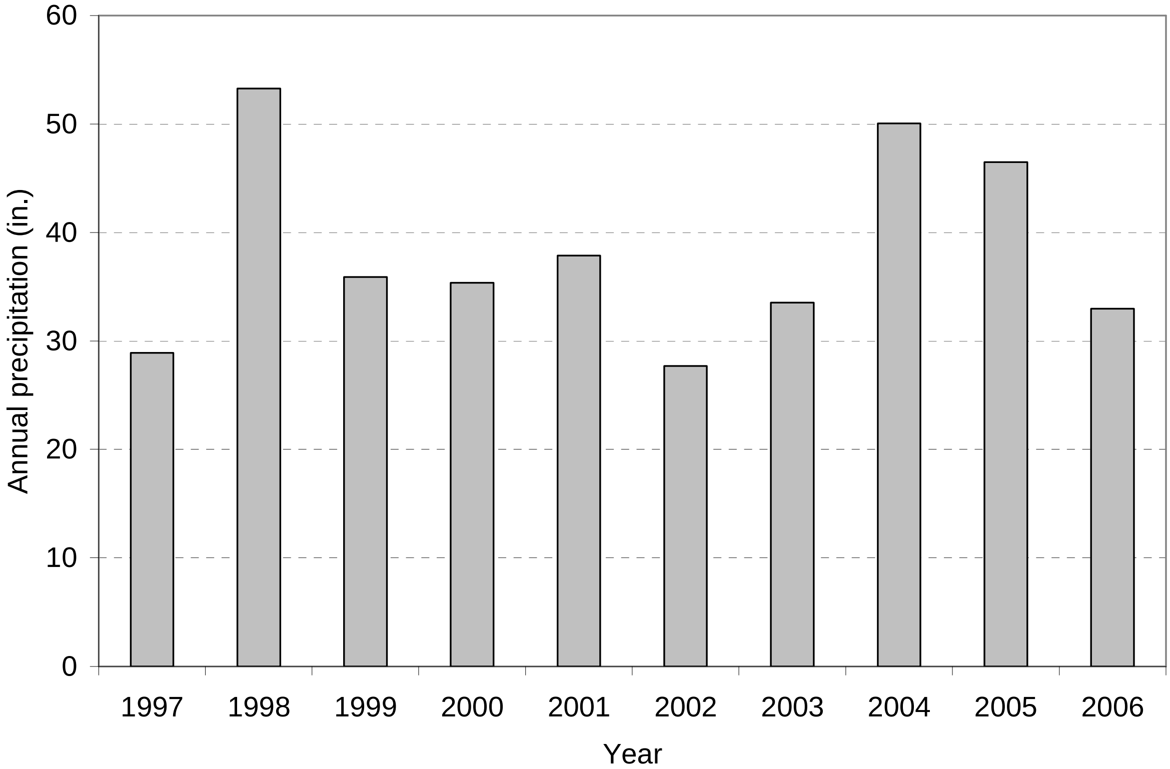


Figure 4-1. Annual precipitation at ALERT gage 1100, Overland Park City Hall, 1997-2006

### 4.3 Potential Evapotranspiration

Potential or reference evapotranspiration is not measured directly, but rather computed from meteorological data. The preferred method for calculation of reference ET is the Penman-Monteith method as presented in the United Nations Food and Agriculture Organization's report FAO-56 (Allen et al., 1998). The required meteorological inputs are solar radiation, temperature, humidity and wind speed. No long-term records of solar radiation are available for Johnson County. However, these data have been measured at Kansas State University's East Central Kansas Experiment Field near Ottawa, Kansas, since 1985. A record of daily values of reference ET for grass at this site for the period 1997-2006, computed by the FAO-56 Penman-Monteith method, were provided by the Kansas Weather Data Library at Kansas State University (www.oznet.ksu.edu/wdl) Table 4-2 shows the monthly and annual values and statistics for 1997-2006. Figure 4-2 shows the daily values of reference ET for calendar year 2006.

The Johnson County ALERT system now includes a complete weather station that records solar radiation and the other weather data needed to compute net radiation. This weather station is located at the Johnson County Transit Building in Olathe. The data are recorded at 15-minute intervals. The complete data records, dating from February 2006, are accessible through the ALERT system website, www.stormwatch.com.

Table 4-2. Monthly reference ET for grass, Ottawa, 1997-2006

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ann |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1997 | 0.85 | 1.07 | 2.85 | 3.12 | 4.89 | 5.48 | 5.98 | 4.76 | 3.64 | 2.36 | 1.00 | 0.53 | 36.53 |
| 1998 | 0.67 | 0.97 | 1.61 | 3.41 | 5.35 | 5.77 | 5.02 | 5.05 | 3.71 | 2.06 | 1.15 | 0.72 | 35.49 |
| 1999 | 0.60 | 1.33 | 2.39 | 2.71 | 4.23 | 4.28 | 6.47 | 5.40 | 3.73 | 3.36 | 2.67 | 1.29 | 38.46 |
| 2000 | 1.52 | 1.78 | 2.28 | 3.68 | 4.67 | 4.73 | 5.84 | 7.01 | 5.24 | 2.44 | 0.93 | 0.49 | 40.61 |
| 2001 | 0.58 | 0.75 | 2.07 | 3.94 | 4.60 | 5.23 | 6.12 | 5.78 | 3.44 | 2.65 | 1.45 | 0.89 | 37.50 |
| 2002 | 1.26 | 1.58 | 2.38 | 3.19 | 3.98 | 5.51 | 6.12 | 5.46 | 4.70 | 1.65 | 1.21 | 0.89 | 37.93 |
| 2003 | 0.88 | 0.90 | 2.21 | 3.45 | 4.37 | 4.66 | 7.19 | 5.92 | 3.27 | 2.39 | 1.06 | 0.71 | 37.01 |
| 2004 | 0.67 | 1.03 | 2.17 | 3.31 | 4.07 | 4.50 | 4.92 | 4.29 | 3.96 | 1.80 | 0.86 | 0.74 | 32.32 |
| 2005 | 0.51 | 0.96 | 2.21 | 3.36 | 4.74 | 5.25 | 5.84 | 4.31 | 3.75 | 2.50 | 1.90 | 0.78 | 36.11 |
| 2006 | 1.68 | 1.66 | 2.74 | 4.56 | 4.75 | 6.11 | 6.69 | 5.44 | 3.62 | 2.48 | 1.66 | 1.01 | 42.40 |
| | | | | | | | | | | | | | |
| Min | 0.51 | 0.75 | 1.61 | 2.71 | 3.98 | 4.28 | 4.92 | 4.29 | 3.27 | 1.65 | 0.86 | 0.49 | 29.32 |
| Max | 1.68 | 1.78 | 2.85 | 4.56 | 5.35 | 6.11 | 7.19 | 7.01 | 5.24 | 3.36 | 2.67 | 1.29 | 49.09 |
| Avg | 0.92 | 1.20 | 2.29 | 3.47 | 4.57 | 5.15 | 6.02 | 5.34 | 3.91 | 2.37 | 1.39 | 0.81 | 37.44 |
| S.D. | 0.42 | 0.36 | 0.35 | 0.50 | 0.41 | 0.59 | 0.69 | 0.81 | 0.60 | 0.48 | 0.56 | 0.23 | 2.76 |

S.D. = standard deviation

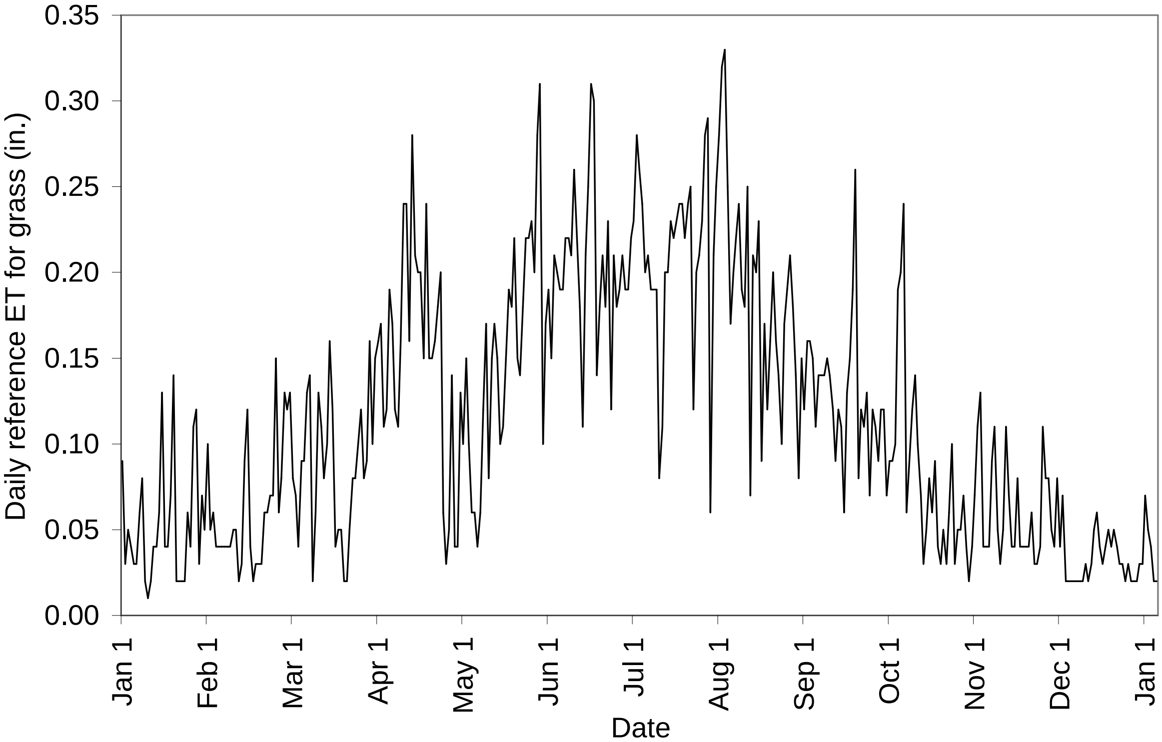


Figure 4-2. Daily reference ET for grass, Ottawa, 2006

### 4.4 Partitioning of Soil Storage

In HEC-HMS, soil-profile storage accounts for water that can be removed from the top layer of the soil by percolation or evapotranspiration. It does not include water retained in the soil at the wilting point, which cannot be removed by these processes. Therefore, the soil-profile storage capacity in HEC-HMS is the difference between the water content at saturation (the porosity of the soil) and the water content at the wilting point (the water content below which ET ceases). The water content of a soil is defined as the volume of water in a unit bulk volume of soil. It is a dimensionless quantity.

The soil-profile storage is partitioned into an upper zone with percolation potential and a tension zone with no percolation. The water content below which no percolation occurs is commonly termed the field capacity. The upper-zone capacity is the difference between the water contents at saturation and field capacity. The tension-zone capacity is the difference between the water contents at field capacity and wilting point.

According the *Soil Survey of Johnson County, Kansas* (USDA, 1979), soils classified as silt loams cover the majority of the land area in Johnson County. Test data published by the Agricultural Research Service (ARS) of the U. S. Department of Agriculture (Rawls, et al., 1982) indicate the following average water-retention characteristics for silt-loam soils:

Water content at saturation (porosity) = 0.501
Water content at field capacity (1/3 bar suction) = 0.284
Water content at wilting point (15 bars suction) = 0.136

These water contents represent inches of water in storage per inch of soil depth. The corresponding dimensionless values of soil storage, tension-zone storage and upper-zone storage, as defined by HEC-HMS, are:

Soil storage = 0.365 inches per inch of soil depth
Tension-zone storage = 0.148 inches per inch of soil depth
Upper-zone storage = 0.217 inches per inch of soil depth

These average characteristics indicate that, for a typical silt-loam soil, the tension storage is approximately 40% of the soil storage. In the continuous simulation model for Johnson County, soil storage is used as a calibration parameter and tension-zone storage is set to 40% of soil storage in all cases to simplify the calibration.

### 4.5 Durations and Time Steps for Continuous Simulations

Ideally, a decade or more of streamflow record should be simulated to average out the year-to-year variability. Because small watersheds respond quickly to rainfall, a short computational time step is needed to obtain a realistic streamflow hydrograph. (The NRCS unit-hydrograph guidelines state that the computational time step should not exceed 29% of the watershed's time of concentration.) A computational time step of 5 minutes is desirable; however, practical constraints may dictate a 15-minute time step. If runoff volumes are the primary concern, a one-hour time step may be adequate.

The duration of the simulation and the computational time step determine the size of the time-series records that the HEC-HMS program and the user must manipulate. Table 4-3 shows the array sizes for several combinations of duration and time step. A decade of simulation with a 5-minute time step requires HEC-HMS to process time-series records containing more than a million values.

Table 4-3. Sizes of time-series records for different durations and time steps

| Duration of simulation | Time step | Number of values in record |
|---|---|---|
| 1 year | 1 hr | 8760 |
| 1 year | 15 min | 35,040 |
| 1 year | 5 min | 105,120 |
| 10 years | 1 hr | 87,600 |
| 10 years | 15 min | 350,400 |
| 10 years | 5 min | 1,051,200 |

HEC-HMS stores input data and simulation results in a HEC-DSS Data Storage System database. Input data are normally entered manually through the graphical user interface. Copy-and-paste operations are used to transfer time-series input from spreadsheets or text files into HEC-HMS tables, and to transfer time-series output from HEC-HMS tables to spreadsheets or text files for post-processing. Alternatively, time-series data can be input to the HEC-DSS database or extracted from the database using the HEC-DSSVue utility. In our tests, all time-series records were transferred into and out of HEC-HMS through the graphical user interface. We found that Excel 2007 works much better than Excel 2003 for pre-processing and post-processing of long time-series records. Excel 2007 worksheets can contain up to 1,048,576 rows; Excel 2003 worksheets are limited to 65,536 rows.

We ran trial simulations for the combinations of duration and step size in Table 4-3 to test the program's ability to handle large time-series arrays. Our test computer was a typical 2006-era business PC, a Dell Optiplex GX280 with an Intel Pentium 4 processor with a 3.4-GHz clock speed. This computer had 1 GB of RAM initially. Over the course of testing, we increased the amount of RAM twice: first to 2 GB, and then to 4 GB. We found that HEC-HMS Version 3.1.0 can run a 10-year simulation with a rainfall time step of one hour, or a one-year simulation with a rainfall time step of 5 minutes, on the test computer with 1 GB of RAM. Increasing the RAM from 1 GB to 2 GB enabled the program to run a 10-year simulation with a rainfall time step of 15 minutes. Increasing the RAM from 2 GB to 4 GB did not further increase the program's capabilities. HEC-HMS would not run a 10-year simulation with a rainfall time step of 5 minutes. When the rainfall data table was opened, the program slowed to a halt. The capabilities of the graphical user interface may be the limiting factor. Transferring the long time-series records into and out of HEC-HMS through the HEC-DSS database might sidestep this limitation. At present, we recommend the following:

- If runoff volumes are the main concern, simulate a decade of record with a one-hour time step.

- If peak runoff rates (i.e., peak discharges on small streams) are the main concern, run one-year simulations for selected years using a 5-minute time step.

### 4.6 Computational Quirks

Our tests of the simplified SMA model revealed some apparent bugs in this component of HEC-HMS Version 3.1.0. Setting the soil percolation rate or the groundwater layer 1 coefficient to zero can cause the program to behave erratically and return different, obviously incorrect results when repeated identical simulations are run. These problems, which probably result from division by zero, can be sidestepped by assigning these two inputs miniscule non-zero values. In our tests, we set the soil percolation rate to $10^{-10}$ inches per hour and the groundwater layer 1 coefficient to $10^{-6}$ hours.

### 4.7 Model Calibration

In the simplified SMA model for Johnson County described in Section 4.1, the canopy, surface and soil storage units are characterized by six parameters. Setting the soil tension storage to 40% of the total soil storage, as explained in Section 4.2, eliminates one parameter. The remaining five parameters are:

Canopy storage (inches)
Surface storage (inches)
Impervious surface area (%)
Maximum infiltration rate (inches per hour)
Soil storage (inches)

Much more precipitation is “lost” to soil infiltration than to canopy interception and depression storage; therefore, maximum infiltration rate and surface storage are more useful than canopy and surface storage for model calibration. The percentage of impervious surface area is a measurable quantity and should not be used as a calibration parameter.

The simplified SMA model for Johnson County was calibrated by adjusting the maximum infiltration rate and soil storage to achieve a target value of mean annual runoff. Canopy storage and surface storage were assigned typical values of 0.05 inches, and the impervious percentage was set to zero. The model was calibrated for the decade 1997-2006 with precipitation data from Overland Park City Hall (Section 4.2) and monthly average values of potential ET (reference ET for grass) from Kansas State University’s East Central Kansas Experiment Field near Ottawa (Table 4-2). Initial conditions were set to typical values for January 1: canopy storage 0% filled, surface storage 0% filled and soil storage 70% filled. The calibration target was a mean annual runoff of approximately 10 inches, a typical for rural watersheds in Johnson County (Chapter 2).

The calibration target was a mean annual runoff of approximately 10 inches, a typical for rural watersheds in Johnson County (Chapter 2).

### 4.7.1 Simulations with a One-Hour Time Step

Simulations were run for all possible combinations of six soil-storage values and five maximum infiltration rates, using one-hour time steps for rainfall and computations. Figure 4-3 shows the effects of these two inputs on mean annual runoff. Several combinations of soil storage and maximum infiltration rate yield mean annual runoffs of approximately 10 inches. Two such combinations are (1) a soil storage of 6 inches and a maximum infiltration rate of 0.5 inches per hour, and (2) a soil storage of 4 inches and a maximum infiltration rate of 1.0 inches per hour. Figure 4-4 compares runoff-duration curves developed from simulated streamflow records for these two combinations of inputs. The two curves differ slightly because the input combination with the larger soil storage and lower maximum infiltration rate results in runoff events with slightly higher peak rates and slightly shorter durations.

The inputs selected for the calibrated SMA model for Johnson County are a soil storage of 6 inches and a maximum infiltration rate of 0.5 inches per hour. These inputs are recommended for general use in simulations with one-hour time steps.

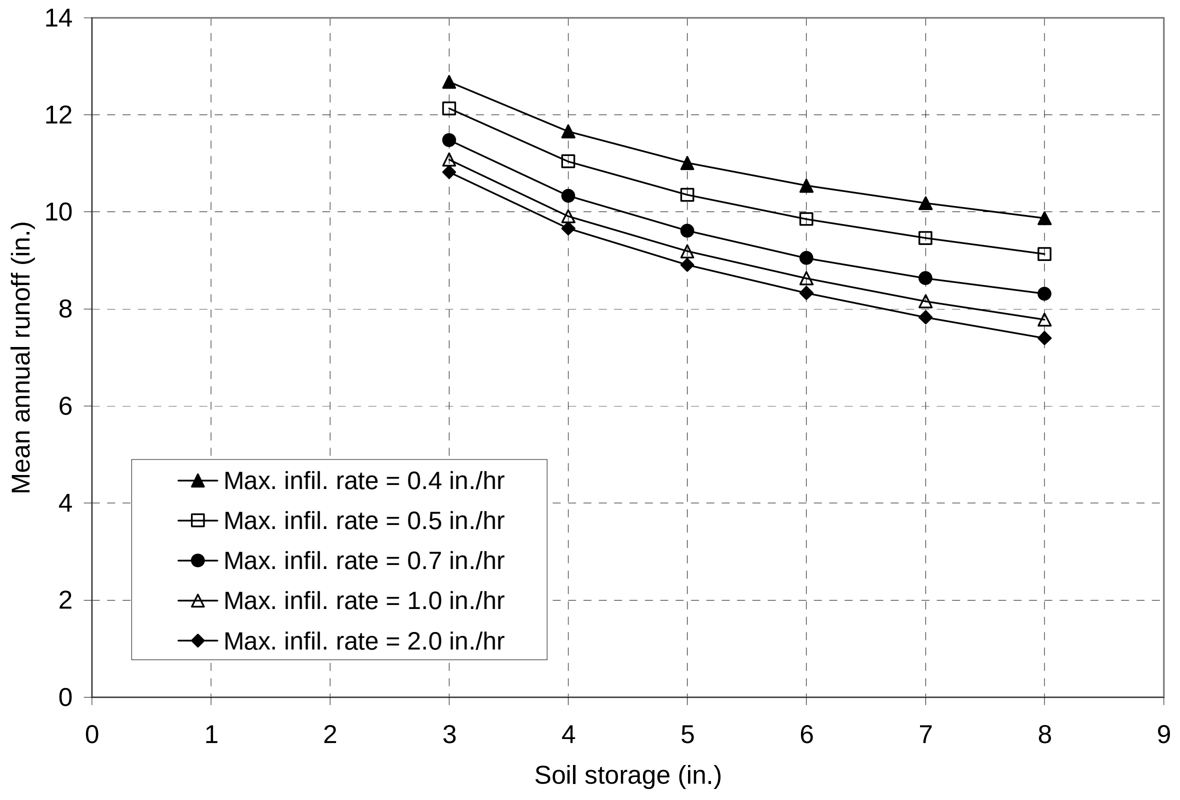


Figure 4-3. Effect of soil storage and maximum infiltration rate on mean annual runoff (one-hour time step)

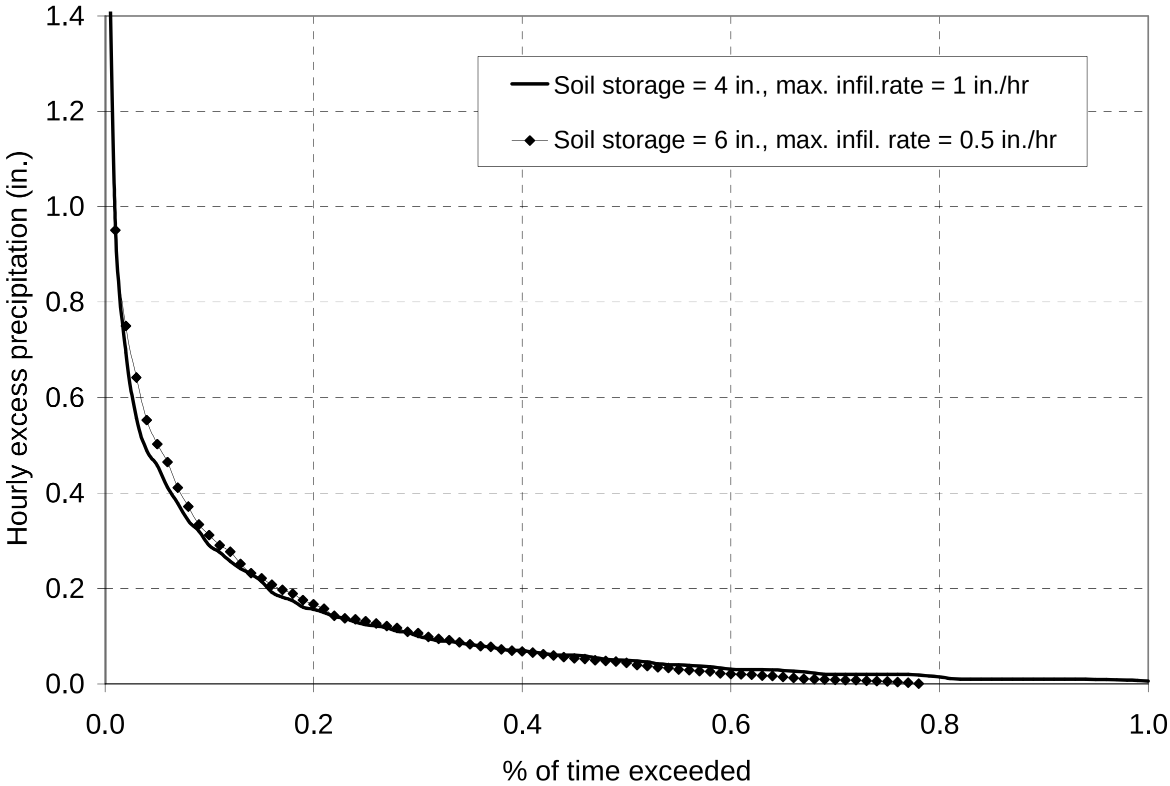


Figure 4-4. Comparison of simulated runoff-duration curves for two combinations of inputs yielding the same total runoff for 1997-2006

The initial soil-moisture condition can greatly affect the amount of runoff in the first several months of the simulation. To quantify this effect, we repeated the simulation for the decade 1997-2006 with the recommended inputs, varying the initial soil-moisture content from 10% to 90% of capacity. Table 4-8 summarizes the results. The initial soil-moisture condition has a large effect on the runoff in the first year and no effect on runoff in subsequent years. The impact on the mean annual runoff for the decade is small but not negligible. Figure 4-5 compares the soil-moisture records for 1997 from two simulations with different initial conditions. The two records gradually converge and become identical after several months; beyond this point the simulated runoff records are also identical.

Table 4-4. Effect of initial soil-moisture condition on simulated runoff for 1997-2006

| Soil storage filled initially (%) | Runoff in 1997 (inches) | Runoff in 1998-2006 (inches) | Mean annual runoff, 1997-2006 (in./hr) |
|---|---|---|---|
| 10 | 1.61 | 94.15 | 9.58 |
| 30 | 2.02 | 94.15 | 9.62 |
| 50 | 3.14 | 94.15 | 9.73 |
| 70 | 4.32 | 94.15 | 9.85 |
| 90 | 5.52 | 94.15 | 9.97 |

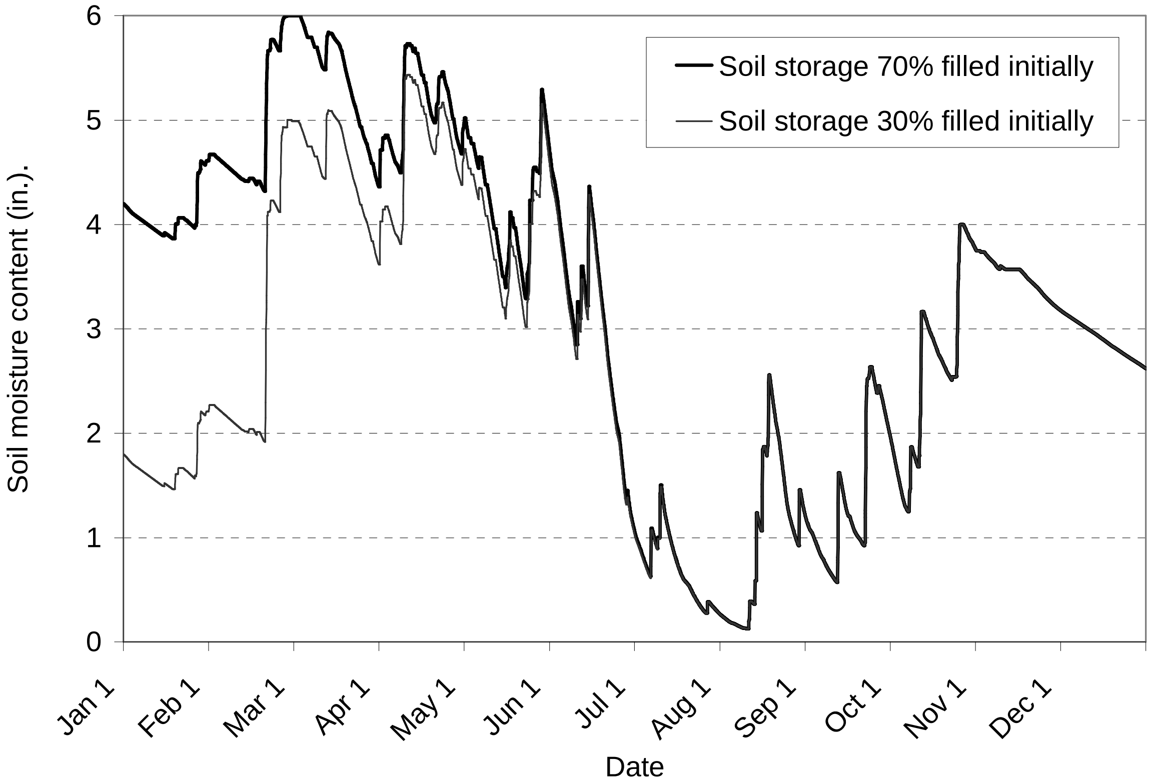


Figure 4-5. Comparison of soil-moisture records for 1997 from simulations with two different initial conditions

Figure 4-6 shows the average annual soil-moisture pattern for the period 1998-2006, developed from simulation from the results of a simulation for the decade 1997-2006. The first year of the simulation was excluded from the averaging period because the soil moisture conditions during this year were influenced by the initial condition. The average soil-moisture content, expressed as a percentage of the soil storage capacity, ranges from approximately 70% in the winter months to approximately 35% in late summer.  The average values for late December are slightly higher than those for early January because the nine-year averaging period began with an unusually dry January and ended with unusually wet December.  An initial soil-moisture content of 70% is recommended for simulations starting on January 1.  Typical soil-moisture conditions for other start dates can be obtained from Figure 4-6.

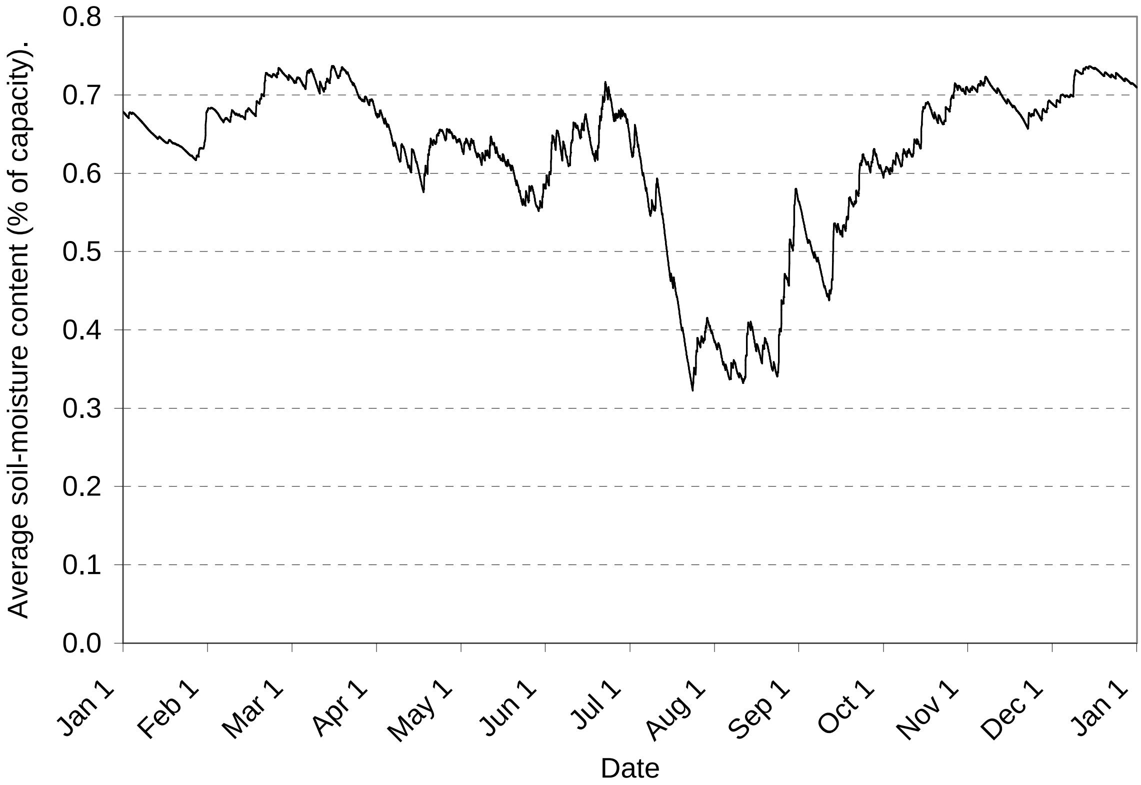


Figure 4-6. Average annual soil-moisture pattern for period 1998-2006, from simulation with calibrated SMA model

4.7.2 Simulations with 15-minute and 5-minute Time Steps

Time-step effects on runoff depth were investigated through additional simulations for a single year of record.  The year 2001 was selected for these tests because its total precipitation of 37.88 inches approximated the mean annual precipitation of 38.19 inches for 1997-2006 (Table 4-1 and Figure 4-1).  Table 4-5 compares runoff amounts for time steps (for both rainfall data and computations) of one hour, 15 minutes and 5 minutes, from simulations with the SMA inputs calibrated for a one-hour time step.  The simulated runoff increases substantially as the time step is shortened.  These results demonstrate the necessity of recalibrating the SMA inputs for the shorter time steps.  Our recalibration consisted of increasing the maximum infiltration rate to obtain the same total runoff as with the one-hour time steps, while holding all other inputs constant.  Table 4-6 displays the calibrated inputs for the three time steps.

Table 4-5. Effect of time step on runoff for year 2001, from simulation with calibrated inputs for one-hour time step

| Time step* (minutes) | Mean annual runoff (inches) |
|---|---|
| 60 | 9.20 |
| 15 | 11.18 |
| 5 | 11.68 |

*for rainfall data and computations

Table 4-6. Recommended values of soil storage and maximum infiltration rate

| Time step* (minutes) | Soil storage (inches) | Maximum infiltration rate (in./hr) |
|---|---|---|
| 60 | 6 | 0.50 |
| 15 | 6 | 0.75 |
| 5 | 6 | 0.90 |

*for rainfall data and computations

## 4.8 Summary of Recommended Inputs for Soil-Moisture Accounting

The following SMA inputs are recommended for general use in Johnson County:

Canopy storage = 0.05 in.
Surface storage = 0.05 in.
Maximum infiltration rate = (depends on time step; see Table 4-6)
Impervious surface area (%) = (actual value)
Total soil storage (inches) = (depends on time step; see Table 4-6)
Soil tension storage (inches) = (40% of total soil storage)
Soil percolation rate = $10^{-10}$ in./hr (a miniscule non-zero value)
Groundwater layer 1 storage = 0 in.
Groundwater layer 1 maximum percolation rate = 0 in./hr
Groundwater layer 1 storage coefficient = $10^{-6}$ hr (a miniscule non-zero value)
Groundwater layer 2 storage = 0 in.
Groundwater layer 2 maximum percolation rate = 0 in./hr
Groundwater layer 2 storage coefficient = 0 hr

The recommended initial conditions are:

Canopy storage initially filled = 0%
Surface storage initially filled = 0%
Soil storage initially filled = (70% for January 1; see Figure 4-9 for other start dates)
Groundwater layer 1 storage initially filled = 0%
Groundwater layer 2 storage initially filled = 0%

These inputs represent average conditions in Johnson County. Different inputs might be appropriate for specific locations with atypical soils or surface conditions. Different initial conditions might be appropriate for short-term simulations of specific time periods.

# CHAPTER 5

# EXAMPLE APPLICATIONS

This chapter explores some practical applications of continuous simulation in urban hydrology and stormwater management. The first three examples investigate the impacts of land development and stormwater best-management practices (BMPs) on runoff volumes and rates. The final example investigates the suitability of HEC-HMS for continuous simulation of streamflow in a complex watershed with numerous subbasins and channel reaches.

## 5.1 Effects of Imperviousness on Runoff

Most but not all precipitation falling over impervious surfaces becomes direct runoff. A small amount of precipitation, typically less than 0.1 inches, is retained in surface depressions and later evaporates. An even smaller amount of precipitation might be intercepted by overhanging foliage. These initial losses have an insignificant effect on peak flows for major storms. However, their effect on annual runoff volumes is significant because most precipitation events total a few tenths of an inch or less. Developed areas typically include a mix of directly and indirectly connected impervious surfaces. An indirectly connected impervious surface is one that drains onto a pervious surface, such as a roof with downspouts that drain onto a lawn. A directly connected impervious surface is one that provides no second chance for infiltration, such as a pavement that drains to a storm-sewer inlet. Directly connected impervious surfaces produce slightly more runoff than indirectly connected impervious surfaces.

In the SMA module, the losses associated with impervious surfaces are not modeled realistically. Equal depths of canopy interception are deducted from precipitation over pervious and impervious surfaces, which tends to overestimate canopy interception over impervious surfaces. On the other hand, depression-storage losses on impervious surfaces are neglected. All impervious surfaces are assumed to be directly connected, so second-chance infiltration is not considered. The calibrated SMA model for Johnson County overestimates canopy interception over impervious surfaces by approximately 0.05 inches per event, an amount that roughly compensates for the neglected depression-storage losses.

The effect of imperviousness on simulated runoff was investigated for the decade 1997-2006 using the calibrated SMA model with one-hour time steps. The mean annual runoff from impervious surfaces is 34.69 inches, or 90.8% of the mean annual precipitation. The mean annual loss is 3.50 inches, or 9.2% of precipitation. Although the SMA module attributes this loss to canopy interception, we consider it a reasonable estimate of the actual depression-storage loss. However, the runoff from impervious surfaces is most likely overestimated to some extent because second-chance infiltration from indirectly connected impervious surfaces is neglected. Figure 5-1 shows the linear relationship between the impervious percentage and the simulated mean annual runoff. Table 5-2 compares the runoff-duration relationships for surfaces with three different impervious percentages. The composite runoff rate in this table is a weighted average of the runoff rates from the pervious and impervious surfaces. A change in imperviousness from

0% to 40% increases the composite runoff rates at the high end of the spectrum by approximately 0.1 in./hr, or 0.1 cfs/ac, and increases the percentage of time with non-zero runoff from less than 1% to more than 5%.

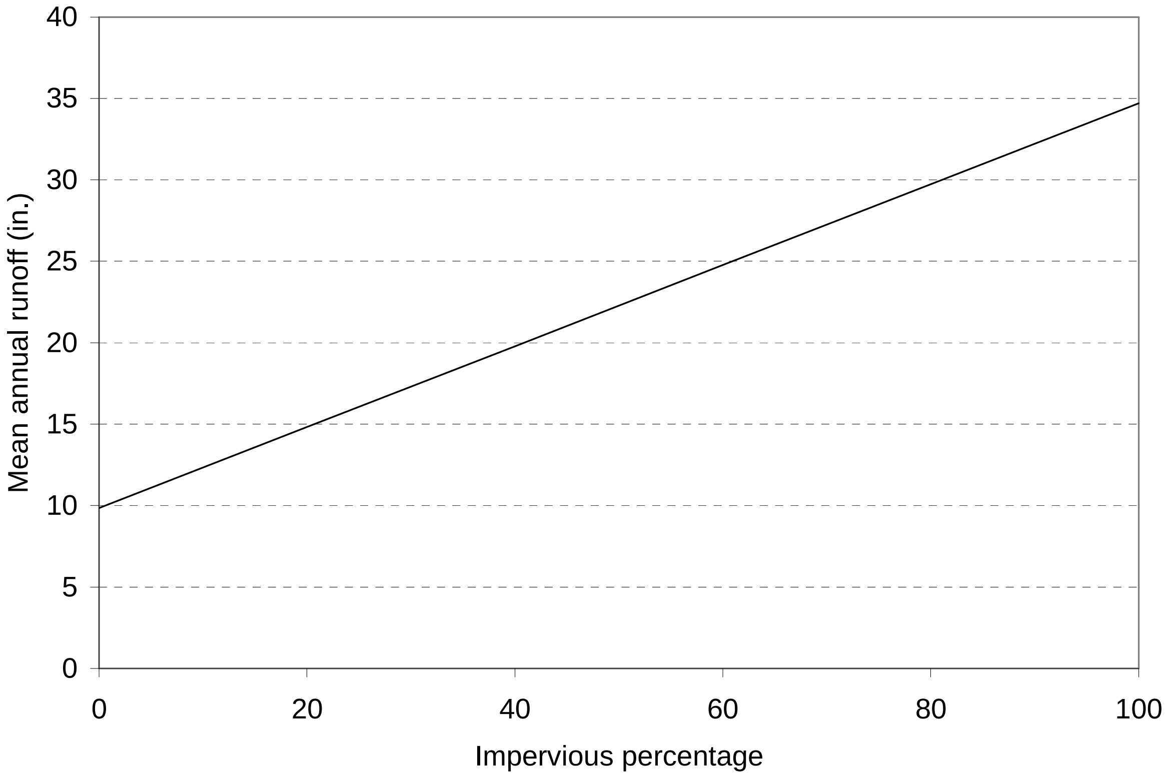


Figure 5-1. Effect of imperviousness on mean annual runoff

Table 5-1. Effect on imperviousness on runoff rate-duration relationship

| Percentage of time exceeded | Composite runoff rate (in./hr) | | |
|---|---|---|---|
| | 0% imperv. | 20% imperv. | 40% imperv. |
| 0.01 | 0.927 | 0.980 | 1.041 |
| 0.02 | 0.778 | 0.799 | 0.834 |
| 0.05 | 0.515 | 0.561 | 0.595 |
| 0.1 | 0.304 | 0.346 | 0.397 |
| 0.2 | 0.167 | 0.206 | 0.243 |
| 0.5 | 0.036 | 0.063 | 0.099 |
| 1 | 0.000 | 0.025 | 0.047 |
| 2 | 0.000 | 0.009 | 0.017 |
| 5 | 0.000 | 0.001 | 0.001 |

## 5.2 Effects of Soil Storage on Runoff

Grading and excavation during land development can reduce the water-storage capacity of the upper soil layer. The magnitude of the reduction in the soil storage capacity depends on the extent of the soil disturbance and compaction and the depth of topsoil replaced or added. A reduction in soil storage capacity increases runoff, reduces ET and increases lawn irrigation requirements.

The effect of soil storage capacity on runoff was investigated for the decade 1997-2006 using the calibrated SMA model with one-hour time steps. Figure 5-2 shows the pronounced impact of soil storage on mean annual runoff. The relationship is markedly nonlinear: a reduction in soil storage from 6 inches to 4 inches increases the mean annual runoff by 1.2 inches (12%), whereas a reduction from in soil storage from 6 inches to 2 inches increases the mean annual runoff by 4.2 inches (42%). Table 5-2 compares the runoff-duration relationships for three different soil-storage capacities. A reduction in soil storage from 6 inches to 2 inches increases the percentage of time with a non-zero runoff from 0.7% to 1.4% increases runoff rates slightly.

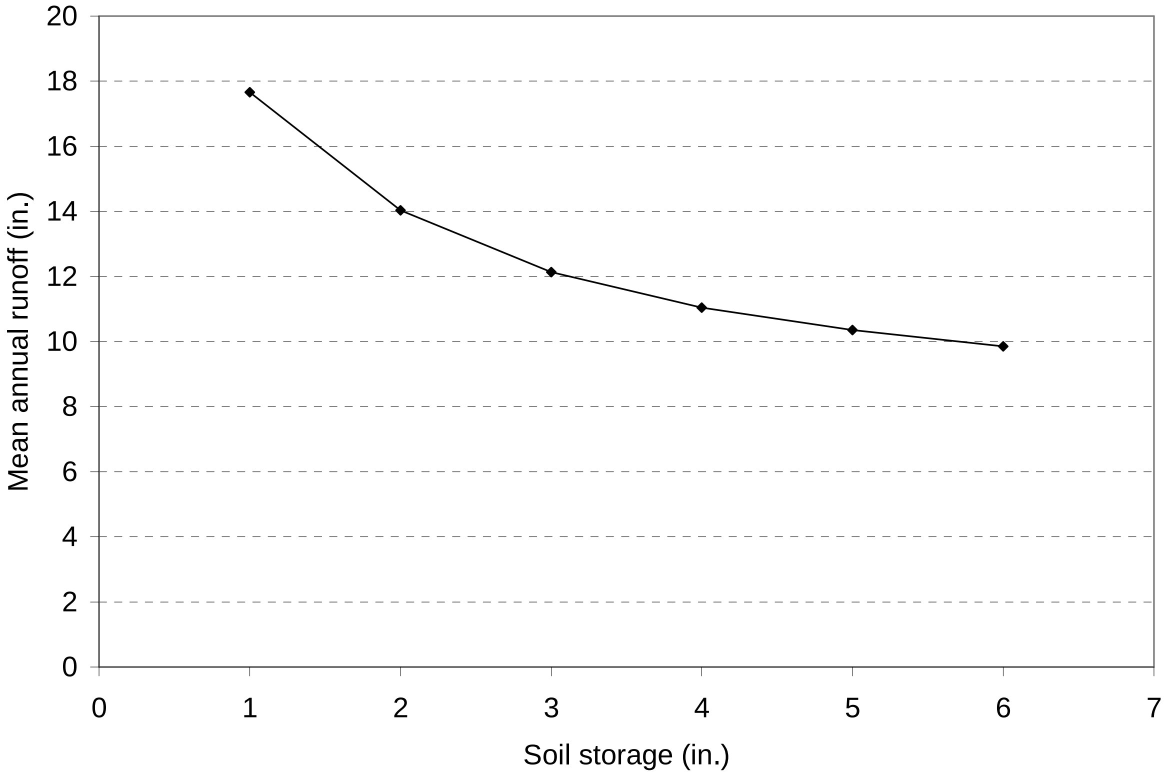


Figure 5-2. Effect of soil storage on mean annual runoff

Table 5-2. Effect of soil storage on runoff rate-duration relationship

| Percentage of time exceeded | Runoff rate (in./hr) | | |
|---|---|---|---|
| | 6 in. soil storage | 4 in. soil storage | 2 in. soil storage |
| 0.01 | 0.927 | 0.992 | 0.993 |
| 0.02 | 0.778 | 0.797 | 0.810 |
| 0.05 | 0.515 | 0.542 | 0.571 |
| 0.1 | 0.304 | 0.322 | 0.365 |
| 0.2 | 0.167 | 0.182 | 0.223 |
| 0.5 | 0.036 | 0.051 | 0.083 |
| 1 | 0.000 | 0.000 | 0.016 |
| 2 | 0.000 | 0.000 | 0.000 |

## 5.3 Continuous Simulation with a Complex Basin Model

Our final tests explored the suitability of HEC-HMS for continuous simulation of streamflow in a complex watershed. Indian Creek Tributary 4 was selected as a test case. The Tributary 4 portion of the HEC-1 model from the Indian Creek Watershed Study (Phelps Engineering, Inc., 2004) was imported into HEC-HMS and converted automatically into a HEC-HMS single-event model. Figure 5-3 shows a schematic diagram of the HEC-HMS basin model, which contains nine subbasins and six channel reaches. The Tributary 4 watershed has total drainage area of 1160 acres and is 34% impervious overall. The individual subbasins range in size from 78 to 174 acres, with impervious percentages ranging from 30% to 43%.

The single-event model for Tributary 4 was converted to a continuous streamflow model by switching the loss method for each subbasin from the NRCS curve-number method to the SMA method. All SMA inputs except impervious percentage were set to the calibrated values for Johnson County.

Because peak flows as well as runoff volumes were of interest, the continuous simulation tests were performed for a single year with 5-minute time steps for rainfall and computations. Calendar year 2001 was selected as the test period because the total precipitation of 37.88 inches at ALERT gage 1100 closely approximated the mean annual precipitation of 38.19 inches for the decade 1997-2006. The meteorological time-series inputs to the continuous simulation were the 5-minute precipitation data for ALERT gage 1100 and the daily net radiation and temperature data for Ottawa. The soil-water content at the start of 2001 was set at 81% filled, based on the results of a preliminary simulation for the decade 1997-2006 with a one-hour time step.

The test simulation for the year 2001 executed properly and yielded continuous streamflow records at 5-minute intervals at the 17 locations shown in Figure 5-3. Figure 5-4 shows a 24-hour segment of the hydrograph at location T4-01L, directly upstream of the confluence with Indian Creek. The annual peak flow at location T4-01L was 2031 cfs on 6/20/2001. The annual runoff volume at this location was 1802 acre-feet, which equates to an average runoff depth of 18.64 inches.

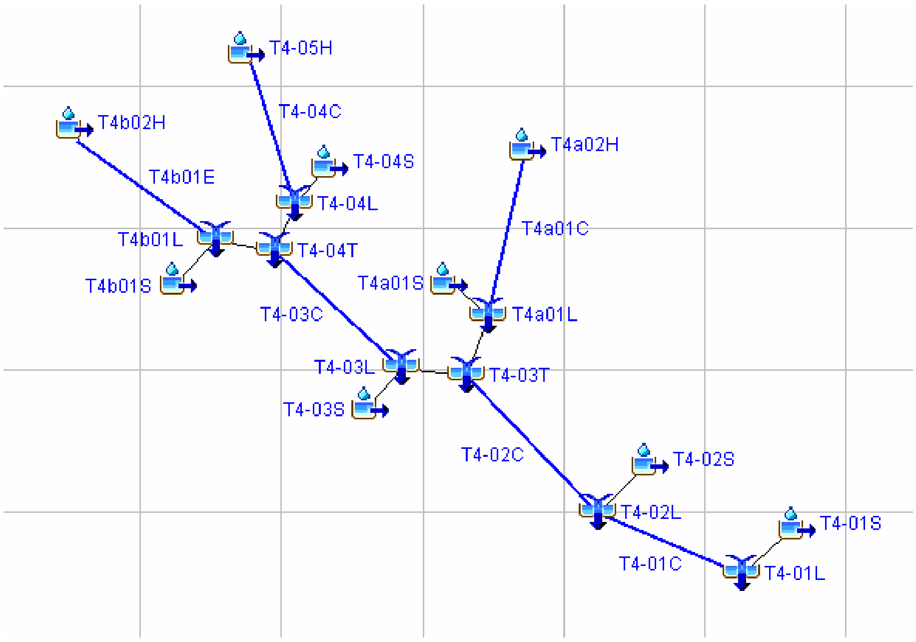


Figure 5-3. Schematic diagram of HEC-HMS model for Indian Creek Tributary 4.

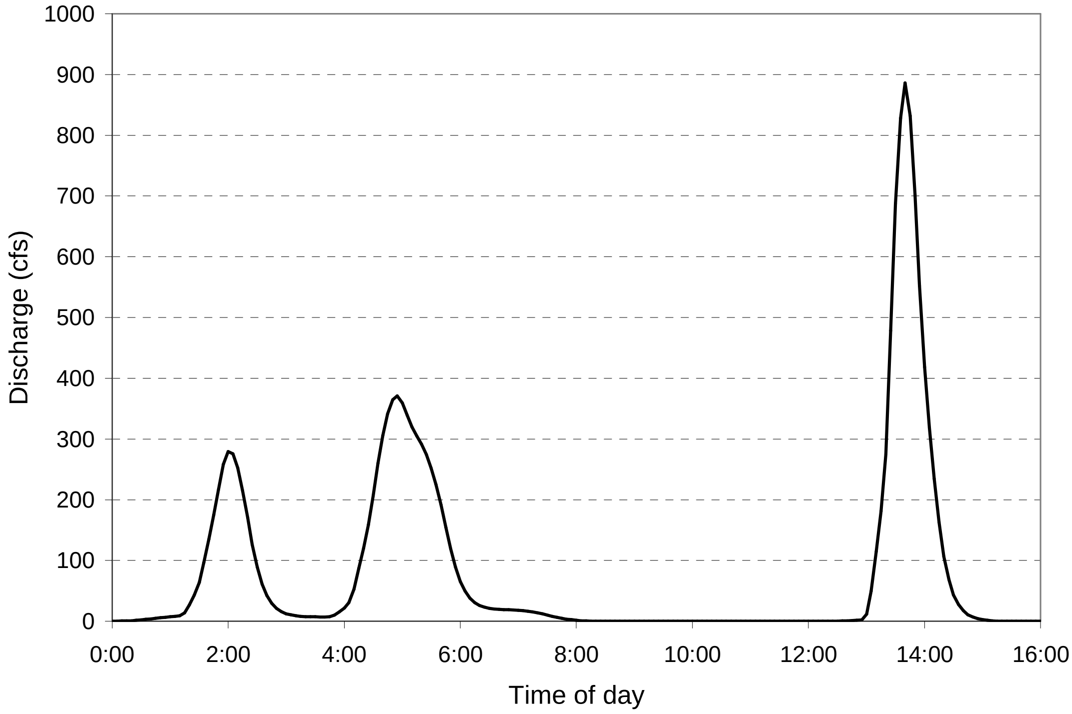


Figure 5-4. Streamflow hydrograph in Tributary 4 at confluence with Indian Creek on 6/04/2001

# CHAPTER 6

# CONCLUSIONS

The continuous simulation capabilities in HEC-HMS are useful for evaluating the streamflow impacts of development and stormwater management practices. This report shows how these capabilities can be applied to streams in Johnson County. The recommended soil-moisture accounting model for Johnson County simulates direct runoff from rainfall but neglects interflow, groundwater flow, snowpack accumulation and snowmelt. The neglected processes have minimal impact on the high and mid-range flows that affect stream stability. However, these processes can have a significant impact on low flows. The calibrated SMA model yields a mean annual runoff depth of approximately 10 inches from pervious surfaces. USGS streamflow gaging records indicate that a mean annual runoff of 10 inches is typical for rural areas in Johnson County. HEC-HMS assumes all impervious surfaces are directly connected, so runoff from indirectly connected impervious surfaces (such as rooftops that drain onto lawns) may be overestimated slightly. A HEC-1 flood model can be readily converted into a HEC-HMS continuous-simulation model, as was demonstrated for Indian Creek Tributary 4.

HEC-HMS Version 3.4 has difficulty with time-series arrays containing more than a few hundred thousand values when the data are transferred into and out of the program through the graphical user interface. The program can simulate a decade of record with a one-hour time step or a year of record with a 5-minute time step. A short time step (e.g., 5-minutes) is needed to obtain realistic hydrographs for small subbasins. The first few months of simulated streamflow are affected to some extent by the specified initial soil-water content. The use of the HEC-DSSVue utility in conjunction with HEC-HMS should be investigated. Transferring long time-series records into and out of HEC-HMS through HEC-DSS might enable HEC-HMS to perform simulations with a larger number of time steps (e.g., a decade of simulation with a 5-minute time step).

The HEC-HMS implementation of the Priestly-Taylor evapotranspiration method is poorly documented at present. The required radiation input is not incident solar radiation, as the program and User's Manual state, but rather net radiation. Appendix A presents the recommended procedure for calculation of daily net radiation from solar radiation, temperature and humidity data.

Future improvements to the recommended continuous-simulation procedure should focus on the low end of the streamflow spectrum. The modeling of low flows could be improved by accounting for (1) baseflow recession resulting from drainage of saturated hill slopes following major precipitation events and (2) snowpack accumulation and snowmelt. The general groundwater/baseflow and snowpack/snowmelt modeling capabilities in HEC-1 would need to be simplified and calibrated for local conditions. Future studies should also focus on adjustment of the calibrated SMA inputs to account for local differences in soils, vegetation and land use.

# REFERENCES


Allen, R. G., et al. (1998). “Crop Evaporation: Guidelines for Computing Crop Water Requirements,” *FAO Irrigation and Drainage Paper 56*, Food and Agriculture Organization of the United Nations.

Hydrologic Engineering Center (2000). *Hydrologic Modeling System HEC-HMS Technical Reference Manual*, U. S. Army Corps of Engineers.

Hydrologic Engineering Center (2006). *Hydrologic Modeling System HEC-HMS User’s Manual, Version 3.1.0*, U. S. Army Corps of Engineers.

Priestly, C. H. B., and R. J. Taylor (1972). “On the Assessment of Surface Heat Flux and Evaporation Using Large Scale Parameters, *Monthly Weather Review*, Vol. 100, pp. 81-92.

Rasmussen, P. P. and C. A. Perry (2000). “Estimation of Peak Streamflows for Unregulated Rural Streams in Kansas,” *Water-Resources Investigations Report 00-4079*, U. S. Geological Survey.

Rawls, W. J., D. L. Brakensiek and K. E. Saxton (1982). "Estimation of Soil Water Properties," *Transactions of the American Society of Agricultural Engineers*, pp. 1316-1320.

Rossman, L. A. (2005) *Storm Water Management Model User’s Manual, Version 5.0*, EPA/600/R-05-040, U. S. Environmental Protection Agency.

Shuttleworth, W. J. (1993). “Chapter 4 - Evaporation,” in *Handbook of Hydrology*, edited by D. R. Maidment, McGraw-Hill, Inc.

U. S. Department of Agriculture, Soil Conservation Service (1979). *Soil Survey of Johnson County, Kansas*.

# APPENDIX A

## Calculation of Daily Net Radiation

The Priestly-Taylor evapotranspiration method in HEC-HMS requires net radiation data as input. This appendix presents the relationships for calculation of daily net radiation from solar radiation and weather data by the United Nations Food and Agriculture Organization's recommended method (Allen, et al., 1998). The required inputs are the Julian date, latitude, elevation, solar radiation, mean relative humidity, and maximum and minimum temperatures. The steps are as follows.

1. Convert the solar radiation, $R_s$, from units of langley/min or W/m$^2$ to units of MJ/m$^2$/day:

   $$\text{MJ/m}^2\text{/day} = \text{langley/min} \cdot 60.3$$

   $$\text{MJ/m}^2\text{/day} = \text{W/m}^2 \cdot (86400 / 10^6)$$

2. Compute the net solar radiation for the grass reference crop with an albedo of 0.23:

   $$R_{ns} = (1 - 0.23)\, R_s$$

   in which

   $R_{ns}$ = net solar radiation (MJ/m$^2$/day)
   $R_s$ = solar radiation (MJ/m$^2$/day)

3. Compute the solar declination angle:

   $$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right)$$

   in which

   $\delta$ = solar declination angle (radians)
   J = Julian date

4. Convert the latitude from decimal degrees to radians if necessary, and then compute the sunset hour angle:

   $$\text{radians} = \text{degrees} \cdot \pi/180$$

   $$\omega_s = \arccos\left(-\tan\varphi \cdot \tan\delta\right)$$

in which

$\omega_s$ = sunset hour angle (radians)
$\varphi$ = latitude (radians)

5. Compute the inverse relative Earth-Sun distance, $d_r$ (dimensionless):

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)$$

6. Compute the extraterrestrial radiation:

$$R_a = \frac{12\,(60)}{\pi} G_{sc}\, d_r \left(\omega_s \sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \sin\omega_s\right)$$

in which

$R_a$ = extraterrestrial radiation ($MJ/m^2$/day)
$G_{sc}$ = solar constant = 0.0820 $MJ/m^2$/min

7. Convert the elevation from feet to meters if necessary, and then compute the clear-sky solar radiation:

meters = feet · 0.3048

$$R_{so} = \left(0.75 + 0.00005\, z\right) R_a$$

in which

$R_{so}$ = clear-sky solar radiation ($MJ/m^2$/day)
z = elevation (m)

8. Convert maximum and minimum temperatures from Fahrenheit to Celsius if necessary, and then compute the saturation vapor pressures at the maximum and minimum temperatures:

ºC = (ºF -32) · 5/9

$$e_{sat}(T_{max}) = 0.6108 \exp\left(\frac{17.27\, T_{max}}{T_{max} + 237.3}\right)$$

$$e_{sat}(T_{min}) = 0.6108 \exp\left(\frac{17.27\, T_{min}}{T_{min} + 237.3}\right)$$

in which

$e_{sat}(T_{max})$ = saturation vapor pressure at maximum temperature (kPa)
$e_{sat}(T_{min})$ = saturation vapor pressure at minimum temperature (kPa)
$T_{max}$ = maximum temperature (ºC)
$T_{min}$ = minimum temperature (ºC)

9. Compute the mean actual vapor pressure:

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e_{sat}(T_{max}) + e_{sat}(T_{min})}{2}\right]$$

in which

$e_a$ = mean actual vapor pressure (kPa)
$RH_{mean}$ = mean relative humidity (%)

10. Compute the net outgoing longwave radiation:

$$R_{nl} = \sigma\left[\frac{T_{max,K}{}^4 + T_{min,K}{}^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right)$$

in which

$R_{nl}$ = net outgoing longwave radiation ($MJ/m^2/day$)
$\sigma$ = Stefan-Boltzmann constant [4.903 x 10-9 $MJ/(ºK^4m^2day)$]
$T_{max,K}$ = maximum absolute temperature (ºK = ºC + 273.16)
$T_{min,K}$ = minimum absolute temperature (ºK = ºC + 273.16)

11. Compute the net radiation, $R_n$, in $MJ/m^2/day$:

$$R_n = R_{ns} - R_{nl}$$

12. Convert the net radiation from $MJ/m^2/day$ to $W/m^2$:

$W/m^2$ = $MJ/m^2/day \cdot (10^6 / 86400)$