Evaluating Temporal and Spatial Scale Issues with Hydrologic Models in the Black Hills, South Dakota

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Abstract

The relative accuracy of rainfall runoff models is an important issue. Some models may perform better than others in specific scenarios (e.g. wet vs. dry climates; forested vs. agricultural land use; long vs. short time steps for simulation). Two widely used models were selected for comparison to simulate runoff for watersheds in the Black Hills of South Dakota. The two models, the Precipitation Runoff Modeling System (PRMS) and Hydrological Simulation Program Fortran (HSPF), are both semi-distributed, deterministic hydrological tools that simulate the impacts of precipitation, land use and climate on basin hydrology and streamflow. PRMS is primarily used by the U.S. Geological Survey (USGS) to simulate basin hydrology across the United States. HSPF is used by a larger base of public and government modelers to simulate basin hydrology, sediment processes, and water quality worldwide. One of the primary applications of this research is to help potential users select the more appropriate hydrologic model, HSPF or PRMS, when working with a specific size of watershed. Results indicate that HSPF better estimated annual, monthly, and daily water budget than the PRMS for a small watershed. HSPF better estimated annual water budget than the PRMS for a large watershed. PRMS better estimated monthly and daily water budget than HSPF for a large watershed when wet and dry periods were calibrated individually. The results indicate that the temporal and spatial scale variability influences the accuracy of HSPF and PRMS model simulations. The study indicates that an appropriate selection of a model for specific size of a watershed should be based on a specific hydrologic question that a user is seeking to answer.

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1. Introduction

Watershed models can simulate rainfall/runoff, streamflow, sediment transport, chemical, nutrients and microbial organisms within a watershed (Pedraza and Ockerman, 2012). Simulation of these processes is useful in addressing a wide range of water resource and environmental related problems such as quantification of water availability over time, effects of climate change, land use, and urbanization on water resources.

Hydrologic simulation started in the 1950's with the arrival of computer technology (Singh and Frevert, 2005). The Stanford Watershed Model (SWM), developed in early 1960's was one of the first computer programs to predict streamflow using observed meteorological data. With advances in computing power, a number of models were developed in the 1980's such as the Storm Water Management Model (SWMM), National Weather Service (NWS) River Forecast System, Precipitation Runoff Modeling System (PRMS), Streamflow Synthesis and Reservoir Regulation (SSARR), System Hydrologique Europeen (SHE), TOPographic MODEL (TOPMODEL), Institute of Hydrology Distributed Model (IHDM), and others (Singh and Frevert, 2005). With support from the United States Environmental Protection Agency (U.S. EPA), SWM (Stanford Watershed Model), now referred as Hydrological Simulation Program Fortran (HSPF) became a more comprehensive model. These models replaced manual computations performed by hydrologists in earlier days.

In 1991, the Bureau of Reclamation recorded 64 hydrologic models. Most of the federal agencies in United States have their own model for a specific application. The Hydrologic Modeling System (HEC-HMS) developed by U.S. Army Corps of Engineers is used for simulation of flood hydrology (Singh and Frevert, 2005). The National

Weather Service (NWS) model is used for flood forecast. The Precipitation Runoff Modeling System (PRMS) developed by U.S. Geological Survey (USGS) is used for water resources planning and management. The Hydrological Simulation Program Fortran (HSPF) expanded under U.S. EPA sponsorship simulates watershed hydrology and water quality. Since 1981, AQUA TERRA Consultants has been providing consulting services to the U.S. EPA for the HSPF maintenance and software development (Bicknell et al., 2005).

A general principle of any watershed model is to convert precipitation into streamflow at a specific point. Some models use comprehensive data sets where others use minimal data sets to simulate basin hydrology. Generally, model complexity increases as the number of parameters increase.

A new generation of watershed models is more diverse with larger data set and computational requirements (Singh and Frevert, 2005). It takes time and effort to understand a model (Bicknell et al., 2001). Models can differ in conceptual framework, space and time scale and data requirements. Models are imperfect because they cannot truly represent all parameters influencing hydrology. As a result, they introduce errors and uncertainties in their results. A sound understanding of a model is essential for its suitable application. Borah and Bera (2003) suggest that the selection of model for a specific application depends primarily on the watershed size, desired spatial and temporal scales, and data availability. This thesis will address the spatial and temporal scale bias in PRMS and HSPF that may help an end user in choosing the best model for a specific application.

1.1 Problem Statement

The Hydrological Simulation Program Fortran (HSPF) and the Precipitation Runoff Modeling System (PRMS) are semi distributed, deterministic hydrological tools for simulating the impacts of precipitation, land use and climate on basin hydrology and streamflow. HSPF supported by the United States Environmental Protection Agency (U.S. EPA), has a larger user base of public and government modelers who use the model to simulate basin hydrology, sediment processes, and water quality on the land surface and in the stream channel. PRMS, developed by the U.S. Geological Survey (USGS), is primarily used by the USGS to simulate basin hydrology across the United States. These are two popular hydrological models for continuous watershed simulation. Both models have been applied independently at different scales for watersheds across the United States. At the present there is no study conducted to evaluate their performance for the same watershed. In general, model performance varies with watershed size. One of the primary questions addressed by this study will be to determine if a model that performs well for a small watershed can also perform well for a large watershed.

1.2 Relevance

Findings from this research will help common end users to choose the appropriate hydrologic model, HSPF or PRMS, of their application based on the watershed size and the availability of input data.

1.3 Objectives

The primary objective of this research was to evaluate the accuracy of model runoff results on various temporal (daily, monthly, annual) and spatial scale (small vs. large watershed). Both models were applied in comparison studies on well-instrumented catchments in the Black Hills of western South Dakota. Specific objectives of this research were:

- Identify potential sources of model uncertainty and model sensitivity
- Identification of most important parameters and common sources of error
- Discuss advantages and limitations of each model

1.4 Scope

HSPF can have a minimum time step of 1 minute while PRMS can have a minimum time step of one day. For this research, HSPF simulations used an hourly time step and PRMS simulations used a daily time step. All flow values presented here after are mean values, derived from model output at the stipulated time step. The HSPF and the PRMS models for this study were developed based on standard guidelines set forth by the developer of each model. The study areas (Figure 1.1) consisted of:

1. Rapid Creek watershed upstream of Pactola Reservoir, South Dakota: 294 square miles (large watershed)
2. Spring Creek watershed upstream of Sheridan Lake, South Dakota: 127 square miles (small watershed)

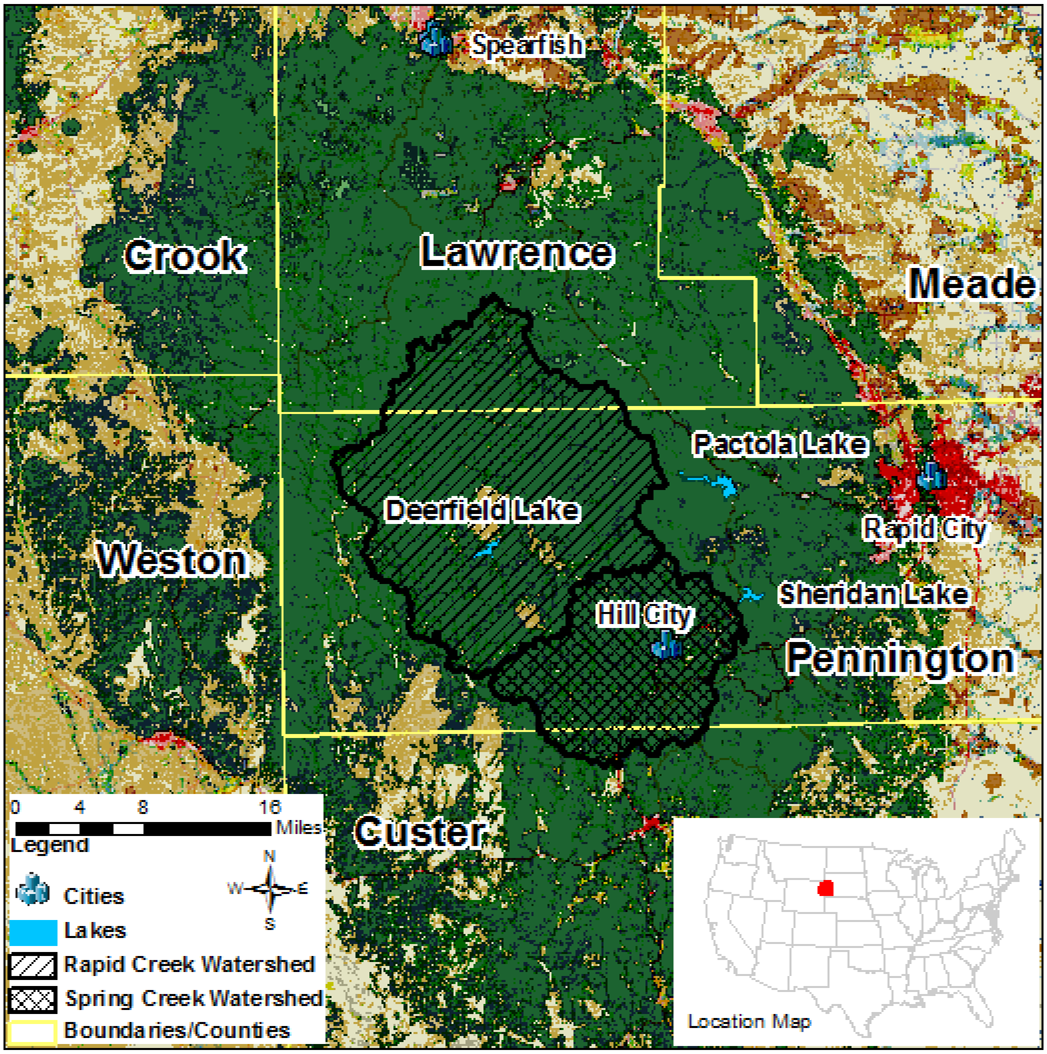

Figure 1.1 Study areas

2. Literature Review

The literature review section of this research presents some examples of HSPF and PRMS applications in different watersheds across the world.

2.1 Examples of HSPF Applications

Laroche et al. (1996) applied HSPF to simulate atrazine transport in an agricultural watershed (0.30 square mile) in Canada. Using a 20 month calibration period (June 1991 - January 1993), Nash-Sutcliffe efficiency (NSE) for daily and monthly flow were 0.51 and 0.66 respectively. For 10 month validation period (February 1993 - November 1993), NSE for daily and monthly flow were 0.12 and 0.79 respectively. The model results were worse for the small time step. The result indicates that as the time step gets closer to the time step of input data, accuracy of streamflow simulated by HSPF is reduced.

Srinivasan et al. (1998) applied HSPF to simulate streamflow for two small watersheds: Purdy Creek (9 square miles) and Ariel Creek (15 square miles), a glaciated region in northeastern Pennsylvania. The HSPF model was calibrated in one watershed (Purdy Creek) and verified in another (Ariel Creek) for June 1992 to December 1993. The total volume error between observed and simulated flow in Purdy Creek and Ariel Creek were 5 percent and 17 percent respectively for the simulation period. The differences between simulated and observed streamflow ranged from 60 to 90 percent in Purdy Creek and Ariel Creek during rainfall runoff events. The percent errors for HSPF simulated flow were high during the period of snowmelt runoff events and rainfall runoff events. The results indicate that the HSPF model weakly estimates streamflow during the snowmelt runoff events.

Albek et al. (2004) applied HSPF model for the Seydi Suyo watershed (700 square miles) in Turkey to estimate deep-rooted vegetation and temperature effect on the streamflow. The model was calibrated for 2 years and validated for 1 year. The results indicate that the increase in mean annual temperature by 3 degrees centigrade would reduce streamflow by 21 percent. The evapotranspiration (ET) effects of existing deep-rooted vegetation may reduce the streamflow by 37 percent and the complete removal of deep-rooted vegetation may increase the streamflow by 40 percent. The study concluded that HSPF can be a valuable tool to predict the impacts of future climate conditions in streamflow.

Im et al. (2003) applied HSPF to simulate the effect of urbanization in the Polecat Creek Watershed (47 square miles) in Virginia. The model was calibrated for 4 years and validated for 1 year. Total runoff errors for HSPF estimated flows were 0.4 percent and -0.4 percent during the calibration and validation periods respectively. The study investigated six possible land use changes that might affect the watershed. With a 22 percent increase of impervious area in the watershed, the HSPF estimated 33 percent and 51 percent rise in total streamflow and peak flow rate respectively as compared to baseline condition. The results indicate that the runoff volume and peak flow rate increased with increasing urban areas.

Hayashi et al. (2004) used HSPF to simulate the streamflow and sediment load in upper Changjiang River basin (386,100 square miles), a very large watershed in China. International Satellite Land Surface Climatology Project (ISLSCP) precipitation data was used as an input. During a rather short calibration and validation period (1987-1988), the NSE for 5 days average estimated streamflow was 0.95. During flood season, the model under-estimated peak flow by as much as 71 percent. The results indicate that the errors of HSPF simulated flow varied for different regions within the watershed. The study suggests that the input precipitation data may be the reason for poor performance of the HSPF.

Ribarova et al. (2008) applied HSPF to simulate nutrient pollution during flood events in Iskar River watershed (400 square miles) in Bulgaria. Hourly time step was used for the model simulation. The model was calibrated for 2 years and verified for 1 year. For the 3-year simulation period, the percent volume error of HSPF estimated flow was less than 5 percent. The HSPF better estimated daily streamflow than the hourly. The results indicate that as the time step gets smaller, accuracy of streamflow simulated by HSPF is reduced.

Donigian et al. (2011) developed a HSPF model in Santa Clara River basin (1,770 square miles) in Southern California for watershed planning, water resources assessment, and water quality management. HSPF was applied for modeling of baseline condition, natural condition, and flood events. The calibration period was 1997-2005, and the validation period was 1987-1996. The later time span (1997-2005) was selected for the calibration period because it includes both wet and dry years. During the calibration period, the correlation coefficient (r) for daily and monthly flow was 0.91 and 0.97 respectively. During the validation period, the r for daily and monthly flow was 0.89 and 0.97. The results indicate that as the model output time step gets larger, accuracy of streamflow estimated by HSPF is increased.

Diaz-Ramirez et al. (2011) applied HSPF to simulate streamflow in Luxapallila Creek watershed (717 square miles, upland basin) in Alabama and Mississippi, Fish

River watershed (54 square miles, coastal) in Alabama, and Rio Caonillas watershed (38 square miles, steep slope) in Puerto Rico. Coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) statistics for daily flow were utilized to evaluate the model performance for the simulation period (1999-2001). During the simulation period, the statistics based on daily flow simulations were (NSE = 0.61, R^2 = 0.62) for the Luxapallila Creek watershed (large), (NSE = 0.44, R^2 = 0.46) for the Fish River watershed (medium), and (NSE = 0.68, R^2 = 0.71) for the Rio Caonillas watershed (small). The statistics based on monthly flow simulations were (NSE = 0.94, R^2 = 0.95) for the Luxapallila Creek watershed, (NSE = 0.78, R^2 = 0.76) for the Fish River watershed, and (NSE = 0.77, R^2 = 0.84) for the Rio Caonillas watershed. The results indicate that HSPF better estimates daily flow for a small watershed and monthly flow for a large watershed. HSPF performance improved as the model output time step increased from a daily interval to a monthly interval.

2.2 Examples of PRMS Applications

Fontaine (1989) applied PRMS for hydrological studies in Bald Mountain Brook watershed (1.7 square miles) and Bishop Mountain Brook watershed (1.2 square miles) in Maine. The simulated total flow for validation period (1982-1983) was within 7 percent for Bald Mountain Brook watershed and 3 percent in Bishop Mountain Brook watershed. For daily flows, the coefficient of determination (r) was 0.71 and 0.84 for Bald Mountain Brook watershed and Bishop Mountain Brook watershed respectively. The study based on the Bald Mountain Brook watershed and Bishop Mountain Brook watershed concluded that the PRMS model could be used for simulation of daily flow in the northeastern United States.

Steuer and Hunt (2001) used PRMS to estimate future effect of urbanization on upper Pheasant Brank Creek basin (18 square miles) in Wisconsin. The average annual percent volume error was – 2 percent for the 6 year simulation period. The model estimated monthly flow accounted for 52 percent variation of the observed for the simulation period. The model estimated that 5 to 10 percent development in low residential area would increase mean annual streamflow and surface runoff by 53 percent and 84 percent respectively and decrease base flow by 14 percent. In addition, it estimated that 50 percent commercial and 50 percent medium residential development would increase stream runoff by 450 percent.

Viger et al. (2011) applied PRMS to evaluate effect of urbanization and climate change on the Flint River basin (2900 square miles) in Georgia. The model was used to evaluate streamflow condition at 2050 for different climate change and increasing impervious area due to urbanization scenarios. The study indicates that the total streamflow in 2050 might decrease due to increased temperatures due to global warming, however, the reduced streamflow would be manage by increased surface runoff due to increases in impervious area by the effect of urbanization.

Markstrom et al. (2012) used PRMS to evaluate hydrologic response to different climate change scenarios (projected carbon emission) for 14 basins from different hydroclimatic regions in the United States. The 14 PRMS models were evaluated for calibration period 1988 to 1999. The models were used to study the hydrologic response based on estimated climate change scenarios in 21st century (2000 to 2099). The projected climate change scenarios for 21st century were acquired from the World Climate Research's Programme's Coupled Model Intercomparison Project. Different methods were utilized to create PRMS input files by statistical downscaling of these scenarios. The PRMS results indicate that earlier spring snowmelt and an increase in evapotranspiration might result from the increase in minimum and maximum temperatures caused by 21st century progress. The overall volume of annual streamflow would increase but the timing of streamflow could change if the above results hold true. The streamflow will increase in winter and early spring but will decrease in late spring and throughout summer. The earlier snowmelt and increase in evapotranspiration might dry the forest and threaten the ecosystem. The study did not include population growth and landuse change impact on the streamflow. The combined effect of urbanization and climate change might alter quality and quantity of streamflow. The study suggested that the continuous study of these basins would give better results. The study recommended that the future hydrologic models should address the problems with temporal and spatial scales, data availability and needs, and calibration approach. It also suggested conducting research on developing a national hydrologic modeling structure, which will enhance the overall climate change study.

2.3 Summary of Literature Review

The HSPF model was applied for simulation of streamflow, sediment process, and water quality. The results indicate that HSPF performance improved as the model output time step increased. HSPF better estimated daily flow for a small watershed and monthly flow for a large watershed. PRMS model was applied for simulation of streamflow especially with climate change scenarios. PRMS simulation performance for different time step and watershed size has not been explicitly documented yet. These earlier studies of HSPF and PRMS applications have focused on the model performance for different watersheds. However, no direct comparisons of HSPF and PRMS simulation performance on the same watersheds has been documented to date. The following experiments explore this issue.

3. Conceptual Framework

3.1 Rainfall Runoff Processes

The rainfall runoff process is a mechanism to convert precipitation to runoff on the earth surface (Tarboton, 2003). Runoff includes overland flow, interflow, and base flow. The schematic of the rainfall runoff process illustrates the physical processes involved in runoff generation (Figure 3.1).

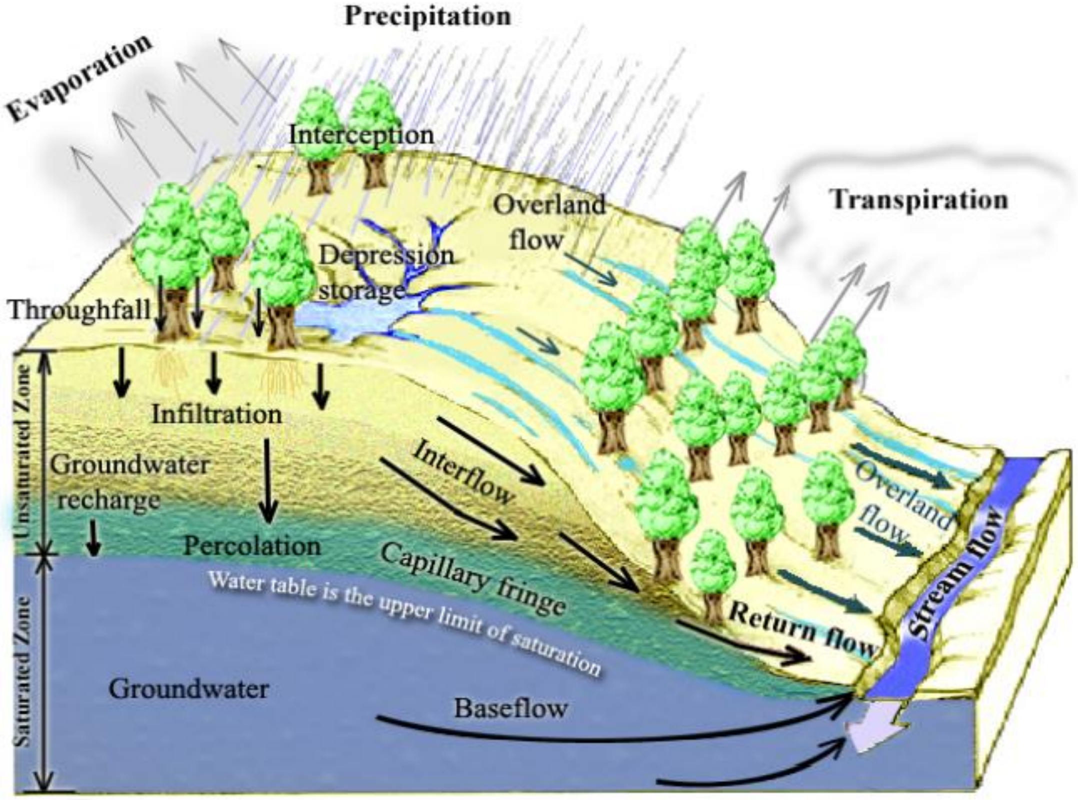

Figure 3.1 Schematic of runoff generation mechanism (Tarboton, 2003)

3.2 Water Balance

A hydrologic model is a mathematical representation of rainfall runoff processes. Hydrologic model simulation results depend on an accurate interpretation of the system water balance. The water balance equation describes the flow of water in or out of a system and is represented as,

$$R = P - ET - IG - \Delta S \qquad [3.1]$$

where R is the runoff, referred to as streamflow [L/T], P is the precipitation [L/T], ET is the evapotranspiration [L/T], IG is the deep or inactive groundwater loss [L/T], and ΔS is the change in soil moisture storage [L/T].

3.3 Conceptual Model Diagrams

HSPF is categorized into three modules: pervious land segment, impervious land segment and channel & reservoir processes (reaches). Each pervious and impervious land segment is connected through reaches. A conceptual model of HSPF developed from the Stanford Watershed Model for hydrologic simulation of PWATER section in a pervious land segment is shown in Figure 3.2 & Figure 3.3. The Figure 3.3 is a continuation of Figure 3.2, the symbols 1 and 2 connect these diagrams. The PWATER section in the HSPF is a major component of a water budget and simulates total runoff from a pervious area.

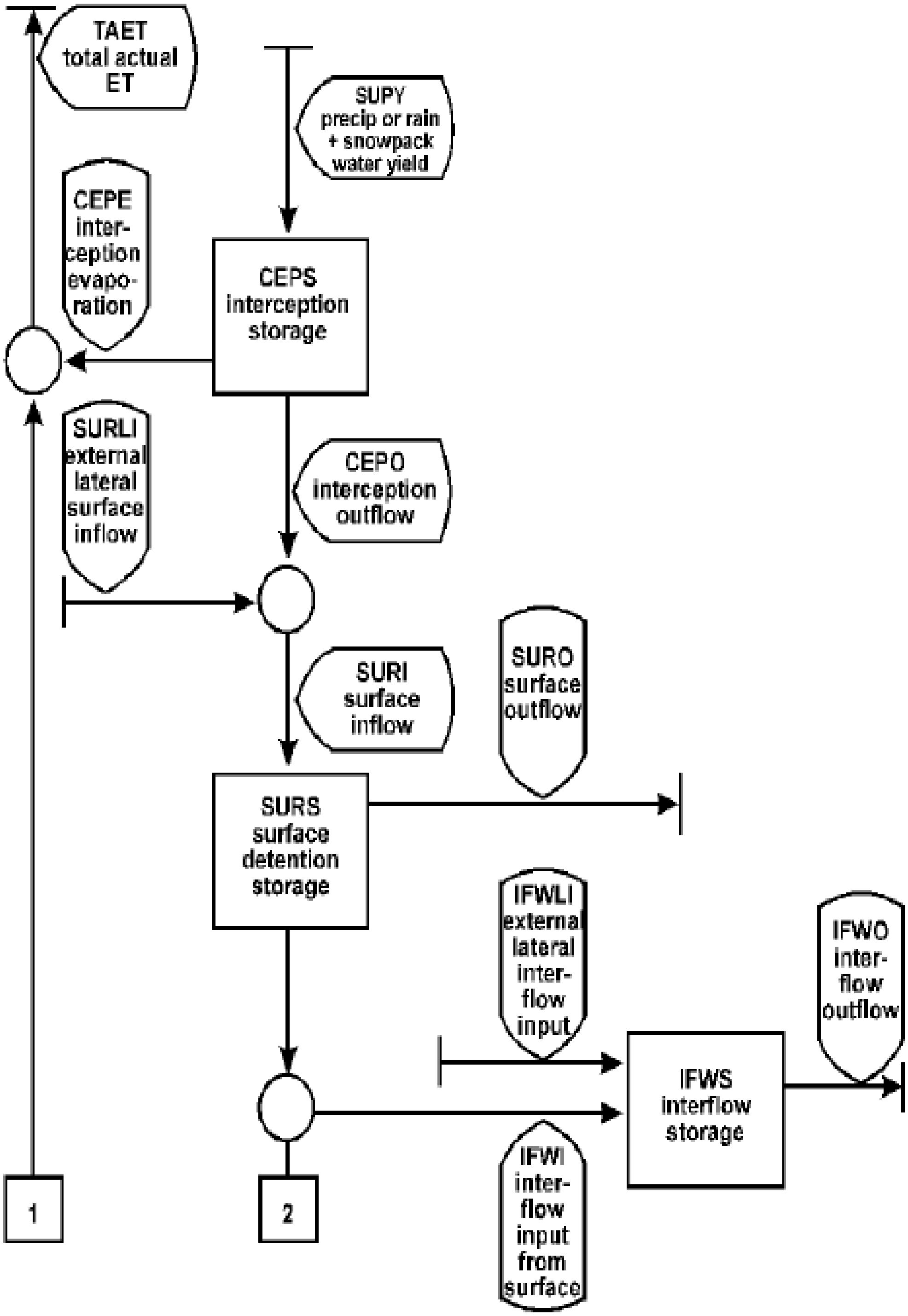

Figure 3.2 Flow diagram of HSPF PWATER section in pervious land segment (part 1) (Bicknell et al., 2005)

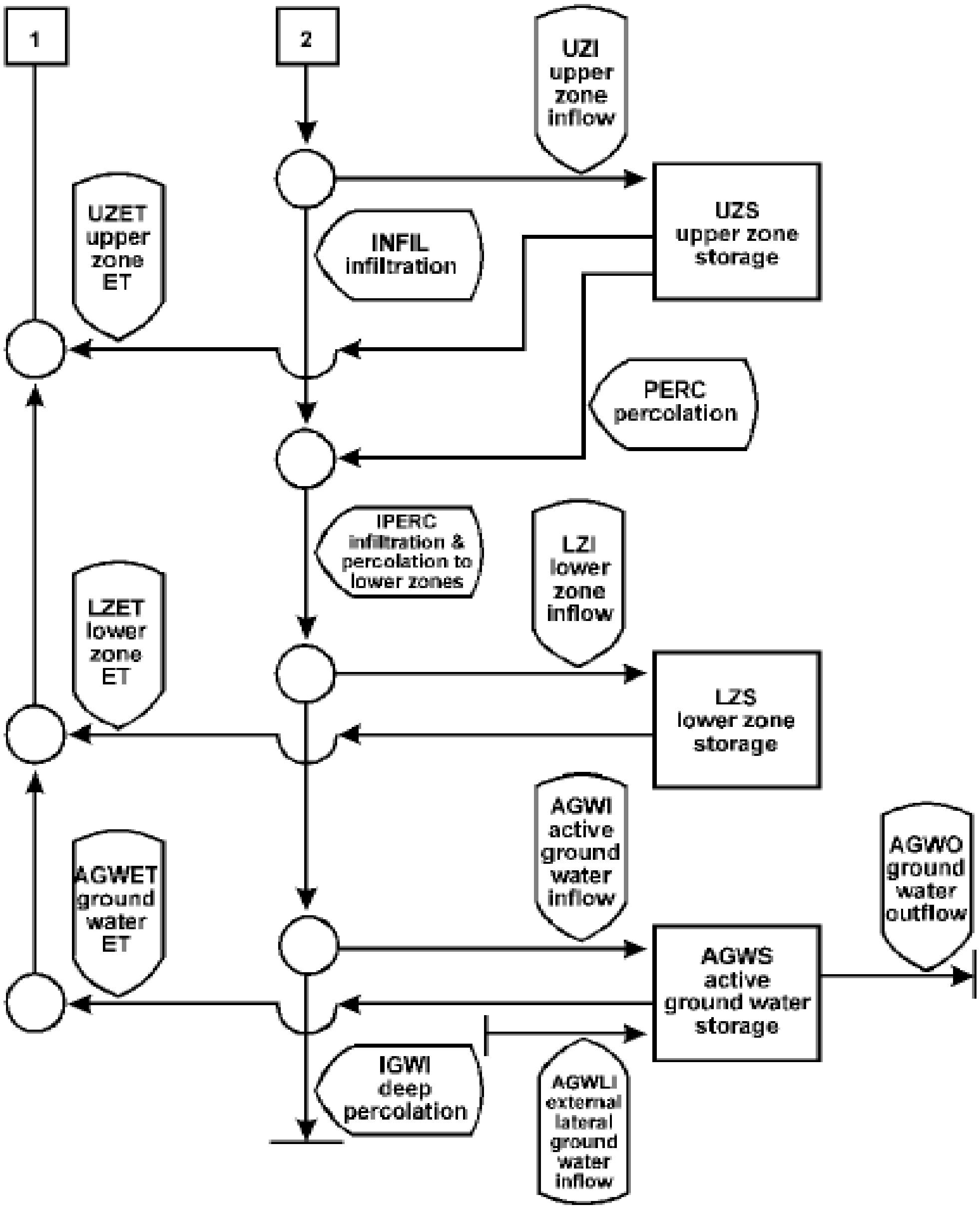

Figure 3.3 Flow diagram HSPF PWATER section in pervious land segment (part 2) (Bicknell et al., 2005)

PRMS consists of a network of discretized land segments called Hydrologic Response Units (HRUs). Physical and hydrological characteristics of each HRU are assumed homogenous (like a pervious land segment in HSPF). A group of HRUs that contribute to a specific stream is called a subbasin. A conceptual model of PRMS is shown in Figure 3.4.

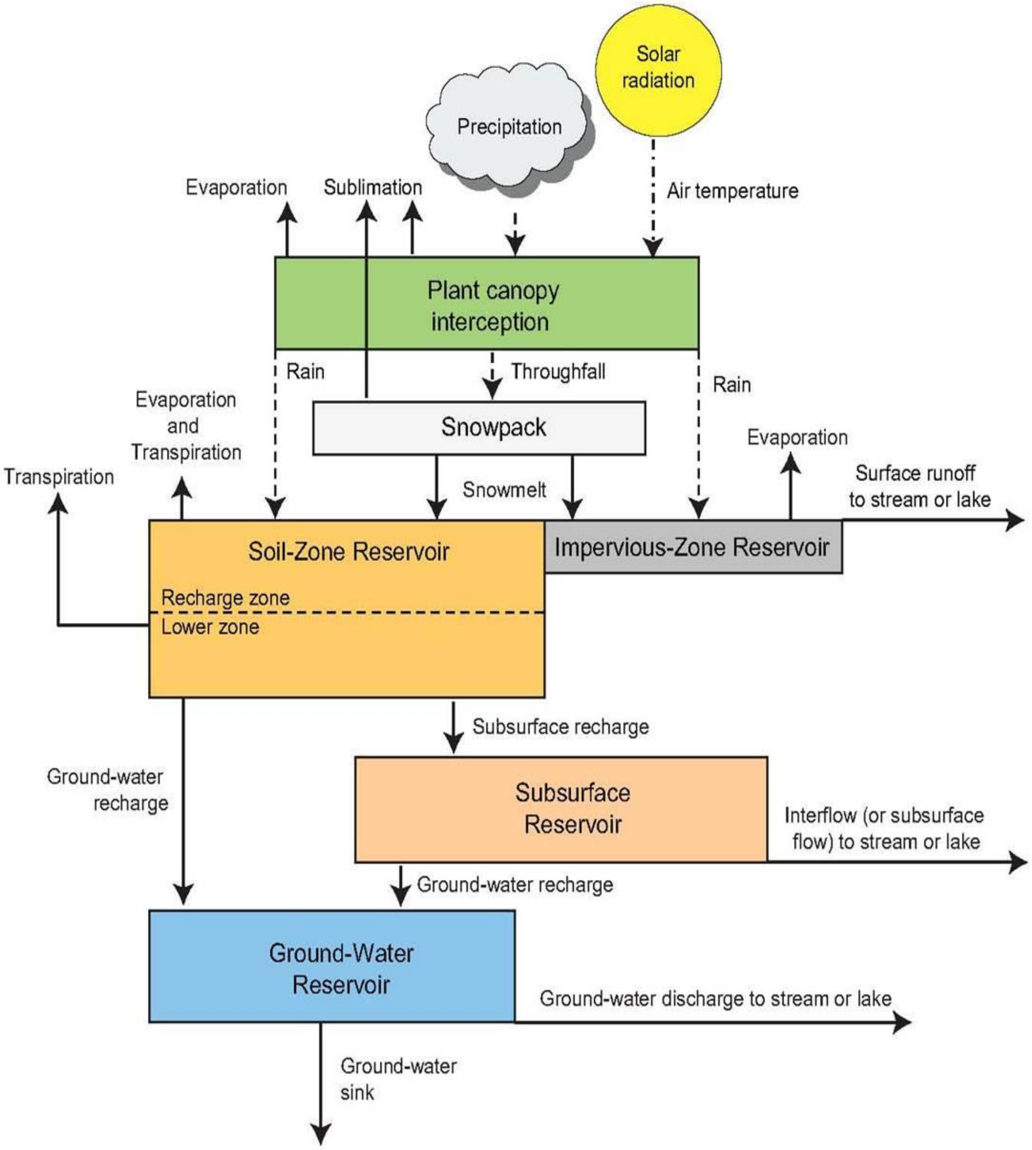

Figure 3.4 Schematic diagram of PRMS conceptual watershed system and its inputs (Leavesley et al., 1983; Markstrom et al., 2008)

3.4 Infiltration

Infiltration is a process of movement of water into the soil from the ground surface. Infiltration is an important process relative to the generation of surface runoff in land segments. Infiltration is function of rainfall rate, soil permeability, land use, land slopes, soil surface condition, and soil moisture content. Infiltration rate is an actual rate at which water enters the soil. It varies with time and space.

For the computation of infiltration, PRMS uses the Green Ampt model. In 1911, Green Ampt describes infiltration capacity of soil (maximum rate at which water can enter the soil) as a function of suction head, porosity and hydraulic conductivity of the soil (Tarboton, 2003). Green Ampt applies the Darcy's law to calculate infiltration capacity as,

$$f_c = K_{sat}\,(1+\frac{|\psi|\Delta\theta}{F}) \qquad [3.2]$$

where f_c is the infiltration capacity of soil [L/T], K_{sat} is the saturated hydraulic conductivity of soil [L/T], ψ is the soil suction head [L], $\Delta\theta$ is the soil moisture deficit (difference between saturated soil moisture θ_s and initial soil moisture θ_i), and F is the depth of infiltrated water [L]. This equation shows that the infiltration capacity is a function of cumulative infiltrated depth.

If the moisture supply rate is less than the infiltration capacity of soil then all the water enters the soil. The infiltration capacity decreases with increasing duration of moisture supply. Ponding occurs when moisture supply rate equals the infiltration capacity.

For initial moisture supply rate i [L/T] over the time period of t [T], the cumulative infiltration prior to ponding can be calculated as,

$$F = i * t \qquad [3.3]$$

The cumulative infiltration (F_p) at ponding is calculated as,

$$F_p = \frac{K_{sat}|\psi|\Delta\theta}{(i-K_{sat})},\ i > K_{sat} \qquad [3.4]$$

The time to ponding (t_p) is calculated as,

$$t_p = \frac{F_p}{i} = \frac{K_{sat}|\psi|\Delta\theta}{i\,(i-K_{sat})} \qquad [3.5]$$

The cumulative infiltration (F) after ponding is calculated as,

$$t\text{-}t_p = \frac{F-F_p}{K_{sat}} + \frac{|\psi|\Delta\theta}{K_{sat}}\,\frac{\ln(F_p+|\psi|\Delta\theta)}{F+|\psi|\Delta\theta} \qquad [3.6]$$

where F_p is the cumulative infiltration depth at time to ponding t_p and F is the cumulative infiltration depth at time t after ponding. The above equation can be solved using MS excel or applying numerical methods to get the cumulative infiltration (F) at time (t) after ponding.

HSPF uses empirical relations (derived from the Philips equations) for the estimation of infiltration which represents both the continuous variation of infiltration rate with time as a function of soil moisture and the areal variation of infiltration over the land segment. The soil infiltration capacity is a function of both fixed watershed characteristics (e.g. soil permeability and land slope) and variable watershed characteristics (e.g. soil surface conditions and soil moisture conditions). These characteristics vary spatially over the land segment. Areal variation of watershed is accounted using a linear probability density function.

3.5 Evapotranspiration

Evapotranspiration (ET) is the volume of water loss in the form of evaporation and transpiration from the watershed. The actual evapotranspiration reflects the availability of water to satisfy potential evapotranspiration.

In HSPF, the actual ET is estimated using five different sources in the following order 1) baseflow ET 2) interception ET 3) upper zone ET 4) active ground water ET, and 5) lower zone ET. The lower zone is the last storage from which ET is drawn if the potential ET demand is not meet by other four sources of ET.

ET from interception storage and upper zone storage occurs at a potential rate. Evapotranspiration opportunity (maximum amount of water accessible for evapotranspiration in a time interval at a point in the watershed) controls the ET from lower zone storage and minor evapotranspiration occurs from ground water storage and the stream surface (Crawford and Linsley, 1966). During wet periods, the major evapotranspiration occurs from the interception storage and the upper zone storage. However, more evapotranspiration might occur from lower zone storage over a long dry period. As there is no available water in the interception and upper zone storage, the deep rooted vegetation continually draw water from the lower zone storage. The concept of evapotranspiration opportunity is used to calculate actual evapotranspiration from the lower zone storage. The maximum ET opportunity (RPARM) is calculated as,

$$\mathrm{RPARM} = \left[\frac{0.25}{1-\mathrm{LZETP}}\right] * \left[\frac{LZS}{\mathrm{LZSN}}\right] * \left[\frac{\mathrm{DT}}{24}\right] \qquad [3.7]$$

where LZETP = Lower Zone Evapotranspiration (L/T), LZS = Lower Zone Storage (L/T), LZSN = Lower Zone Nominal Storage (L/T), and DT = Hour per interval

In PRMS, the evapotranspiration occurs from interception, soil zone, and recharge zone. Only transpiration occurs from lower zone. In general, the soils in each HRU are mainly sand, loam, and clay. The actual ET and potential ET relationship for these types of soils are computed as a function of soil water ratio (Leavesley et al., 1983).

3.6 Surface Runoff

HSPF and PRMS use the contributing area concept to compute surface runoff. The contributing area concept considers the areal variation of infiltration capacity over the watershed. The percent of watershed area contributing to the surface runoff can be computed using the linear function of antecedent soil moisture and rainfall amount (Figure 3.5). The diagonal line indicates the infiltration capacity of soil corresponding to percentage area of the watershed. The excess rainfall between infiltration capacity line and moisture supply line represents the volume of water that is free to move towards a stream as a surface runoff (overland flow and interflow). For a uniform moisture supply rate 'P' (mm/hr), total volume of infiltration will be proportional to the shaded area. For example, for a uniform moisture supply rate 'P1', the total infiltration and surface runoff from the 25 percent watershed area will be 'OBC' and 'OP_1B' respectively. The I_{max} represents maximum infiltration capacity of the entire watershed area corresponding to the maximum moisture supply rate P_{max}. This method is applicable at a point in time, or for a small time interval.

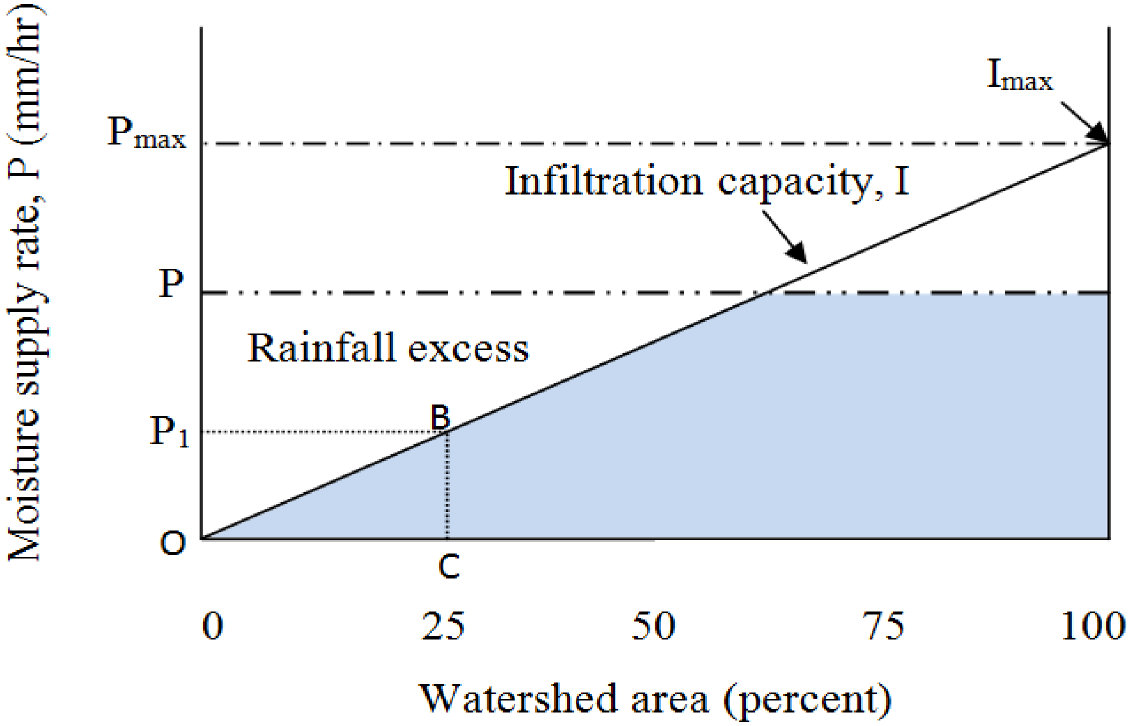

Figure 3.5 Relationship between moisture supply rate, infiltration capacity, and rainfall excess in HSPF and PRMS (Crawford and Linsley, 1966; Leavesley et al., 1983)

3.7 Overland Flow

HSPF simulates overland flow using the Chezy-Manning equation and an empirical expression that relates outflow depth to detention storage (Bicknell et al., 2005). The overland flow in land segment is treated as a turbulent flow. Two different equations are used to calculate the rate of overland flow.

For increasing rate of overland flow (SURSM < SURSE)

$$\text{SURO} = \Delta60 * \text{SRC} * (\text{SURSM} * (1.0 + 0.6\ (\text{SURSM/SURSE})^3)^{1.67} \qquad [3.8]$$

where SURO is the surface outflow (in/interval), Δ60 = Δ/60 (hr/interval) makes the equations applicable to a range of time step Δ, SRC is a routing variable, SURSM is the mean surface detention storage over the time interval (in), and SURSE is the equilibrium surface detention storage (inches) for the current supply rate (in).

For equilibrium or receding rate of overland flow (SURSM ≥ SURSE)

$$\text{SURO} = \Delta60 * \text{SRC} * (\text{SURSM}*1.6)^{1.67} \qquad [3.9]$$

The equilibrium surface detention storage is calculated as,

$$\text{SURSE} = 0.000982 * (\text{NSUR} * \text{LSUR}/\sqrt{SLUR}\ )^{0.6} * \text{SSUPR}^{0.6} \qquad [3.10]$$

where NSUR is the Manning's n for overland flow plane, LSUR is the length of the overland flow plane (ft), SLUR is the slope of the overland flow plane (ft/ft), and SSUPR is the rate of precipitation to the overland flow plane. The routing variable SRC is calculated as,

$$\text{SRC} = 1020 * \sqrt{SLUR}\ /(\text{NSUR} * \text{LSUR}) \qquad [3.11]$$

PRMS simulates overland flow using kinematic wave equations. Overland flow planes are major components of watershed drainage networks or hydrologic response units (HRUs). A HRU can be a single overland flow plane; however, it can be divided into more flow planes to account for variations in land use, slope and surface roughness. Each HRU discharges to a channel segment (i.e. cascading flow is not allowed). A HRU consists of one or more flow planes using the same rainfall excess. The overland flow in pervious area is computed using the rainfall excess. The rainfall excess can be calculated as,

$$QR = PTN - FIN \qquad [3.12]$$

where QR is the rainfall excess (in/hr), PTN is the net rainfall (in/hr) and FIN is the net infiltration (in/hr).

Excess rainfall from each over land flow plane segment can be solved using partial differential equation as,

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = re \qquad [3.13]$$

where, h = depth of flow (ft), q = rate of flow per unit width ($ft^3/s/ft$), re = rate of rainfall excess inflow (ft/s), t = time (s) and x = distance down plane (ft)

The relation between h and q is given as,

$$q = \propto \ h^m \qquad [3.14]$$

where, $\propto$ and *m* are functions of the overland flow-plane characteristics. The parameters $\propto$ and *m* are computed using an equation for selected overland flow-plane and channel segment characteristics. Finite difference scheme can be used to solve the above power relationship between q and h. It uses a network of computational cells based on a four-point grid system (Figure 3.6) (Shultz, 2007).

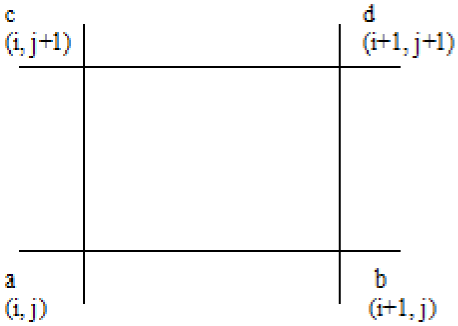

Figure 3.6 Finite difference grid scheme (Shultz, 2007)

The unknown discharge and area at node d can be calculated using known discharge and area at nodes a, b and c.

3.8 Impervious Land

Infiltration is assumed zero in the impervious areas. Both models use the above described overland flow equations to route the flow from impervious land to the stream channel.

3.9 Channel Flow

HSPF uses the storage routing method to route channel flow. The reach flow is assumed unidirectional. All the inflows to a reach are assumed to enter at one point at the u/s end of the reach. The total volume of outflow (ROVOL) leaving a reach in an interval is,

$$\text{ROVOL} = (K_s * \text{ROS} + \text{COKS} * \text{ROD}) * \text{DELTS} \qquad [3.15]$$

where K_s is the weighting factor ($0 \leq K_s \leq 0.99$), COKS is 1-K_s (complement of K_s), ROS is the total rate of outflow from reaches at the start of interval, ROD is the total rate of demand outflow at the end of the interval. DELTS is the modeling time interval in seconds.

PRMS uses the same computational approach to route channel flow, kinematic wave approximation relating discharge and the cross-sectional area of flow equation

[3.14] . The kinematic wave parameters $\propto$ and m are computed from the equations for selected channel segment characteristics and are given in table 2 of PRMS user manual (Leavesley et al., 1983). User defined values for $\propto$ and m can be used to replace these equations. Finite difference approximation is used to solve the power relationship between q and h as similar to overland flow.

4. Materials and Methods

4.1 Study Areas

The study areas consist of two catchments: a large catchment, Rapid Creek just above Pactola Reservoir, and a small catchment, Spring Creek just above Sheridan Lake. Both watersheds lie in the central Black Hills of western South Dakota. The method section consists of:

- Acquire datasets for simulations (time series and physical watershed characteristics)
- Develop simulation models
- Calibration and validation of models
- Statistical and graphical analysis of model output

4.2 Rapid Creek Watershed Characteristics

Rapid Creek is a perennial stream that lies in Pennington and Lawrence counties in the state of South Dakota. The total catchment area of Rapid Creek is about 718 square miles at the confluence with Cheyenne River. However, the study area of Rapid Creek watershed consists of 294 square miles from its origin to Rapid Creek above Pactola Reservoir at Silver City, South Dakota (Figure 4.1).

Rapid Creek emerges from the Black Hills National Forest, flows through Rapid City, and meets the Cheyenne River near southwest Wasta, South Dakota. Rapid Creek is a tributary of the Cheyenne River, which flows into the Missouri River. Castle Creek is a major tributary of Rapid Creek, passes through Deerfield Dam that merges with the North Fork of Rapid Creek near Mystic, South Dakota.

4.3 Topography of Rapid Creek Watershed

The elevation of the drainage area varies from 4,630 to 7,175 feet above mean sea level. The slope of the land surface varies from horizontal to steep vertical with an average slope of 19 percent. The channel bed consists of boulders, cobbles, gravel, sand and silt. The channel slope varies from 1 to 29 percent with an average slope of 9 percent.

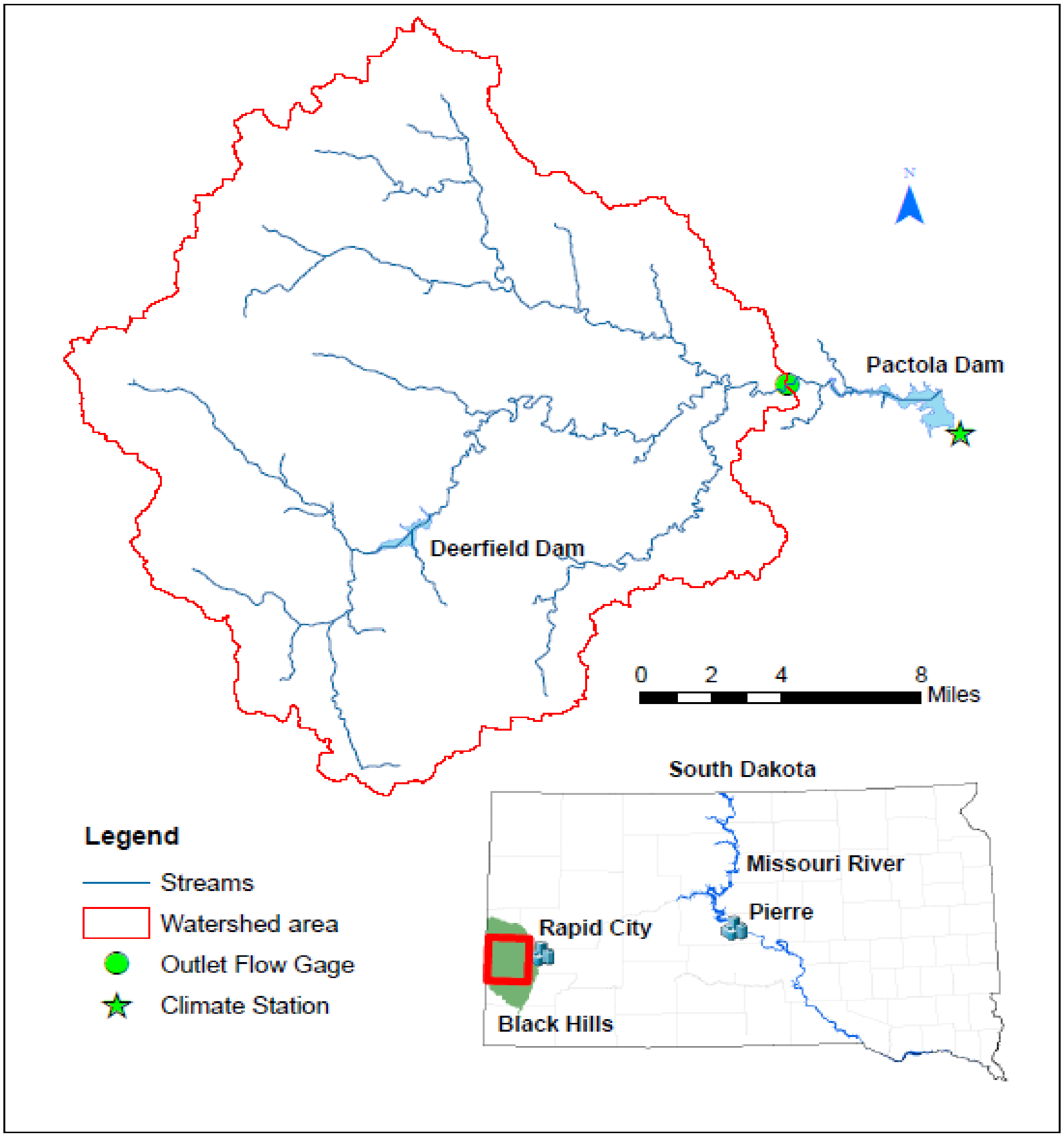

Figure 4.1 Location map of Rapid Creek watershed above Pactola Reservoir

4.4 Spring Creek Watershed Characteristics

Spring Creek is a continuous stream that lies in Pennington and Custer counties in the state of South Dakota. The total drainage area of Spring Creek is about 425 square miles at the confluence with the Cheyenne River. However, the study area consists of 127 square miles from its origin to above Sheridan Lake near Keystone, SD (Figure 4.2).

Spring Creek rises from the Black Hills National Forest, passes through Sheridan Lake, and meets the Cheyenne River. It is a tributary of the Cheyenne River, which flows into the Missouri River. Newton Fork Creek and Palmer Gulch Creek are two major tributaries of the Spring Creek. Sheridan Lake is an important feature of Spring Creek that is located 31 miles downstream from its origin (SD DENR, 2006). Hill City, a small town, is located in the southern part of the watershed area and lies 6.5 miles upstream from Sheridan Lake.

4.5 Topography of Spring Creek Watershed

The elevation of the drainage area varies from 4,630 to 7,200 feet above mean sea level. The slope of the land surface varies from 2 to 60 percent with an average slope of 24 percent. The slope of the channel varies from 4 to 23 percent with an average slope of 10 percent. The channel bed consists of boulders, cobbles, gravel, sand, and silt.

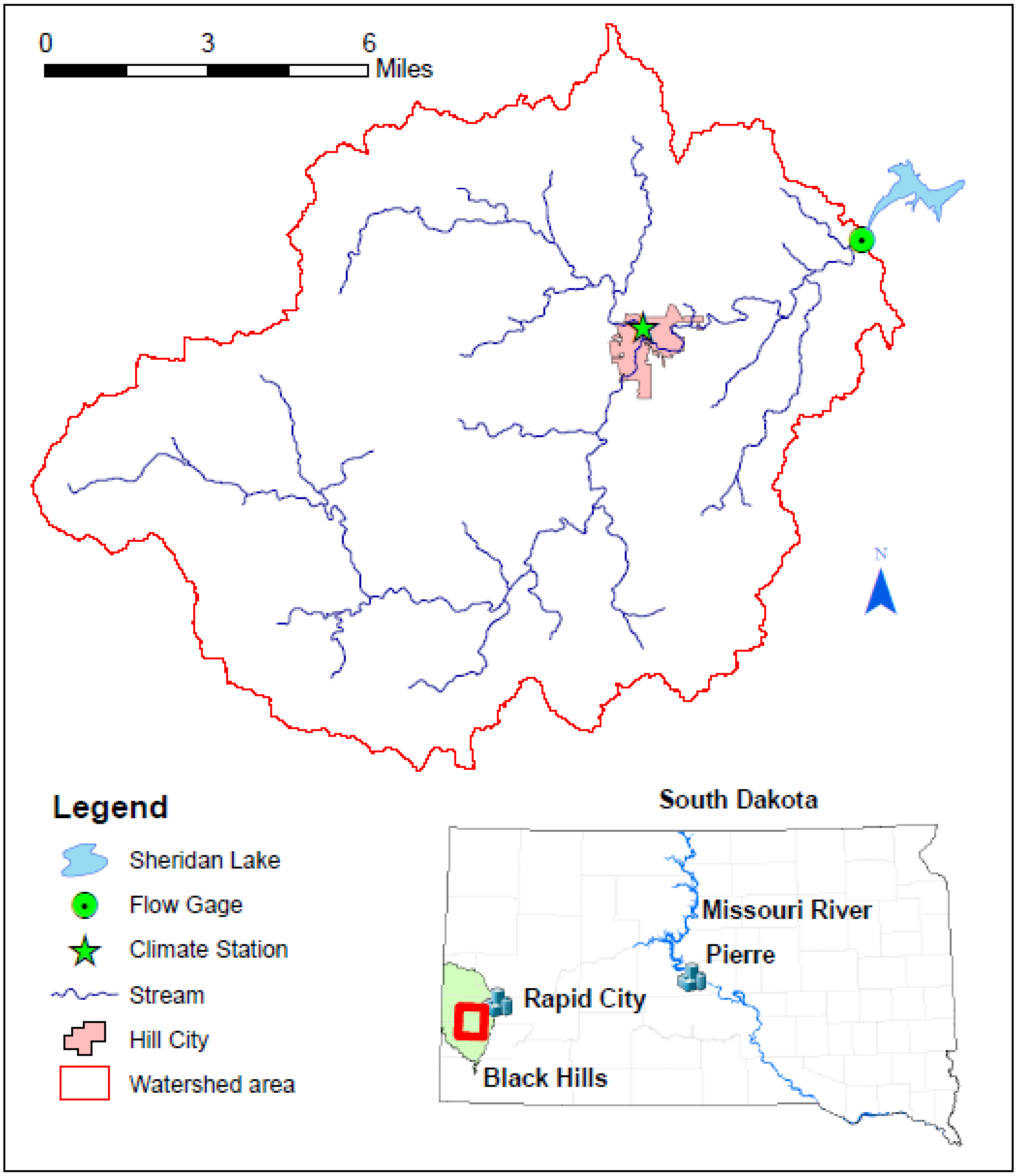

Figure 4.2 Location map of Spring Creek watershed above Sheridan Lake

4.6 Climate of Rapid Creek and Spring Creek Watersheds

The study areas lie in a continental semi-arid climate, with extreme variability of precipitation and temperature. Hot summers and cold winters are common in the watershed. The major rainfall occurs during April through August in the form of high intensity thunderstorms, which can produce very intense downpours. October to February are relatively dry months. Generally, June is the wettest month and January is the driest month of the year. The snowpack generally develops during early winter to early spring and the majority of snowmelt occurs in late spring. The snowmelt contributes flow to Rapid Creek and Spring Creek during late spring. The average potential evapotranspiration is generally exceeds the average annual precipitation in the study area. The amount of precipitation and soil moisture availability controls the evapotranspiration in the southern Black Hills area. For example, average pan evaporation or free water surface evaporation for April through October is approximately 30 inches at Pactola Reservoir (Driscoll et al., 2002).

The National Oceanic and Atmospheric Administration (NOAA) station (SD 396427) below Pactola Dam provides historical meteorological data for the study of Rapid Creek watershed. The average monthly precipitation and temperature data of the watershed area are shown in Table 4-1 and Table 4-2.

Table 4-1 Average monthly temperature data at NOAA station SD 396427 from 1971-2000

Average Monthly Temperature (Degree Fahrenheit)												
Units	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Max	34.7	38.5	43.6	51.3	61.4	71.5	78.5	78.2	68.5	57.1	43	36.9
Min	8.3	11.4	17.5	25.3	34.7	43.4	48.7	46.8	36.8	27.5	17.7	10.6

Table 4-2 Average monthly precipitation data at NOAA station SD 396427 from 1971-2000

Average Monthly Precipitation (Inches)												
Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
0.3	0.44	1.03	2.36	3.7	3.81	3.18	2.14	1.5	1.59	0.65	0.4	21.1

The NOAA station at Hill City (SD 393868) is the only station located in the Spring Creek watershed. The average monthly precipitation and temperature data of the watershed area are shown in Table 4-3 and Table 4-4.

Table 4-3 Average monthly temperature data at NOAA station SD 393868 from 1971-2000

Average Monthly Temperature (Degrees Fahrenheit)												
Units	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Max	6.9	11.3	18	25.6	35.7	43.6	48.7	46.5	36	27	16	8.7
Min	36	39.5	45	53.4	63.4	73.5	79.9	79.2	70	58	44	37

Table 4-4. Average monthly precipitation data at NOAA station SD 393868 from 1971-2000

Average Monthly Precipitation (Inches)												
Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
0.32	0.53	1.05	2.35	3.61	3.62	3.39	2.11	1.47	1.51	0.69	0.41	21.1

4.7 Geology of Rapid Creek and Spring Creek Watersheds

The Black Hills uplift formed about 60 to 65 million years ago as a result of the Laramide Orogeny. Subsequent uplift exposed igneous and metamorphic rock in central core of the Black Hills with outcrops of limestone and surrounding formations (Figure 4.3). Headwater springs originate from the limestone plateau on the western side of the central crystalline core. These provide base flow for many streams. The central crystalline core has low permeability and provides high amounts of direct runoff. Recharge that occurs from extensive fractured and weathered zones provides ground water discharge as a base flow to streams. The base flow can quickly diminish during periods of minimum precipitation. The groundwater flow in the Black Hills aquifers is outward from the central crystalline core of the Black Hills. The study area of Rapid Creek and Spring Creek watershed is located at the central crystalline core and the limestone plateau.

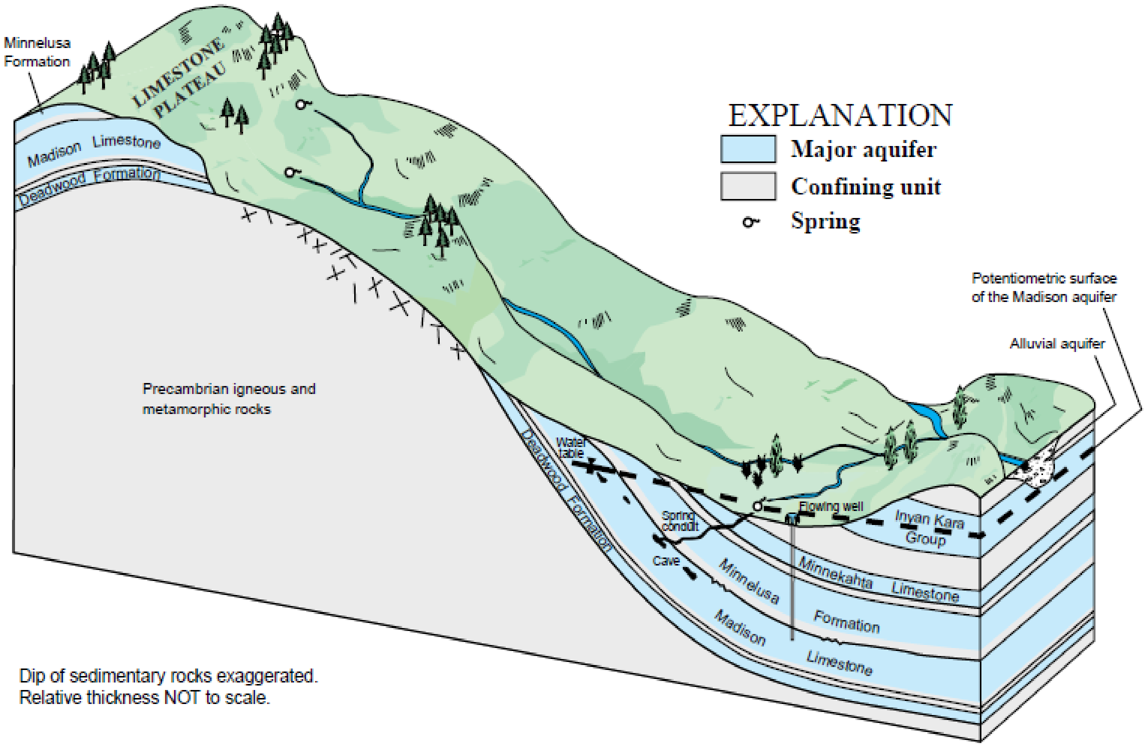

Figure 4.3 Schematic showing geological formations of the Black Hills (Carter et al., 2002)

The eastern side of central crystalline core contains outcrops of the Madison Limestone and Minnelusa Formation, which allow higher amounts of infiltration and recharge to the underlying aquifers. A unique rainfall-runoff process is observed between the central crystalline core area and outcrops of limestone and other formations. Streams that cross these outcrops have large streamflow losses to the underlying aquifers. The downstream sections of Rapid Creek and Spring Creek, below the study areas, pass through these outcrops which undergo significant amount of streamflow losses. The average annual streamflow loss threshold for the Rapid Creek and Spring Creek are 8 and 28 cubic feet per second respectively (Driscoll et al., 2002).

4.8 Soil Characteristics of Rapid Creek and Spring Creek Watersheds

The soil properties of a watershed strongly influence runoff and infiltration volume. Stovho, Mocmont, Pactola, and Buska are the four main soil series present in the study areas (USDA, 1990). Stovho soils are developed from weathered limestone and calcareous sandstone. The Stovho soils are deep and well drained, gently to very steep sloping and are located in limestone plateau of higher elevation. The Stovho soils have moderate permeability. Mocmont soils are loamy soils developed from weathered granite. The Mocmont soil series are located at central crystalline core area and are deep and well drained with low permeability. Pactola soils contain loamy soils developed from weathered metamorphic rocks and are well drained with gentle to very steep slopes. Buska soils were developed from weathered micaceous schist and are similar to Pactola soils. The Pactola and Buska soils are located at limestone outcrops of the Black Hills and have moderate permeability.

4.9 Land Uses in Rapid Creek Watershed

The watershed area consists of 90 percent of evergreen forest, 9.8 percent of rangeland, 0.2 percent of open water, and the remaining of barren land uses (rock/sand/clay) (NLCD 2006) (Figure 4.4). The 2006 National Land Cover Data (NLCD) contains 16 unique land use classes.

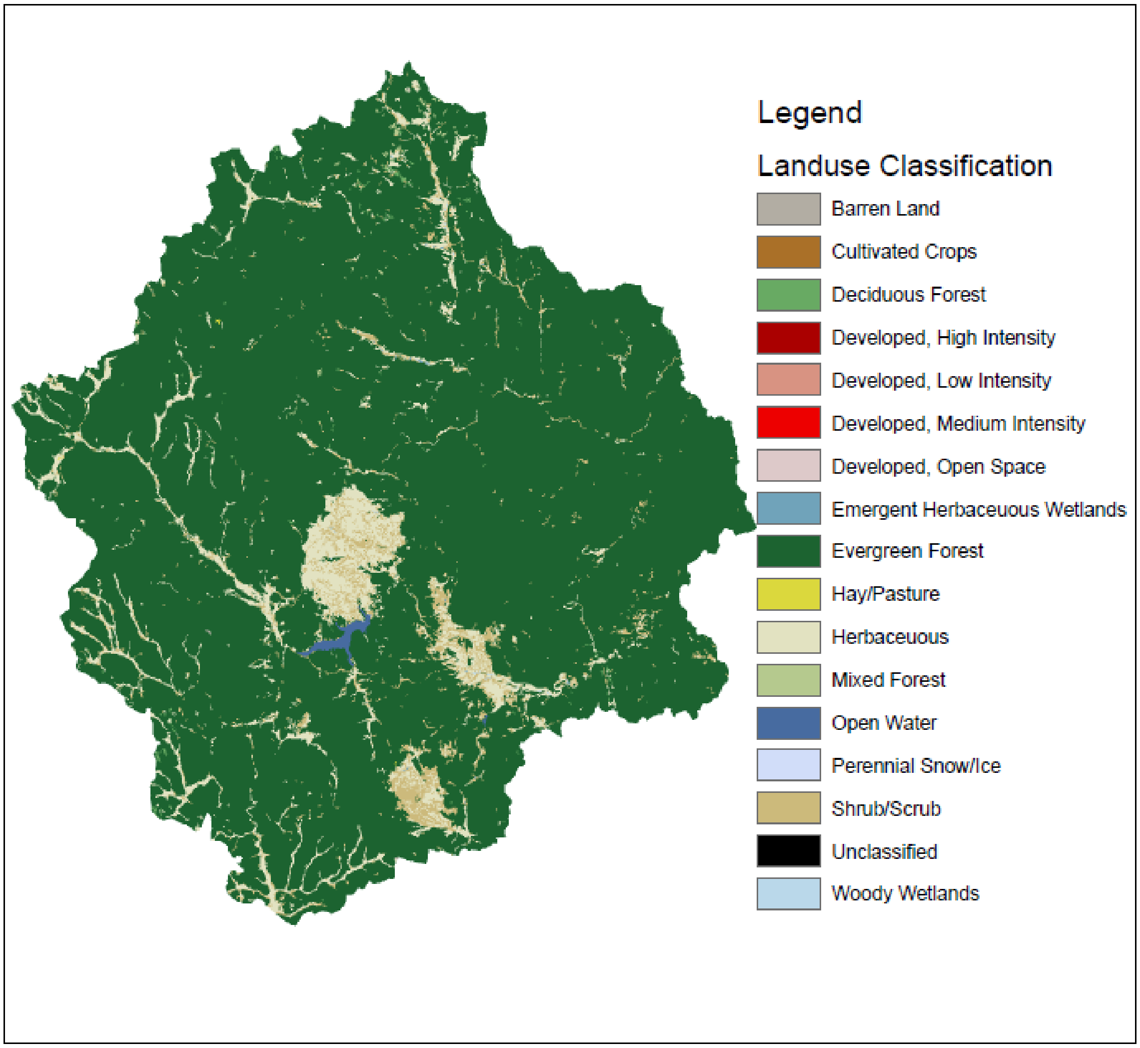

Figure 4.4 Land use classification of Rapid Creek watershed (NLCD 2006)

4.10 Land Uses in Spring Creek Watershed

Ninety one percent of the watershed area is covered by evergreen forest and the remaining by other land use types (NLCD 2006) (Figure 4.5). Ninety Eight percent of the land area is pervious and the remaining two percent is impervious. The land is mainly used for forest growth, recreation, residential, and grazing purposes.

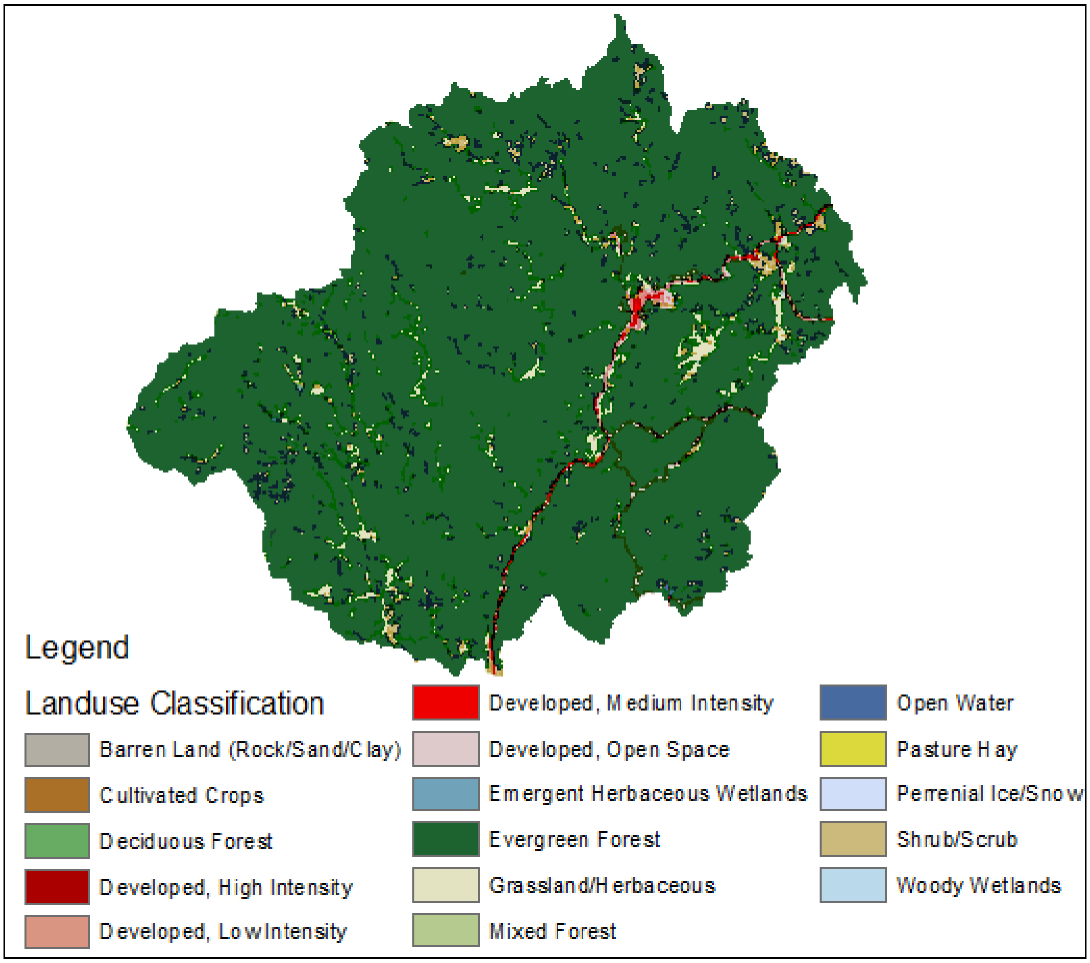

Figure 4.5 Land use classification of Spring Creek watershed (NLCD 2006)

4.11 Rainfall Runoff Processes in the Black Hills

The study areas located in the Black Hills consist of about 90 percent heavy forest with ponderosa pine. These areas usually include a layer of duff, which is partially decayed vegetation or organic matter on the forest floor. The duff layer can significantly control watershed runoff in forest areas of the Black Hills (Nebelsick, Physical Parameter Affecting Rainfall Runoff Response in Small Burned Watershed, Battle Creek Burn Area, South Dakota, MS Thesis, 2004). Duff temporarily holds rainfall and allows more time for infiltration. The duff system creates an inverted capillary fringe that pulls down the rainwater deeper into the soil by capillary tension. The fractured rock below finegrained soil causes lateral runoff in the Black Hills area. In areas with very thin duff layers, the infiltrated water quickly contacts mineral soil or bedrock and initiates lateral runoff, which can reach stream channels quickly.

4.12 Model Development

Land surface and subsurface hydrology is incorporated with stream and reservoir processes to predict streamflow hydrology at a desired location. The model development mainly consists of the collection and development of time series data, watershed delineation and characterization.

4.13 HSPF Time Series Data

The minimum meteorologic data needed for streamflow simulation with HSPF is precipitation and potential evapotranspiration data. In this investigation, snow accumulation and melt were also estimated using the energy (heat) balance method, which requires extensive datasets such as air temperature, solar radiation, wind, and dew point temperature. The hourly meteorological data was obtained in the Watershed Data Management (WDM) file from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) system of U.S. EPA (Table 4-5). The WDM uses the Hamon method to compute the potential evapotranspiration.

Table 4-5 NCDC climate stations located in the study areas

Station ID	Station Name	Hourly Data	Start Date	End Date	Use	
SD 396427	Pactola Dam	Precipitation	8/1/1951	12/31/2009	Rapid Creek Watershed	
SD 396427	Pactola Dam	Air Temperature	4/1/1955	12/31/2009		
SD 396427	Pactola Dam	Potential ET	4/1/1955	12/31/2009		Spring Creek Watershed
SD396937	Rapid City RAP	Wind Speed	1/1/1970	12/31/2009		
SD396937	Rapid City RAP	Solar Radiation	1/1/1970	12/31/2009		
SD396937	Rapid City RAP	Cloud Cover	1/1/1970	12/31/2009		
SD396937	Rapid City RAP	Dew Point	1/1/1970	12/31/2009		
SD 393868	Hill City	Precipitation	6/30/1955	12/31/2008		
SD 392087	Custer	Precipitation	1/1/1926	12/31/2008		
SD 392088	Custer	Air Temperature	10/1/1942	12/31/2008		

Daily observed flow was used for model calibration and validation process. The observed flow was obtained from the National Water Information System (NWIS) of U.S. Geological Survey (Table 4-6). The daily flow at downstream of Deerfield Dam (DFR SD) was acquired from the Bureau of Reclamation (BoR).

Table 4-6 Daily flow gage station located in the study areas

Station ID	Station Name	Start Date	End Date
06409000	Castle Creek Above Deerfield Dam, SD	7/1/1948	9/30/2012
DFR SD	Deerfield Dam, SD	1/1/1980	7/1/2013
06408860	Rochford, SD	10/1/1988	9/30/1994
06410500	Rapid Creek Above Pactola Dam, SD	10/1/1953	2/7/2013
06406920	Spring Creek Above Sheridan Lake, SD	10/1/1990	4/30/2004

4.14 HSPF Watershed Delineation and Characterization

Arc GIS 10.0 and Arc Hydro 2.0 tools were used to define a watershed area. Arc Hydro 2.0 requires a digital elevation model (DEM) (a raster file) and stream (a shape file) to designate a watershed. The DEM file was obtained from National Hydrography Dataset Plus (NHDPlus) for the Upper Missouri drainage basin (drainage area: MS, vector unit: 10U, and raster processing unit: 10f) (Horizon Systems Corporations, 2013).

The stream shape file was acquired from National Hydrography Dataset (NHD) through the National Map Viewer. The outlet flow gage location was utilized to assign watershed boundary during Arc Hydro processing. The subbasins were defined using available USGS flow gage stations (Figure 4.6).

A single station (SD 396427) was used to distribute the precipitation for the Rapid Creek watershed. Two stations (SD 393868 and SD 302087) were used to distribute the precipitation for the Spring Creek watershed by developing a meteorological zone using method of Thiessen polygons (Figure 4.7).

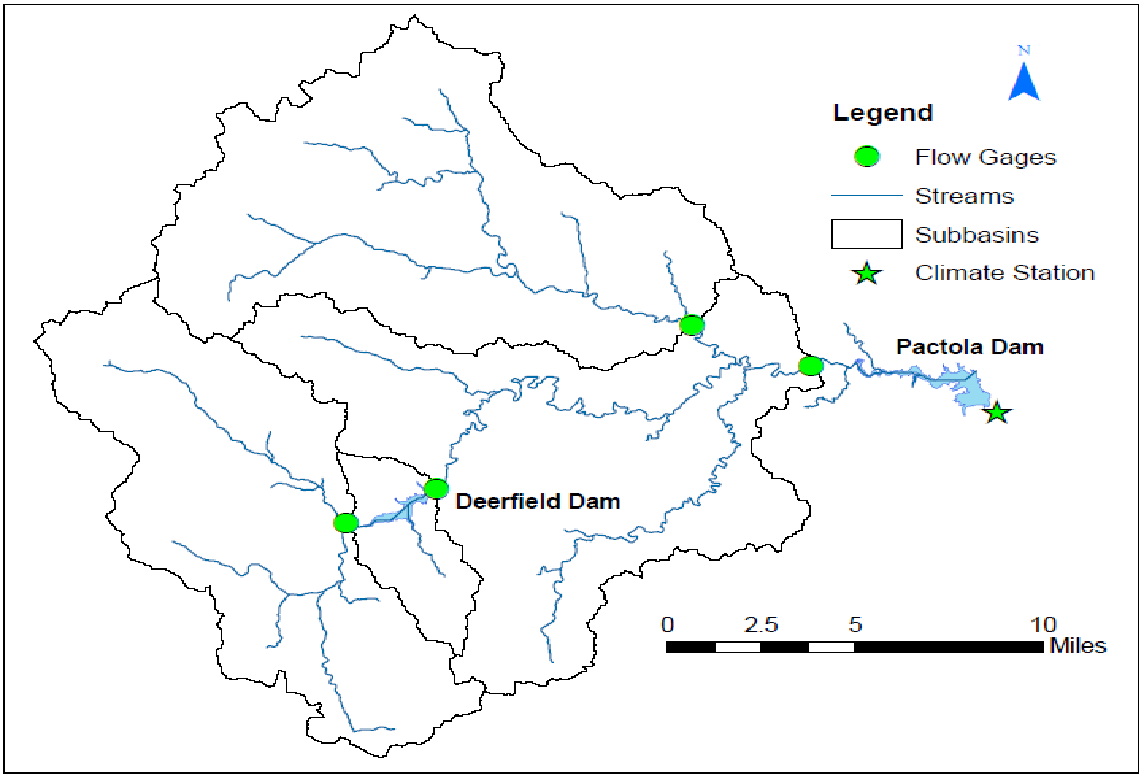

Figure 4.6 Rapid Creek watershed delineation for HSPF

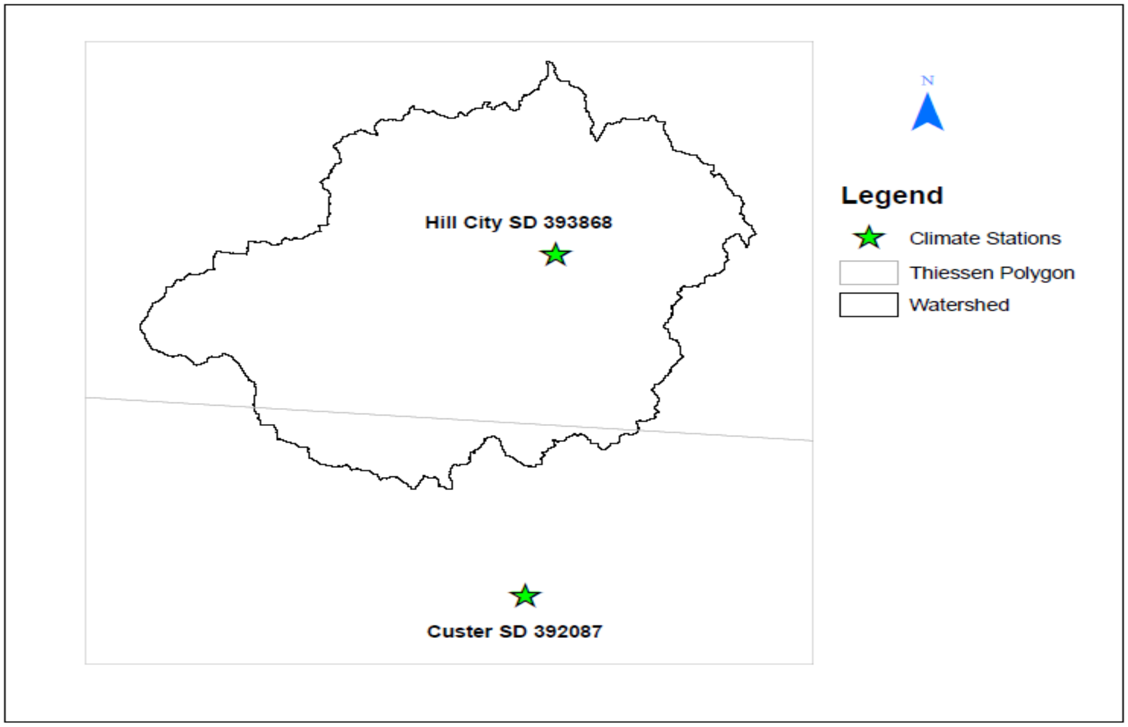

Figure 4.7 Meteorological zone development in Spring Creek watershed for HSPF

Both the Rapid Creek and the Spring Creek watersheds were characterized using land use type. The 16 land use classes were aggregated into 5 different categories based on similar land characteristics (Table 4-7).

Table 4-7 2006 NLCD land use aggregation into HSPF model categories

NLCD Description	HSPF Category	Percent Area (Rapid Creek Watershed)	Percent Area (Spring Creek watershed)
Open Water	Water	0.2	0.04
Perennial Snow/Ice			
Developed, Open Space	Urban		1.6
Developed, Low Intensity			
Developed, Medium Intensity			
Developed, High Intensity			
Barren Land	Barren		0.01
Deciduous Forest	Forest	90	91.09
Evergreen Forest			
Mixed Forest			
Woody Wetlands			
Shrub/Scrub	Rangeland	9.8	7.26
Herbaceous			
Hay/Pasture			
Cultivated Crops			
Emergent Herbaceous Wetlands			

4.15 HSPF Pervious Land Segment

A pervious land segment (PERLND) is defined as an area with similar hydrologic characteristics. The Rapid Creek watershed was characterized with 3 land use categories and 4 hydrozones (subbasins) producing 9 PERLNDs. The Spring Creek watershed was characterized with 5 land use categories and 2 meteorological zones creating 10 PERLNDs. No impervious land segments were used for watershed characterization of Rapid Creek and Spring Creek watersheds.

4.16 HSPF Reach Segments

The surface and sub-surface flow from each land segment enter the reach (RCHRES). The flow is routed through unidirectional channel. The Rapid Creek watershed was characterized with 4 RCHRES. Flow routing was inactivate (no reach segment) for the Spring Creek watershed.

4.17 HSPF Input File

HSPF input files consist of a user control interface (UCI) file and a time series watershed data management (WDM) file. The WDM file can be generated either using BASINS system or manually. The WDM file for Rapid Creek watershed (except flow station DFR SD) and Spring Creek watershed were obtained from the BASINS system. The Deerfield Dam outlet flow (DFR SD) was later appended to the existing WDM file of the Rapid Creek watershed. The UCI file can be generated either using WINHSPF or manually. For this research, the UCI file was prepared manually and its major components are PERLND, IMPLND, RCHRES, FTABLES, Schematics, External Sources, External Target, and Mass Link blocks. Arc GIS 10.0 and Basin Tech Note 6 were used to compute parameter value. The computed parameter value was assigned to each PERLND and RCHRES. The general input parameters of the HSPF model are described below and allowed ranges are provided.

LZSN: Lower zone nominal soil moisture storage represents the amount of moisture stored below the root zone of soil. For semi arid region, the initial value of LZSN parameter at the start of calibration can be estimated as one fourth of mean annual precipitation plus four inches. Typical values of LZSN range from 2 to 15 inch.

AGWRC: Active groundwater recession coefficient is the ratio of current ground water flow to earlier ground water flow at a specific time interval. It can be estimated using the hydrograph separation method (Basins Tech-Note 6, 2000). Typical values of AGWRC range from 0.92 to 0.99.

LZETP: Lower zone evapotranspiration parameter is related to evapotranspiration loss from lower zone of soil. Typical values of LZETP range from 0.6 to 0.8 (forest), 0.4 to 0.6 (grassland), 0.1 to 0.4 (barren land), and 0.6 to 0.9 (wetland).

INFILT: Infiltration capacity index is related to mean soil infiltration capacity, which is a function of soil and land use. The infiltration capacity divides precipitation among surface, subsurface and groundwater flow. Increasing infiltration reduces surface flow but increases subsurface and groundwater flow. The INFILT parameter can be estimated using the Soil Conservation Service (SCS) soil hydrologic group. Typical values of soil infiltration range from 0.001 to 0.25 in/hr.

INTFW: Interflow inflow parameter represents the amount of water that enters from the surface detention storage to ground as an interflow towards a stream. It is used to lower or raise the peak of a hydrograph. It can be estimated using a hydrograph separation method. Typical values of INTFW range from 1.0 to 3.0.

IRC: Interflow recession parameter is the ratio of current interflow to earlier interflow at specific time interval. It effects the shape of falling or rising curve of a hydrograph. Typical values of IRC range from 0.5 to 0.7.

UZSN: Upper zone nominal soil moisture storage is the amount of moisture stored for the upper zone of soil, which will be available for evapotranspiration. The UZSN value changes during the season. The typical value of UZSN is estimated as 0.14 * LZSN, for heavy forest and very mild slope, 0.06 * LZSN, for limited vegetation and steep slope, and 0.08 * LZSN, for moderate slope and moderate type of vegetation. Typical UZSN values range from 0.16 to 0.76 inches.

DEEPFR : it represents the fraction of infiltrating water lost through deep aquifers. Typical values of DEEPFR range from 0 to 0.20.

KVARY: It describes the non-linear ground water recession rate (/inch). It helps to fix the amount of ground water storage especially during the snow events (Kenner Seth, personal communication, September 18, 2013). Typical values of KVARY range from 0 to 3.0.

CCFACT: It represents the rate of heat transfer from the atmosphere to snowpack due to condensation, convection, and field condition. Typical value of CCFACT is near 1.0.

SNOWCF: It is the factor to adjust precipitation for poor gage catch efficiency during a snow event. Wind speed, snow shield, and gage location can affect snow catch in a gage. Typical values of SNOWCF range from 1.0 to 1.5.

4.18 HSPF Function Table

Function table (Ftables), a relationship between discharge and depth in channels and reservoirs, were developed from a rating curve using the Hydrologic Engineering Center River Analysis System (HECRAS). The cross sections data from DEM (Castle Creek above Deerfield Dam, Rapid Creek near Rochford) and field survey (Rapid Creek near Silver City) were used as input for HECRAS.

4.19 PRMS Model Development

In the PRMS, a watershed is discretized into a network of land surfaces, referred to as the hydrologic response units (HRUs). The discretization is based on hydrologic and physical characteristics such as drainage boundaries, land surface altitude, slope, aspect, vegetation type, soil morphology, geology, and precipitation distribution. These HRUs are assumed homogeneous with respect to hydrologic response. A segment is used for simulation of channel flow occurring in a watershed. Each segment receives runoff from 2 HRUs (left and right bank) and routes water through stream network.

The PRMS models for the Rapid Creek and Spring Creek watersheds were obtained from a preliminary version of a national data set, referred to as the Geospatial Fabric for the National Hydrologic Model (NHM) being developed by the USGS. The NHM aggregates the catchment and flowlines defined in the NHDPlus data set into HRUs and segments (Haj et al., in press). The NHM applies methods established in the GIS Weasel software to these features and necessary spatial data to describe the parameters for PRMS simulation. The GIS Weasel uses elevation information to generate HRUs and utilizes forest vegetation, land cover, and soil information to create parameters for the PRMS model (Viger and Leavesley, 2007). The 2001 National Land Cover Database and 100 meter version of the State Soil Geographic (STATSGO) database are used for the spatial description of the HRUs. Segments and HRU contributing areas are determined by a set of specific points called "points of interest" (POIs). The POIs includes USGS stream gages possessing a record of a guaranteed minimum quality (GAGE – II), the set of nodes used by the National Weather Service River Forecast Centers, and the set of nodes used by the USGS National Water Quality Assessment Program's SPARROW modeling project. The POIs are also placed where NHDPlus flowlines equal or exceed a Strahler order of 5 converge and inlets and outlets of waterbodies exceeding 1 million acres.

A USGS stream gage 06410500 at Rapid Creek above Pactola Dam, SD for the Rapid Creek watershed and USGS stream gage 06406920 at Spring Creek above

Sheridan Lake, SD for the Spring Creek watershed were used as POIs to obtain the model parameters. Eighteen HRUs were created for the simulation of the Rapid Creek watershed (Figure 4.8). Ten HRUs were created for the simulation of the Spring Creek watershed (Figure 4.9).

PRMS uses DAYMET daily meteorological data (daily precipitation, minimum temperature, and maximum temperature) to simulate streamflow. The DAYMET generates daily weather parameters in 1 km spatial resolution over the large region by using NCDC daily climate stations (Daymet, 2012). The area weighted DAYMET data was assigned to each HRU. These data were retrieved from USGS geodata portal (USGS-CIDA, 2013).

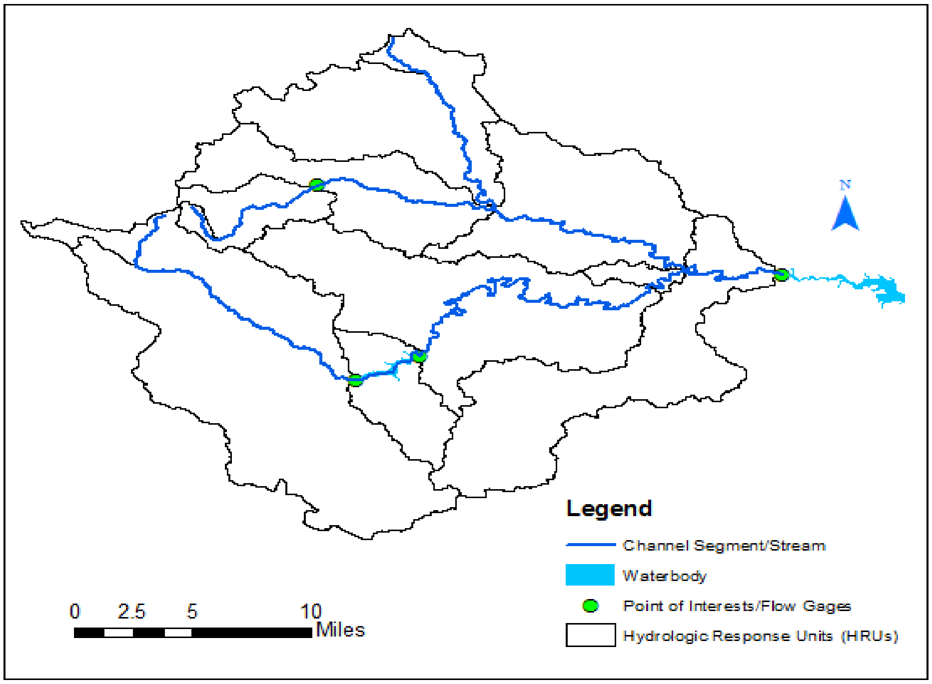

Figure 4.8 Characterization of the Rapid Creek watershed for PRMS

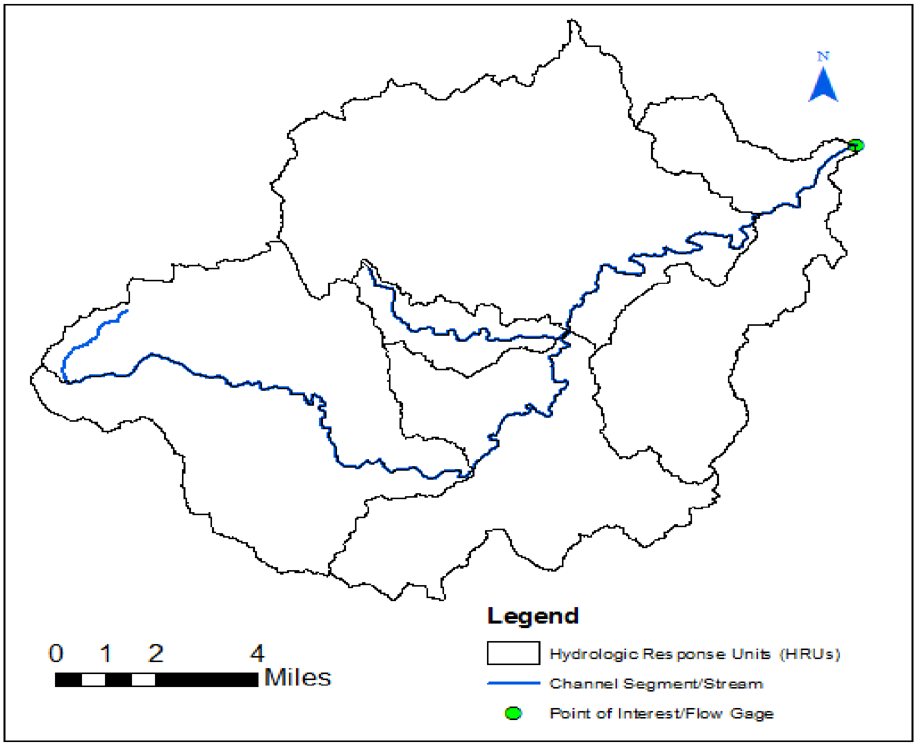

Figure 4.9 Characterization of the Spring Creek watershed for PRMS

The daily observed flow was obtained from National Water Information System (NWIS) of U.S. Geological Survey through a computer application called Downsizer. Downsizer was developed by the USGS and is a graphical user interface that selects, downloads, verifies, and formats station based data for PRMS (Ward-Garrison et al., 2009). The daily flow downstream of Deerfield Dam (DFR SD) was obtained from the Bureau of Reclamation (BoR).

4.20 PRMS Input File

PRMS input files consists of a control, data, and parameter files. The control file specifies input and output file names, content of the input and output files, start and end of simulation period, and active modules. The data file consists of daily measured time series data such as minimum temperature, maximum temperature, precipitation, and runoff. The parameter file consists of header, dimensions, and parameters. The header designates the unique parameter name. The dimension describes a size of parameter and variable name. The parameter describes the hydrologic and physical characteristics of the watershed. The variable describes the surface, subsurface, and groundwater properties of the watershed.

4.21 Calibration and Validation

Model calibration, also referred to as history matching, is an iterative process used to match simulated flow to observed flow by adjusting input parameter values. Model validation is a comparison of model simulated flow with independently derived observed flow. A common period of record was selected for both models during the calibration and validation process.

4.22 Rapid Creek Watershed Calibration Period

The HSPF and the PRMS models were simulated from 1990 to 2008 for the Rapid Creek watershed. The first two years of record (1990 – 1991) were assigned for the initial model period. The next 11 years of record (1992 – 2002) were used for calibration, and remaining 6 years of record (2003 – 2008) were used for the validation period. Model performance was evaluated for the calibration and validation period respectively. Both models performed well for the calibration period and worse for the validation period.

Analyzing average annual flow, it was found that the selected calibration period was mostly wet years (annual average streamflow above 125 percent of historical average annual streamflow) and selected validation period was mostly dry years (annual average streamflow below 75 percent of historical average annual streamflow). The historical average annual streamflow was calculated as 47.55 cubic feet per second (USGS gage # 06410500 Rapid Creek above Pactola Resevoir from 1954 to 2012). The calibration and validation period (1992 to 2008) had 6 wet years (1993, 1995, 1996, 1997, 1998, and 1999) , 6 dry years (1992, 2002, 2004, 2005, 2006, and 2007), and 5 normal years (1994, 2000, 2001, 2003, and 2008) (Table 4-8) . Wet and dry periods referred to group of wet and dry years respectively. All 6 wet years appeared in the calibration period and 4 out of 6 dry years appeared in the validation period. Results of this study indicate that bias selection of calibration period (having mostly wet years) might be a cause for worse results during a validation period. As a result, further study was conducted to know whether a new calibration period having mostly dry years will have similar impact on a validation period having mostly wet years. A separate model was developed having these new periods of calibration and validation.

The models with a calibration period of mostly wet years (calibration scenario 1) were referred to as “wet models.” The models with a calibration period having mostly dry years (calibration scenario 2) were referred as “dry models.” Internal and external comparisons of the models were performed for the different calibration and validation scenarios.

Table 4-8 Calibration scenarios for Rapid Creek watershed

Year	Flow (cfs)	Status	Initial Setup	Calibration issues/scenarios	
1992	26.3	Dry year	Calibration	Calibration Scenario 1 (Wet model, similar to initial setup)	Validation Scenario 2 (Dry model)
1993	64.4	Wet year			
1994	48.7	Normal year			
1995	88.5	Wet year			
1996	93.8	Wet year			
1997	137	Wet year			
1998	135	Wet year			
1999	126	Wet year			
2000	59.4	Normal year			
2001	45.5	Normal year			
2002	32.4	Dry year			
2003	39	Normal year	Validation	Validation Scenario 1 (Wet model, similar to initial setup)	Calibration Scenario 2 (Dry model)
2004	22.6	Dry year			
2005	20.4	Dry year			
2006	29.9	Dry year			
2007	27	Dry year			
2008	55.4	Normal year			

Note: Wet Year: Flow (cfs) > 59.4 cfs, Dry Year: Flow (cfs) < 35.7

4.23 Spring Creek Watershed Calibration Period

The HSPF and the PRMS models were simulated from 1991 to 2003 for the Spring Creek watershed. The first 2 years of records (1991 – 1992) were assigned for the initial model period. The remaining 11 years of record were used as a calibration period. The historical average annual streamflow was calculated as 23.0 cubic feet per second (USGS gage # 06406920 Spring Creek above Sheridan Lake from 1991 to 2003). The calibration period included 5 wet years (1995-1999) and 5 dry years (1994, 2000-2003) (Table 4-9). To avoid the calibration/validation issues (wet vs. dry calibration period), a single calibration period for the entire simulation period (1993-2003) was used. Both models were evaluated using the calibration results.

Table 4-9 Calibration scenario for Spring Creek watershed

Year	Flow(cfs)	Status	Setup
1991	23.2	Normal Year	Calibration/Validation
1992	5.2	Dry Year	
1993	27.3	Normal Year	
1994	9.9	Dry Year	
1995	39.9	Wet Year	
1996	32.9	Wet Year	
1997	43.3	Wet Year	
1998	37.1	Wet Year	
1999	43.8	Wet Year	
2000	11	Dry Year	
2001	11.1	Dry Year	
2002	6.2	Dry Year	
2003	8.7	Dry Year	

Note: Wet year: flow (cfs) > 28.8, Dry year: flow (cfs) < 17.3

4.24 HSPF Calibration Approach

Model calibration can require very significant effort, and requires the user to fully understand the model and the physical system being modeled. Parameters can be correlated, have thresholds, and have other issues that create erratic and unknown influence on the model output. To minimize these issues, HSPF used standard calibration approach, which includes 3 steps: calibrating first the annual water balance, then the monthly water balance, and finally the specific rainfall runoff events. The initial values of LZSN, AGWRC, and LZETP were adjusted to find the best match between observed and estimated average annual flow. The INFILT value was adjusted to achieve best fit for average monthly water balance. The INTFW, IRC, and UZSN were adjusted to find best fit for specific rainfall runoff events.

The parameter values were initially changed by +/- 10 percent from the initial value in the beginning of the calibration. Parameter changes were made smaller (+/-5 percent) near the end of the calibration. Each calibration run was evaluated by comparing model simulated output with observed gage flow. The parameter value was maintained if the new parameter value improved the simulated output. The parameter value was returned to older value if the new parameter value degraded the simulated output. This method of calibration was continued until the best match between the observed and simulated flow was obtained for all three of the water budgets (annual, monthly, and daily). Additional parameters DEEPFR, SNOWCF, and CCFACT were adjusted to improve the overall water balance.

4.25 PRMS Calibration Approach

PRMS was calibrated using Luca, a multiple objective and automated procedure for hydrologic model calibration (Hay and Umemoto, 2006). Luca uses the Shuffled Complex Evolution (SCE) global search algorithm to calibrate any model coupled with the USGS Modular Modeling System. The calibration was performed in six steps: 1) mean monthly solar radiation 2) mean monthly potential evapotranspiration 3) water balance configurations 4) daily flow components 5) daily high flow, and 6) daily low flow. The list of calibrated parameters in each step is shown in Table 4-10.

Table 4-10 PRMS calibration parameters (Haj, written communication, March 4, 2013)

Calibration steps	Parameter name	Parameter description	Parameter range		
			min	max	Default
Solar Radiation	dday_intcp	Intercept in temperature degree-day relation	-60	10	preset
	dday_slope	Slope in temperature degree-day relation	0.2	0.9	0.4
PET	jh_coef	Coefficient used in Jensen-Haise PET computations	0.005	0.09	preset
Water balance	rain_cbh_adj	Precipitation adjustment factor for rain days	0.6	1.4	1
	snow_cbh_adj	Precipitation adjustment factor for snow days	0.6	1.4	1
Daily flow	adjmix_rain	Factor to adjust rain proportion in mixed rain/snow event	0.6	1.4	1
	cecn_coef	Convection condensation energy coefficient	2	10	5
	emis_noppt	Emissivity of air on days without precipitation	0.757	1	0.757
	free2ho_cap	Free-water holding capacity of snowpack	0.01	0.2	0.05
	potet_sublim	Proportion of PET that is sublimated from snow surface	0.1	0.75	0.5
	slow_coef_lin	Linear coefficient in equation to route gravity reservoir storage down slope for each HRU	0.001	0.5	GIS
	soil_moist_max	Maximum available water holding capacity of soil profile	1	10	GIS
	soil_rechr_max	Maximum available water holding capacity for soil recharge zone	0.25	5	GIS
	tmax_allrain	If HRU tmax exceeds this value, precipitation assumed rain	30	40	32
	tmax_allsnow	If HRU tmax is below this value, precipitation assumed snow	30	40	32
	tmax_cbh_adj	Maximum temperature adjustment factor	-5	5	0
	tmin_cbh_adj	Minimum temperature adjustment factor	-5	5	0

Calibration steps	**Parameter name**	**Parameter description**	**Parameter range**		
			min	max	Default
Daily high flow	fast_coef_lin	Coefficient to route preferential flow storage down slope	0.001	0.8	GIS
	pref_flow_den	Fraction of the soil zone in which preferential flow occurs	0	0.1	0
	sat_thresold	Water holding capacity of the gravity and preferential flow reservoirs	1	15	10
	smidx_coef	Coefficient in non-linear surface runoff contribution area algorithm	0.001	0.06	GIS
Daily low flow	gwflow_coef	Maximum amount of capillary reservoir excess routed directly to ground water reservoir	0.001	0.5	GIS
	soil2gw_max	Maximum amount of capillary reservoir excess routed directly to the GWR	0	0.5	GIS
	ssr2gw_rate	Linear coefficient used to route water from the gravity reservoir to ground water reservoir	0.05	0.8	GIS
Daily flow	slowcoef_sq	Non-linear coefficient in equation to route gravity-reservoir storage down slope for each HRU	0	1	0.1
	fastcoef_sq	Coefficient to route preferential-flow storage down slope	0	1	0.8

Phase one of calibration consisted of first two steps (solar radiation and potential evapotranspiration). The phase one calibration continued until the best match between the observed and estimated mean monthly solar radiation and potential evapotranspiration was obtained (e.g. degree day method for solar radiation and Jensen and Haise method for potential ET). Phase two of calibration consisted of four steps, and looped through each step until the best match between the observed and estimated annual, monthly and daily flow was obtained.

4.26 Model Evaluation

The model performance (less or more accurate) was measured by comparing simulated flow to gage flow. The “weight of evidence approach” was used to evaluate the model performance. Statistics (error statistics) and graphical comparison were used to measure model accuracy that provides performance evaluation.

The Nash Sutcliffe efficiency (NSE), ratio of the root mean square error to standard deviation of measured data (RSR), percent volume error (PVE), percent bias (PBIAS), Pearson correlation coefficient (r) and coefficient of determination (R^2) were used to evaluate the models (Moriasi et al., 2007).

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}\right] \qquad [4.1]$$

where Y_i^{obs} is the i^{th} observed value of the flow, Y_i^{sim} is the i^{th} simulated value of the flow, Y_i^{mean} is the mean observed flow, and n is the total number of observations.

The value of NSE lies between -∞ to +1. The positive value of NSE is considered as a acceptable level of model performance. The NSE ≤ 0 represents unacceptable model performance; it indicates that the mean observed value could better estimate flow than the model. The NSE=1 represents the perfect match between model simulated flow and observed flow.

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}\right]} \qquad [4.2]$$

The RSR is the ratio of root mean square error (RMSE) and standard deviation (STDEV) of observed data (Moriasi et al., 2007). RSR standardizes the RMSE, taking the standard deviation of measured data. The RSR value varies from 0 to large positive number. A lower RSR value indicates better model performance.

$$PBIAS = \left[\frac{\sum_{i=1}^{n}({Y_i}^{sim} - {Y_i}^{obs}) * 100}{\sum_{i=1}^{n}({Y_i}^{obs})}\right] \qquad [4.3]$$

PBIAS measures the average tendency of simulated data to be greater than or smaller than the corresponding observed value (Moriasi et al., 2007). The positive value of PBIAS indicates a model over-estimation of observed value and negative value of PBIAS indicates the model under-estimation of observed value. The PBIAS = 0, indicates optimal model simulation.

$$PVE = \frac{({Y_i}^{sim} - {Y_i}^{obs}) * 100}{(Y_i)^{obs}} \qquad [4.4]$$

The average percent volume error (PVE) estimates the accumulation of different streamflow volume between simulated and observed data for particular period of analysis (Moriasi et al., 2007). In this study, the average annual, monthly, and daily error was calculated to evaluate the model performance.

$$r = \frac{\sum_{i=1}^{n}({Y_i}^{sim} - {Y_{sim}}^{mean})\,({Y_i}^{obs} - {Y_{obs}}^{mean})}{\sqrt{\sum_{i=1}^{n}({Y_i}^{obs} - {Y_{sim}}^{mean})^2 * \sum_{i=1}^{n}({Y_i}^{obs} - {Y_{obs}}^{mean})^2}} \qquad [4.5]$$

Pearson's correlation coefficient (r) measures the strength and direction of linear relationship between observed and simulated flow. The value of r is $-1 \leq r \leq +1$, the + and – sign indicates positive and negative linear correlations. If r = 0 it means no or very weak linear relationship, and r = 1 or -1 indicates a perfect linear positive or negative relationship exists between observed and simulated flow. The coefficient of determination (R^2) describes how well the model simulated flow measures the proportion of the variance in observed flow. The value of R^2 is $0 \leq R^2 \leq +1$. If $R^2 = 0$ means none of the variation in observed flow is measured by simulated flow and $R^2 = 1$ means all of the variation in observed flow is measured by the simulated flow. The higher value of r (absolute) and R^2 indicates better model performance.

5. Results, Discussions and Conclusions

Different statistical and graphical methods were used to evaluate each model's accuracy as compared to measured USGS streamflow gage data for the study area. All flow values presented hereafter are mean values, derived from model output at the stipulated time step.

5.1 Rapid Creek Watershed Results

Two calibration/validation scenarios were performed during the study of the Rapid Creek watershed above Pactola Reservoir. The first scenario includes a wet calibration period and a dry validation period. The second scenario includes a dry calibration period and a wet validation period.

5.2 Scenario 1 – Calibration for Rapid Creek Watershed

The HSPF and PRMS were calibrated for 1992 to 2002 (includes a wet period). During the 11 year calibration period, the absolute volume error between observed and HSPF annual streamflow was less than 15 percent for 4 years, 15 to 30 percent for 3 years, and greater than 30 percent for 4 years (Table 5-1). The absolute volume error for PRMS annual streamflow was less than 15 percent for 3 years, 15 to 30 percent for 2 years, and greater than 30 percent for 6 years. The HSPF over-estimated the annual flow (24 to 76 percent) for 4 years and under-estimated it (0.2 to 32 percent) for 7 years. The PRMS over-estimated the annual flow (14 to 116 percent) for 8 years and under-estimated it (5 to 39 percent) for 3 years.

Table 5-1 Comparison of observed and estimated annual streamflow for HSPF and PRMS for the calibration period (1992-2002), (scenario 1, Rapid Creek watershed)

Year	Observed Flow (cfs)	HSPF Flow (cfs)	PRMS Flow (cfs)	Percent Volume Error (HSPF)	Percent Volume Error (PRMS)
1992^{d}	26.31	46.34	56.83	76.11	115.98
1993^{w}	64.38	93.95	83.87	45.93	30.26
1994	48.68	33.07	88.08	-32.06	80.94
1995^{w}	88.49	88.30	101.75	-0.22	14.98
1996^{w}	93.81	125.07	107.15	33.32	14.22
1997^{w}	137.36	110.64	160.56	-19.45	16.89
1998^{w}	135.32	129.21	102.90	-4.52	-23.96
1999^{w}	125.49	156.65	76.54	24.83	-39.01
2000	59.42	59.17	55.91	-0.41	-5.90
2001	45.46	37.33	60.26	-17.89	32.54
2002^{d}	32.43	29.68	47.89	-8.49	47.67
Average	77.92	82.67	85.61	8.83	25.87

Note: w- wet year and d- dry year

The HSPF over-estimated the annual flow during wet years (1993, 1996 and 1999) and under-estimated it during normal years (1994 and 2001) (Figure 5.1). The PRMS over-estimated the annual streamflow during dry years (1992 and 2002) and normal years (1994 and 2001), and under-estimated it during wet years (1998 and 1999).

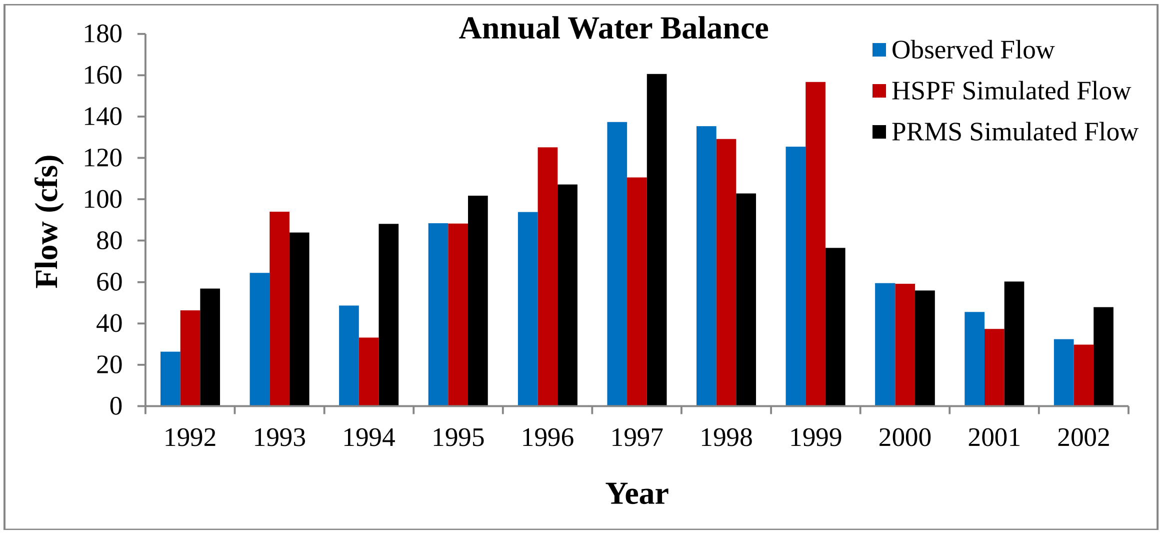

Figure 5.1 Comparison of observed and estimated annual streamflow for HSPF and PRMS for the calibration period (1992-2002), (scenario 1, Rapid Creek watershed)

The HSPF over-estimated the monthly mean flow for rainfall runoff events during wet years (1993, 1996, and 1999) and under-estimated it for normal years (1994 and 2001) (Figure 5.2). The PRMS better estimated the monthly mean flow than the HSPF for rainfall runoff events during wet years (1993 and 1996) and under-estimated it for a wet year (1999). The PRMS over-estimated monthly mean flow for rainfall runoff events for both dry years (1992 and 2002) and normal years (1994 and 2001). The HSPF better estimated monthly mean flow than the PRMS for base flow periods during wet years (1998 and 1999) and a dry year (2002).

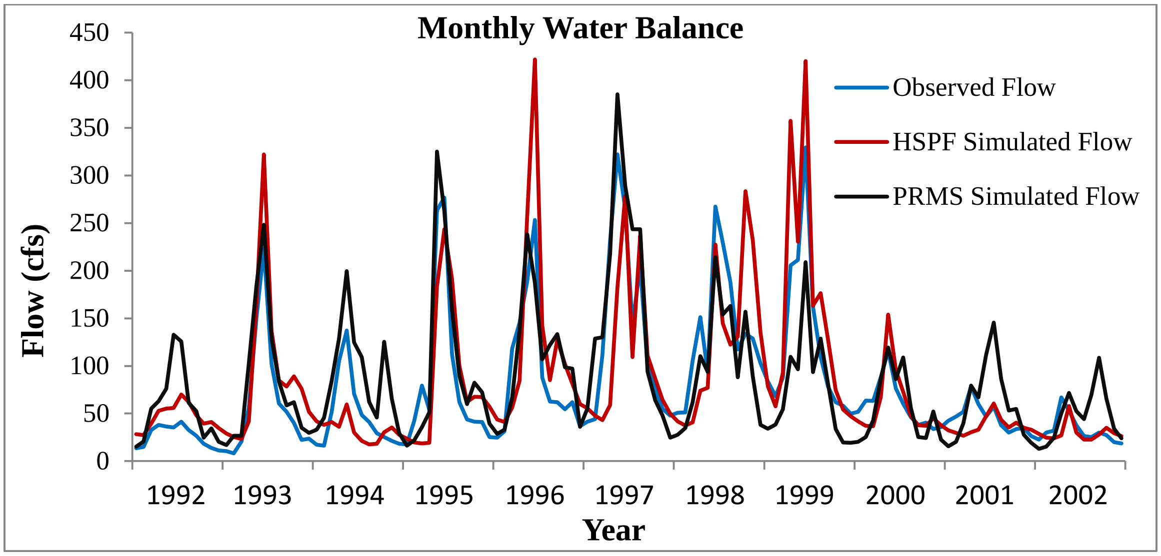

Figure 5.2 Comparison of observed and estimated monthly mean streamflow for HSPF and PRMS for the calibration period (1992-2002), (scenario 1, Rapid Creek watershed)

The percent volume error (PVE) of HSPF monthly mean flow was low and consistent in summer, and high and varied during the winter (Figure 5.3). The PVE of PRMS monthly mean flow was high and varied radically throughout a year except in spring. A high PVE was present in PRMS monthly mean flow in summer during dry years. The PVE of HSPF monthly mean flow was less than the PRMS for the calibration period.

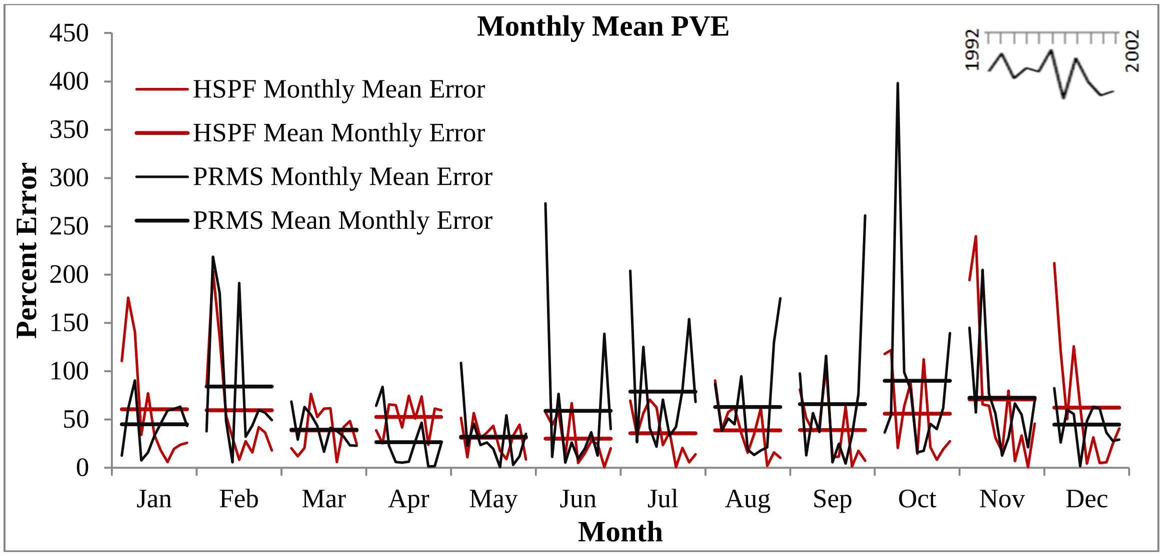

Figure 5.3 Comparison of percent volume error for HSPF and PRMS estimated monthly mean flow for the calibration period (1992-2002), (scenario 1, Rapid Creek watershed)

Both HSPF and PRMS under-estimated mean monthly flow during early spring and over-estimated it during summer to early winter (Figure 5.4). The HSPF over-estimated and the PRMS under-estimated the mean monthly flow during the winter. The PRMS mean monthly flow was better than the HSPF for early summer.

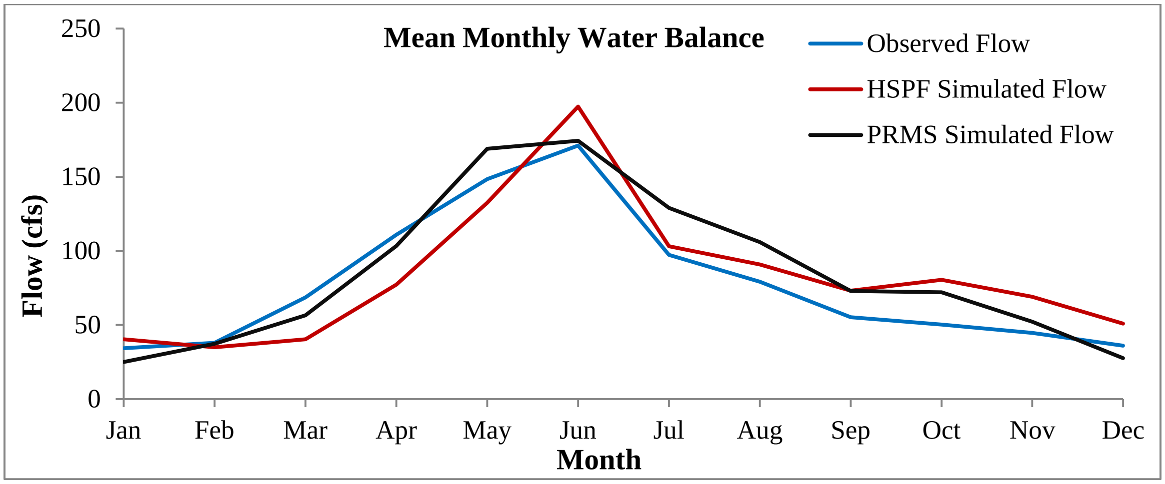

Figure 5.4 Comparison of observed and estimated mean monthly streamflow for HSPF and PRMS for the calibration period (1992-2002), (scenario 1, Rapid Creek watershed)

The flow duration curve showed that about 90 percent of the observed daily flow was represented by HSPF daily flow (Figure 5.5). The PRMS daily flow approximately represented 20 percent of the observed daily flow. This showed that the HSPF better estimated daily flow than the PRMS during the calibration period.

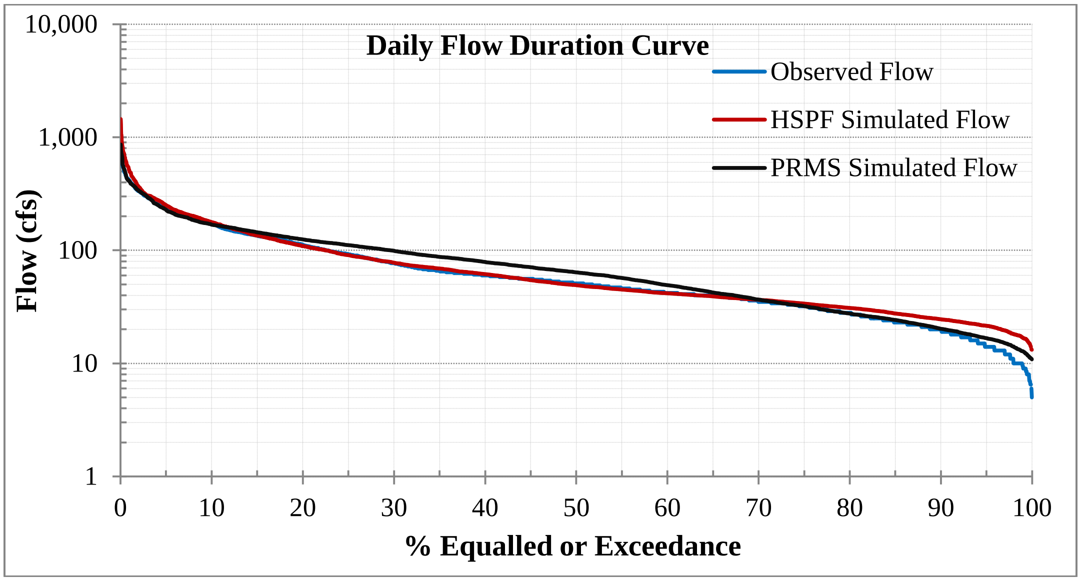

Figure 5.5 Comparison of observed and estimated daily streamflow duration curves for HSPF and PRMS for the calibration period (1992-2002), (scenario 1, Rapid Creek watershed)

During the calibration period, the average volume error for HSPF and PRMS annual flow were 9 and 26 percent, respectively (Table 5-2). The Nash Sutcliffe efficiency (NSE), Pearson's correlation coefficient (r), and coefficient of determination (R^2) statistics for the HSPF annual flow (NSE = 0.74, r = 0.89, and R^2 = 0.79) were better than the PRMS (NSE = 0.54, r = 0.76, and R^2 = 0.58). The average volume error for HSPF monthly mean flow (22 percent) was better than the PRMS (32 percent). However, the NSE, r, and R^2 statistics of the PRMS monthly mean, mean monthly, and daily flow were better than the HSPF.

Table 5-2 Comparison between HSPF and PRMS estimated streamflow for the calibration period (1992-2002), (scenario 1, Rapid Creek watershed)

Items	Annual		Monthly Mean		Mean Monthly		Daily	
	HSPF	PRMS	HSPF	PRMS	HSPF	PRMS	HSPF	PRMS
Avg. % Error	8.83	25.87	21.96	32.44	12.80	8.15	25.74	35.67
PBIAS	6.10	9.87	6.10	9.78	6.10	9.77	6.11	9.88
NSE	0.74	0.54	0.57	0.66	0.77	0.85	0.36	0.59
RSR	0.51	0.68	0.66	0.58	0.48	0.38	0.80	0.64
RMSE	19.75	26.41	46.03	40.63	20.75	16.72	64.69	51.86
r	0.89	0.76	0.82	0.84	0.89	0.96	0.75	0.80
R^2	0.79	0.58	0.67	0.70	0.80	0.91	0.57	0.64

5.3 Summary of Scenario 1 – Calibration for Rapid Creek Watershed

The HSPF better estimated annual flow (8 out of 11 years) than the PRMS during the calibration period. The HSPF better estimated monthly mean flow than the PRMS for rainfall runoff events during the dry years. The PRMS better estimated monthly mean flow than the HSPF for rainfall runoff events during most of the wet years. The PVE of HSPF monthly mean flow was less than the PRMS during the summer. The PRMS better estimated mean monthly flow than the HSPF during early summer. The HSPF better estimated monthly mean flow than the PRMS for base flow periods during most of the wet years. Based on NSE, r, and R^2 statistics, the HSPF better estimated annual flow than the PRMS and the PRMS better estimated monthly mean, mean monthly, and daily flow than the HSPF for the calibration period (1992-2002).

5.4 Scenario 1 – Validation for Rapid Creek Watershed

Both models (HSPF and PRMS) were validated for 2003 to 2008 (includes a dry period). During the 6 year validation period, the absolute volume error between observed and HSPF annual flow was between 15 to 30 percent for 1 year and greater than 30 percent for 5 years (Table 5-3). The absolute volume error for PRMS annual flow was greater than 30 percent for all 6 years.

Table 5-3 Comparison of observed and estimated annual streamflow for HSPF and PRMS for the validation period (2003-2008), (scenario 1, Rapid Creek watershed)

Year	Observed Flow (cfs)	HSPF Flow (cfs)	PRMS Flow (cfs)	Percent Volume Error (HSPF)	Percent Volume Error (PRMS)
2003	38.97	32.08	55.94	-17.67	43.56
2004^{d}	22.61	15.09	45.77	-33.26	102.45
2005^{d}	20.36	13.51	55.07	-33.65	170.55
2006^{d}	29.85	10.27	71.76	-65.60	140.38
2007^{d}	26.96	11.17	59.88	-58.56	122.06
2008	55.40	34.26	109.62	-38.16	97.87
Average	32.36	19.40	66.34	-41.15	112.81

Note: d- dry year

The HSPF under-estimated the annual flow (18 to 66 percent) and the PRMS over-estimated the annual flow (44 to 174 percent) during the entire validation period (Figure 5.6).

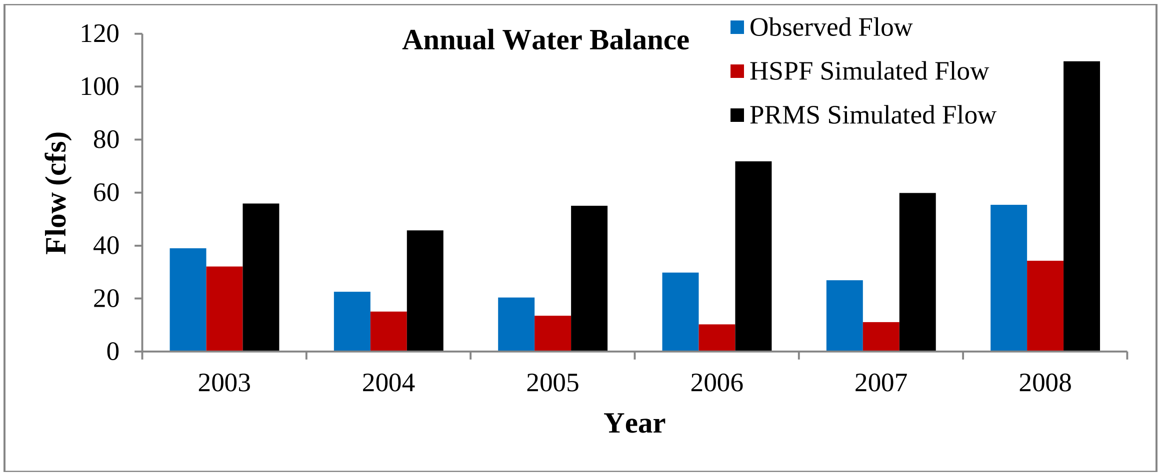

Figure 5.6 Comparison of observed and estimated annual streamflow for HSPF and PRMS for the validation period (2003-2008), (scenario 1, Rapid Creek watershed)

The HSPF better estimated the monthly mean flow during normal years (2003 and 2008) as compared to dry years (2006 and 2007) (Figure 5.7). The PRMS over-estimated the monthly mean flow throughout the validation period.

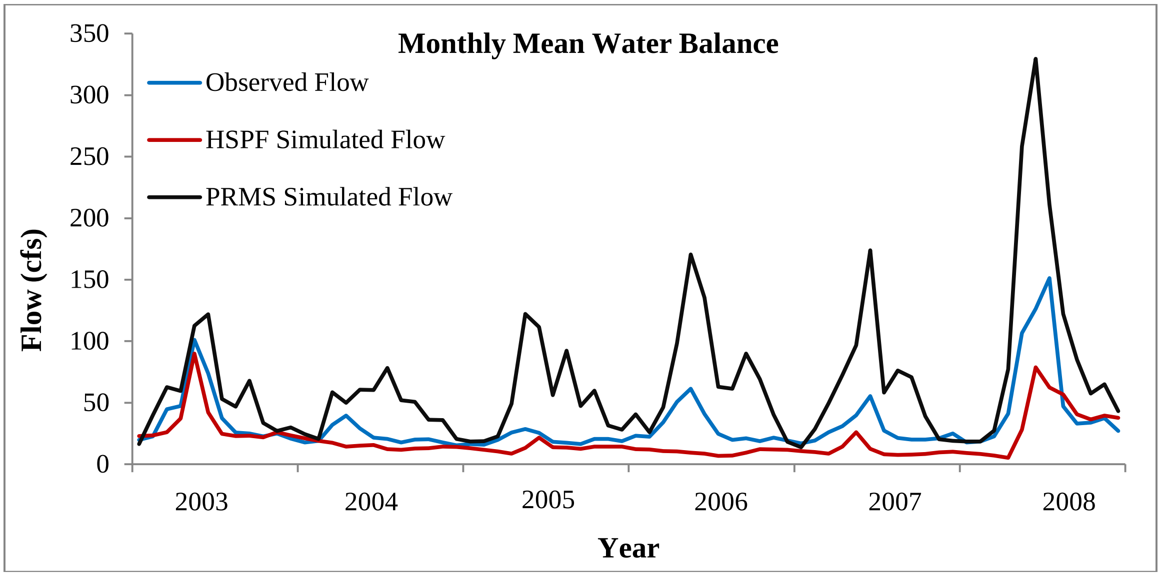

Figure 5.7 Comparison of observed and estimated monthly mean streamflow for HSPF and PRMS for the validation period (2003-2008), (scenario 1, Rapid Creek watershed)

The PVE of HSPF monthly mean flow was less than the PRMS from May to November (Figure 5.8).

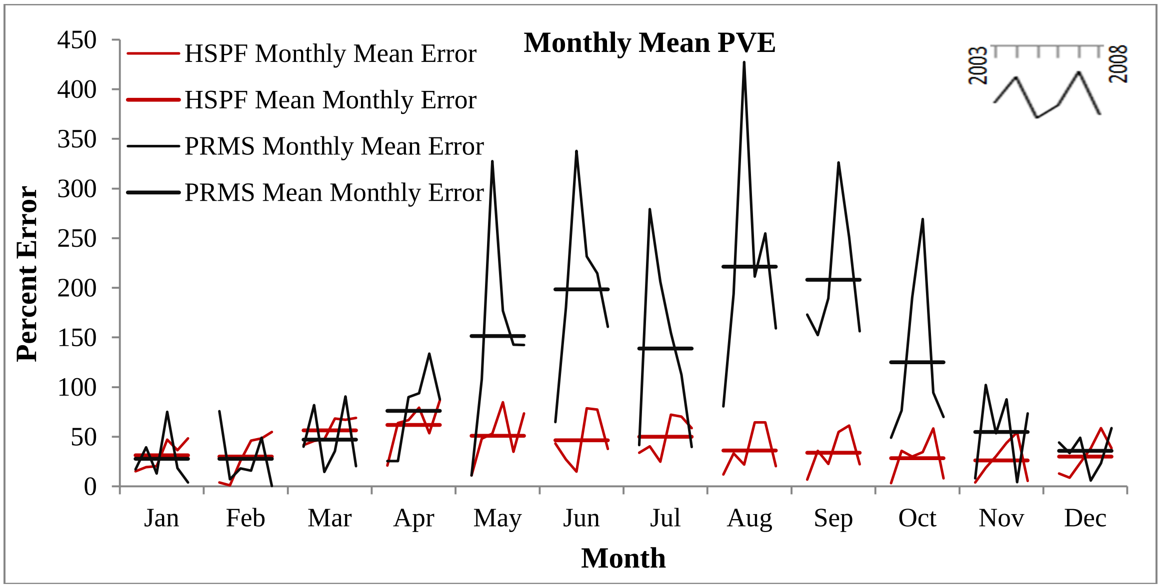

Figure 5.8 Comparison of percent volume error for HSPF and PRMS estimated monthly mean flow for the validation period (2003-2008), (scenario 1, Rapid Creek watershed)

The HSPF under-estimated the mean monthly flow during the summer and under-estimated it during the winter (Figure 5.9). However, the PRMS over-estimated the mean monthly flow during the summer and over-estimated it during the winter.

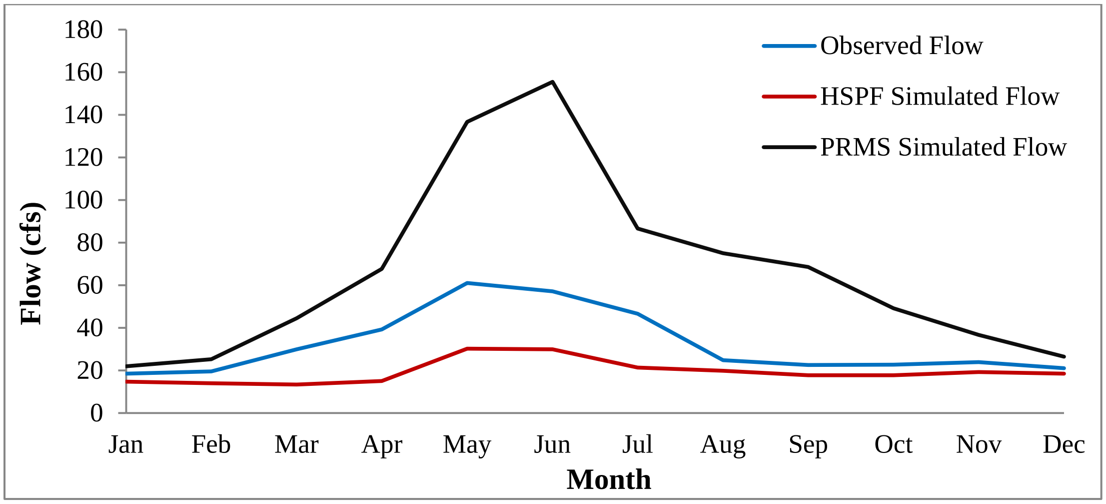

Figure 5.9 Comparison of observed and estimated mean monthly streamflow for HSPF and PRMS for the validation period (2003-2008), (scenario 1, Rapid Creek watershed)

The flow duration curve showed that the HSPF under-estimated and the PRMS over-estimated the daily flow (Figure 5.10). Both models did not perform well for estimating the daily flow during the validation period.

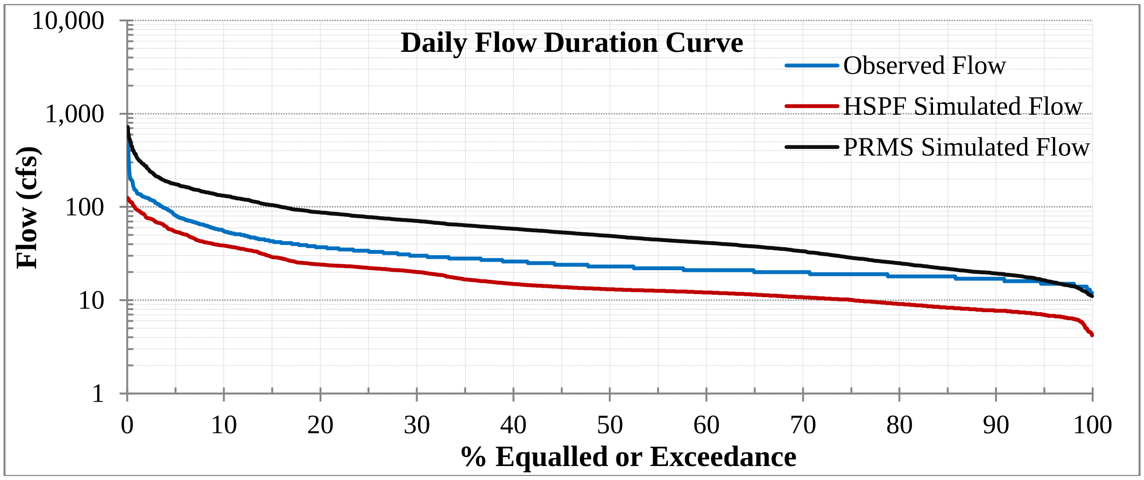

Figure 5.10 Comparison of observed and estimated daily streamflow duration curves for HSPF and PRMS for the validation period (2003-2008), (scenario 1, Rapid Creek watershed)

The average volume errors for HSPF and PRMS annual flow were -41 and 113 percent respectively for the validation period (Table 5-4). The NSE statistic of HSPF annual flow (NSE = -0.45) was better than the PRMS (NSE = -8.20). The r and R^2 statistics for the HSPF annual flow (r = 0.86 and R^2 = 0.74) and the PRMS (r = 0.86 and R^2 = 0.75) were similar. The average volume error for HSPF monthly mean flow (-36 percent) was better than PRMS (107 percent). The NSE statistic of HSPF monthly mean, mean monthly, and daily flow were better than the PRMS. However the r, and R^2 statistics of the PRMS monthly mean, mean monthly, and daily flow were better than the HSPF. The negative value of the annual NSE statistic explains that the mean annual observed flow might better estimate annual flow than the model.

Table 5-4 Comparison between HSPF and PRMS estimated streamflow for the validation period (2003-2008), (scenario 1, Rapid Creek watershed)

Items	Annual		Monthly Mean		Mean Monthly		Daily	
	HSPF	PRMS	HSPF	PRMS	HSPF	PRMS	HSPF	PRMS
Avg. % Error	-41.15	112.81	-35.98	107.45	-34.29	95.89	-34.29	108.82
PBIAS	-40.06	105.02	-40.03	104.99	-40.03	104.98	-40.05	105.01
NSE	-0.45	-8.20	0.26	-3.10	-0.34	-8.44	0.22	-2.55
RSR	1.20	3.03	0.86	2.02	1.16	3.07	0.88	1.88
RMSE	14.32	36.08	21.42	50.27	16.68	44.33	27.00	57.73
r	0.86	0.86	0.73	0.84	0.82	0.91	0.64	0.72
R^2	0.74	0.75	0.54	0.70	0.67	0.84	0.41	0.52

5.5 Summary of Scenario 1 – Validation for Rapid Creek Watershed

The HSPF better estimated annual and monthly mean flow than the PRMS during the validation period. The PVE of HSPF monthly mean flow was less than the PRMS during the summer. The HSPF under-estimated and the PRMS over-estimated the monthly mean flow during the summer. Both models performed weak in estimating the daily flow. The annual, monthly, and daily NSE statistics for the HSPF flow were better than the PRMS. The r and R^2 statistics for PRMS monthly and daily flows were better than the HSPF. In general, the HSPF performed better than the PRMS for the validation period. Both HSPF and PRMS models did not perform well for the validation period (2003-2008) as compared to the calibration period (1992-2002).

5.6 Scenario 2 – Calibration for Rapid Creek Watershed

The HSPF and PRMS were calibrated for 2003 to 2008 (includes a dry period). During the 6 year calibration period, the absolute volume error between observed and HSPF annual streamflow was less than 15 percent for 2 years and greater than 30 percent for 4 years (Table 5-5). The absolute volume error between observed and PRMS annual flow was less than 15 percent for 4 years, 15 to 30 percent for 1 year, and greater than 30 percent for 1 year. The HSPF over-estimated the annual flow for 3 years (51 to 67 percent) and under-estimated it for 3 years (9 to 34 percent). The PRMS over-estimated the annual flow for 5 years (5 to 42 percent) and under-estimated it for 1 year (14 percent).

Table 5-5 Comparison of observed and estimated annual streamflow for HSPF and PRMS for the calibration period (2003-2008), (scenario 2, Rapid Creek watershed)

Year	Observed Flow (cfs)	HSPF Flow (cfs)	PRMS Flow (cfs)	Percent Volume Error (HSPF)	Perecent Volume Error (PRMS)
2003	38.97	58.76	33.42	50.80	-14.23
2004[d]	22.61	37.67	24.69	66.60	9.18
2005[d]	20.36	32.81	28.88	61.19	41.88
2006[d]	29.85	26.53	38.35	-11.11	28.45
2007[d]	26.96	24.46	30.62	-9.29	13.54
2008	55.40	36.54	57.93	-34.04	4.56
Average	32.36	36.13	35.65	20.69	13.90

Note: d- dry year

The HSPF over-estimated the annual flow during dry years (2003 to 2005) and under-estimated it during a normal year (2008) (Figure 5.11). The PRMS better estimated annual flow (4 out of 6 years) than the HSPF during the calibration period.

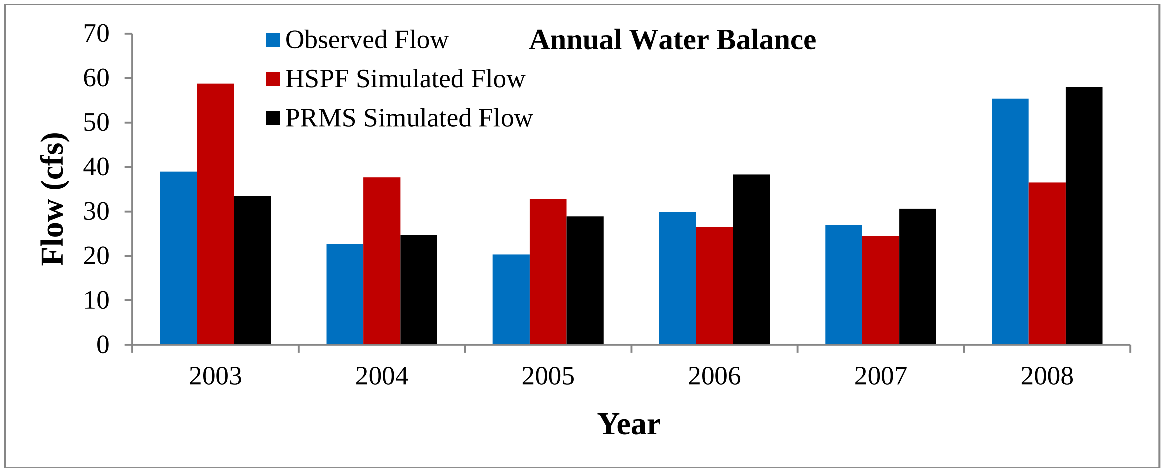

Figure 5.11 Comparison of observed and estimated annual streamflow for HSPF and PRMS for the calibration period (2003-2008), (scenario 2, Rapid Creek watershed)

The HSPF monthly mean flow was inconsistent during the dry years because it over-estimated 1 dry year (2005) and under-estimated the other (2006) (Figure 5.12). The HSPF also over-estimated 1 normal year (2003) and under-estimated another (2008). The PRMS over-estimated the monthly mean flow for rainfall runoff events during dry years (2004, 2005-2007) and a normal year (2008) and under-estimated it for a normal year (2003). The PRMS better estimated monthly mean flow than the HSPF for base flow periods during dry years (2004-2006) and a normal year (2003).

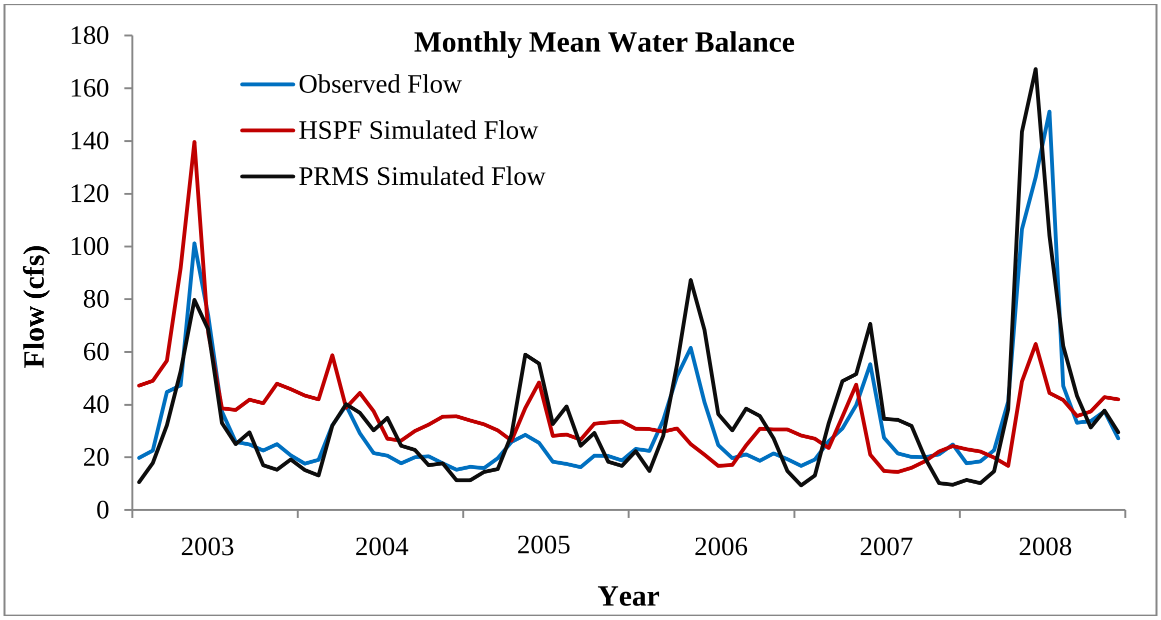

Figure 5.12 Comparison of observed and estimated monthly mean streamflow for HSPF and PRMS for the calibration period (2003-2008), (scenario 2, Rapid Creek watershed)

The percent volume error (PVE) for the HSPF monthly mean flow was high in the winter and low in the summer (Figure 5.13). The PVE for the PRMS monthly mean flow was high in the summer and low in the winter.

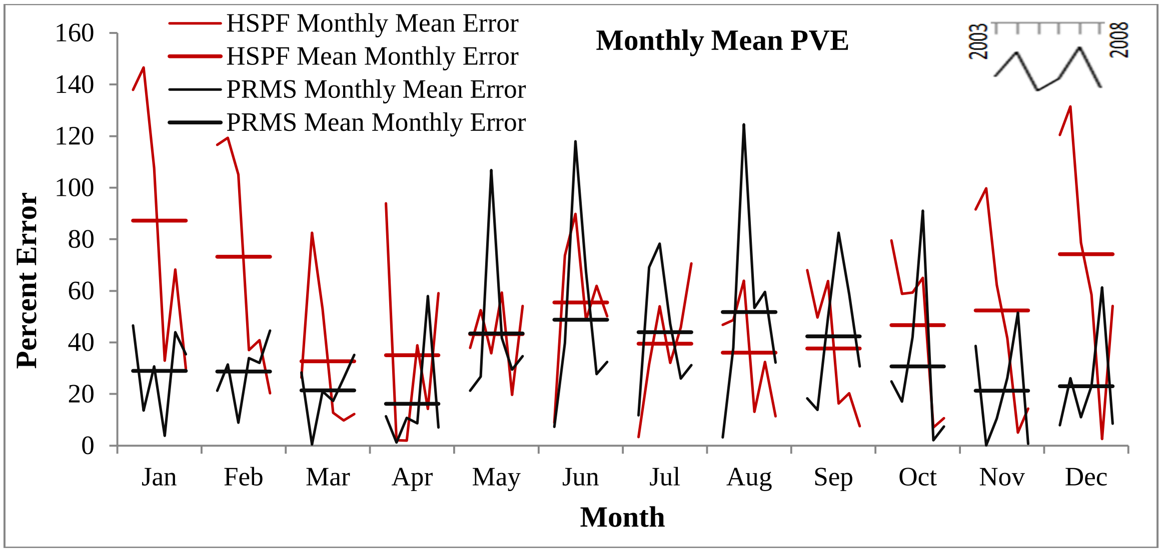

Figure 5.13 Comparison percent volume error of HSPF and PRMS estimated monthly mean flow for the calibration period (2003-2008), (scenario 2, Rapid Creek watershed)

The HSPF over-estimated the mean monthly flow throughout a year except the summer (Figure 5.14). The PRMS over-estimated the mean monthly flow during the summer and under-estimated it during the winter.

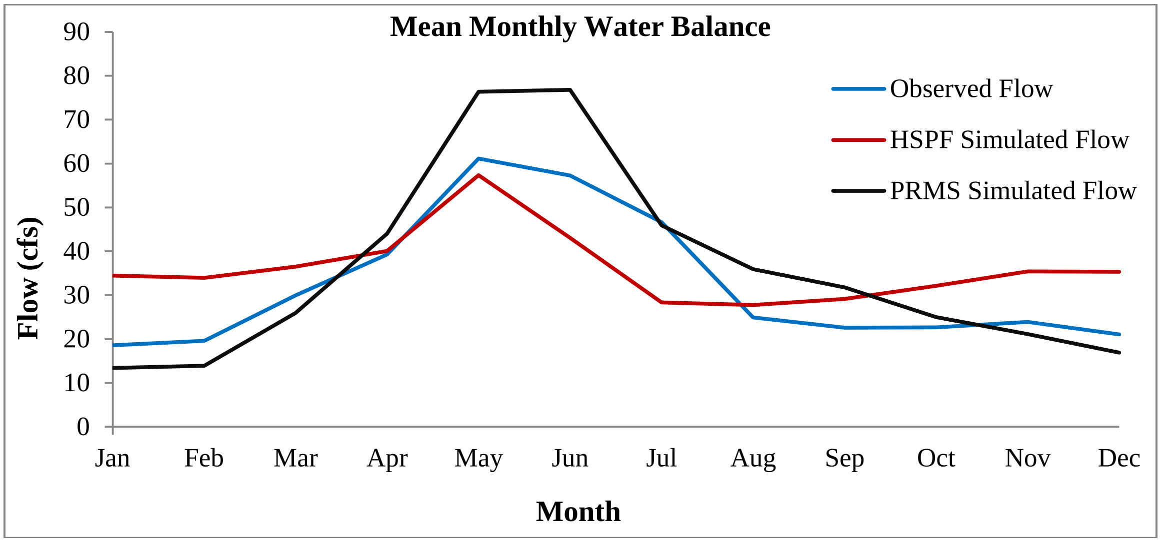

Figure 5.14 Comparison of observed and estimated mean monthly streamflow for HSPF and PRMS for the calibration period (2003-2008), (scenario 2, Rapid Creek watershed)

The HSPF under-estimated the daily high flow and over-estimated the daily minimum flow (Figure 5.15). The PRMS over-estimated the daily high flow and under-estimated the daily minimum flow.

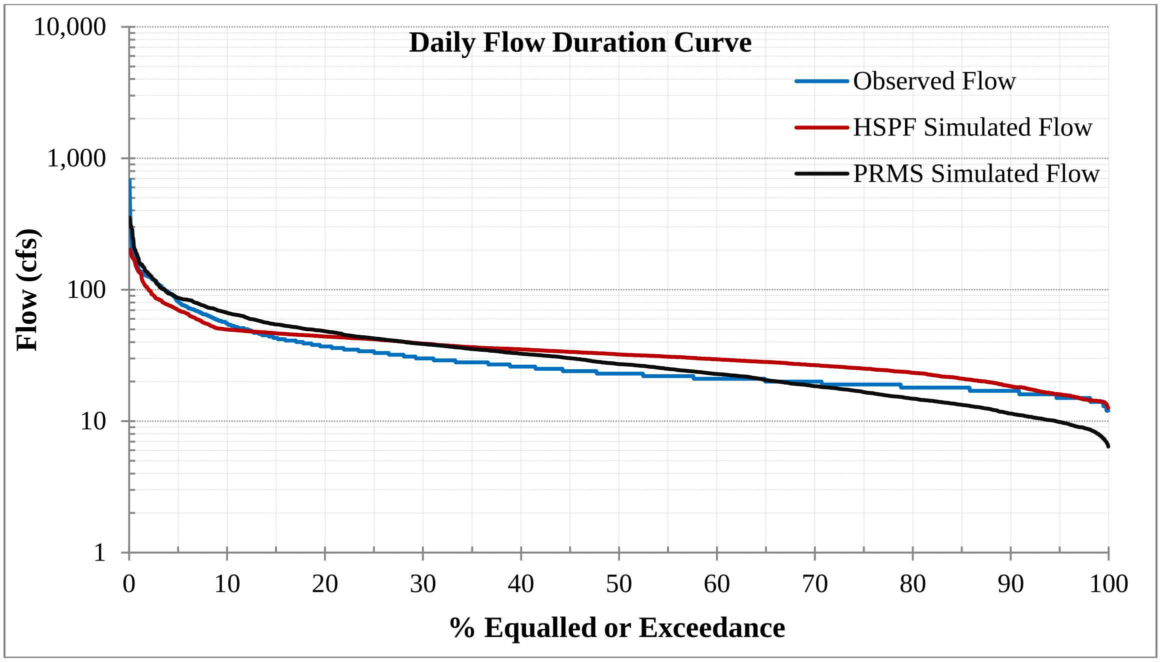

Figure 5.15 Comparison of observed and estimated daily streamflow duration curves for HSPF and PRMS for the calibration period (2003-2008), (scenario 2, Rapid Creek watershed)

During the calibration period, the average volume error for HSPF and PRMS annual flow were 21 and 14 percent respectively (Table 5-6). The NSE, r, and R^2 statistics for the PRMS annual flow (NSE = 0.76, r = 0.92, and $R^2 = 0.84$) were better than the HSPF (NSE = -0.35, r = 0.34, and $R^2 = 0.11$). The average volume error for the PRMS monthly mean flow (11 percent) was better than the HSPF (33 percent). The NSE, r, and R^2 statistics for the PRMS monthly mean, mean monthly, and daily flow were better than the HSPF during the calibration period.

Table 5-6 Comparison between HSPF and PRMS estimated streamflow for the calibration period (2003-2008), (scenario 2, Rapid Creek watershed)

Items	Annual		Monthly		Mean Monthly		Daily	
	HSPF	PRMS	HSPF	PRMS	HSPF	PRMS	HSPF	PRMS
Avg. % Error	20.69	13.90	32.99	10.83	25.76	5.17	35.94	11.91
PBIAS	11.65	10.16	11.80	10.12	11.80	10.12	11.63	10.16
NSE	-0.35	0.76	0.17	0.69	0.39	0.62	0.13	0.50
RSR	1.16	0.48	0.91	0.56	0.78	0.62	0.93	0.71
RMSE	13.82	5.77	22.58	13.90	11.27	8.88	28.60	21.66
r	0.34	0.92	0.50	0.88	0.70	0.96	0.44	0.77
R^2	0.11	0.84	0.25	0.77	0.49	0.92	0.20	0.59

5.7 Summary of Scenario 2 – Calibration for Rapid Creek Watershed

The PRMS better estimated annual flow than the HSPF for most of the calibration period. The PRMS better estimated monthly mean flow than the HSPF for base flow periods during most of the dry and normal years. The PVE for the PRMS monthly mean flow was high in the summer and low in the winter. The PVE for the HSPF monthly mean flow was high in the winter and low in the summer. The PRMS over-estimated the mean monthly flow during the summer and under-estimated it during the winter. The HSPF over-estimated the mean monthly flow throughout a year except during the summer. Both HSPF and PRMS performed weak in estimating the daily flow. Based on NSE, r, and R^2 statistics, the PRMS better estimated annual, monthly mean, mean monthly, and daily flow than the HSPF for the calibration period (2003-2008).

5.8 Scenario 2 – Validation for Rapid Creek Watershed

Both models (HSPF and PRMS) were validated for 1992 to 2002 (includes a wet period). During the 11 year validation period, the absolute volume error between observed and HSPF annual flow was less than 15 percent for 1 year, 15 to 30 percent for 1 year, and greater than 30 percent for 9 years (Table 5-7). The absolute volume error between observed and PRMS annual flow was less than 15 percent for 1 year, 15 to 30 percent for 3 years, and greater than 30 percent for 7 years. The HSPF over-estimated the annual flow (11 to 131 percent) during the validation period. The PRMS under-estimated the annual flow (24 to 68 percent) during the validation period except one dry year (1992, over-estimated 12 percent).

Table 5-7 Comparison of observed and estimated annual streamflow for HSPF and PRMS for the validation period (1992-2002), (scenario 2, Rapid Creek watershed)

Year	Observed Flow (cfs)	HSPF Flow (cfs)	PRMS Flow (cfs)	Percent Volume Error (HSPF)	Percent Volume Error (PRMS)
1992^d	26.31	60.69	29.51	130.66	12.16
1993^w	64.38	127.68	44.90	98.31	-30.26
1994	48.68	56.72	36.58	16.51	-24.85
1995^w	88.49	144.82	47.16	63.66	-46.70
1996^w	93.81	158.62	55.02	69.09	-41.35
1997^w	137.36	152.14	59.72	10.76	-56.52
1998^w	135.32	177.35	56.36	31.06	-58.35
1999^w	125.49	210.27	40.39	67.56	-67.81
2000	59.42	93.22	28.83	56.90	-51.48
2001	45.46	75.87	33.88	66.89	-25.49
2002^d	32.43	70.87	24.65	118.54	-23.99
Average	77.92	120.75	41.55	66.36	-37.70

Note: w- wet year and d- dry year

During the validation period, the HSPF continuously over-estimated the annual flow and the PRMS under-estimated it for most of the years (Figure 5.16).

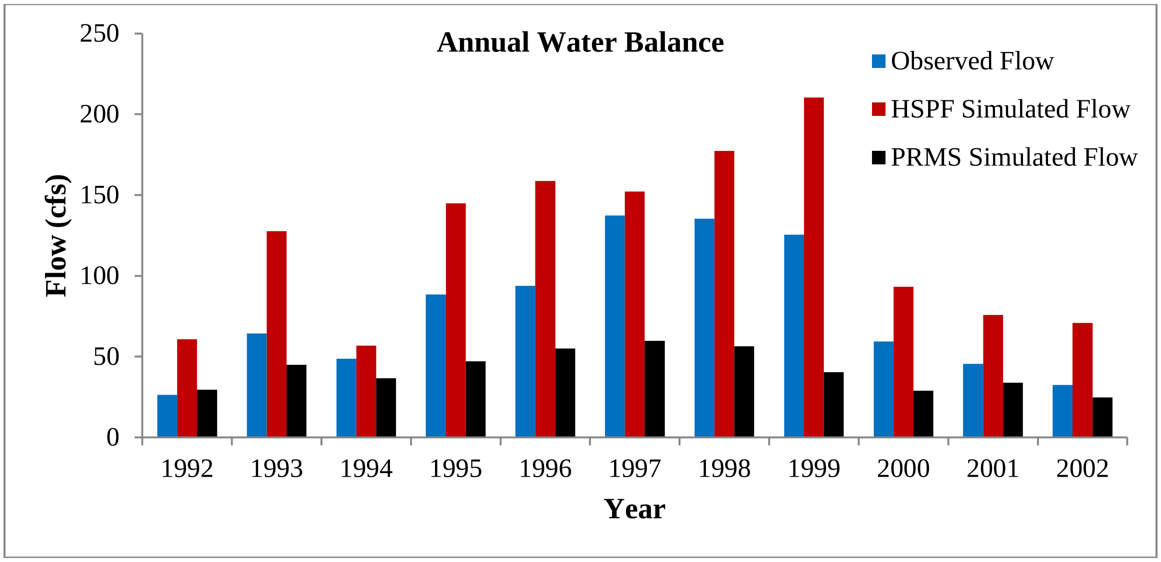

Figure 5.16 Comparison of observed and estimated annual streamflow for HSPF and PRMS for the validation period (1992-2002), (scenario 2, Rapid Creek watershed)

The HSPF over-estimated the monthly mean flow for rainfall runoff events during wet years (1995, 1996, and 1999) (Figure 5.17). The PRMS under-estimated the monthly mean flow for rainfall runoff events during the wet period. The PRMS better estimated monthly mean flow than the HSPF for rainfall runoff events during dry years (1992 and 2001). The HSPF better estimated monthly mean flow for base flow periods during wet years (1998 and 1999) and the PRMS better estimated it for dry years (1992 and 2002) and a wet year (1993).

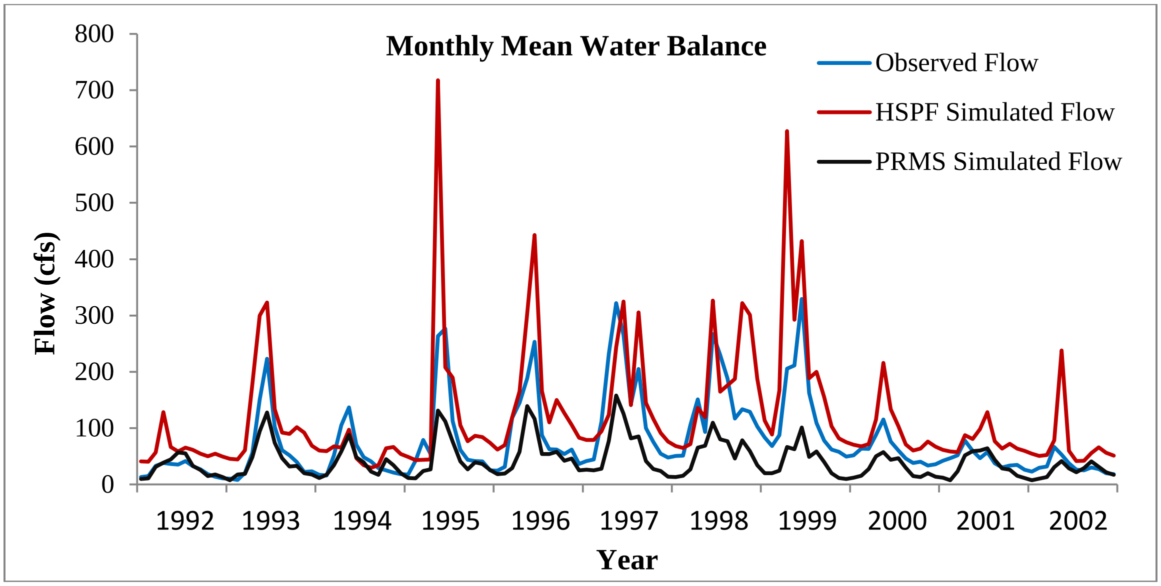

Figure 5.17 Comparison of observed and estimated monthly mean streamflow for HSPF and PRMS for the validation period (1992-2002), (scenario 2, Rapid Creek watershed)

The percent volume error (PVE) for the HSPF monthly mean flow was high in the winter and low in the summer (Figure 5.18). The PVE for the PRMS monthly mean flow was low and consistent throughout a year. The PVEs for the PRMS monthly mean flow were less than the HSPF except March and June.

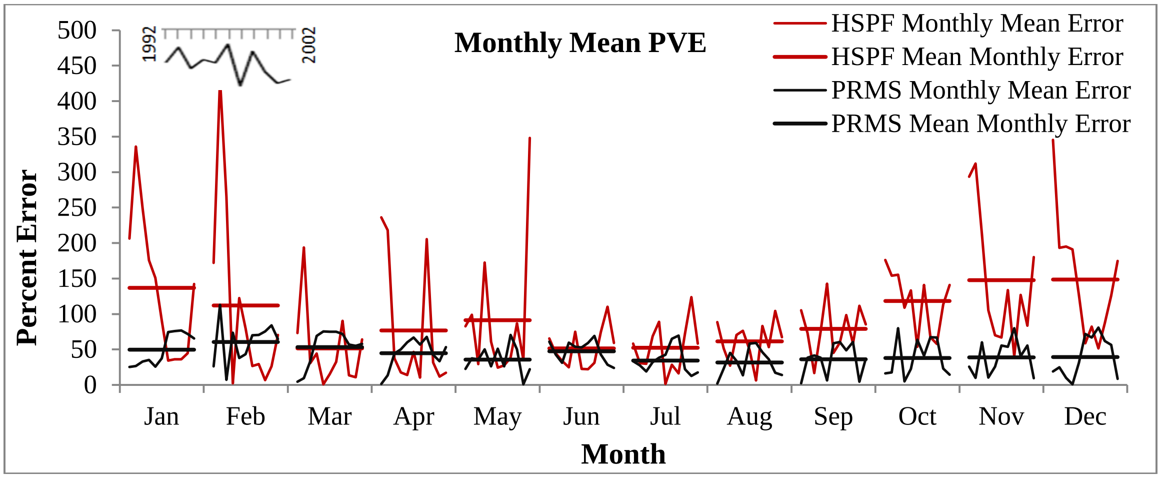

Figure 5.18 Comparison of percent volume error of HSPF and PRMS estimated monthly mean flow for the validation period (1992-2002), (scenario 2, Rapid Creek watershed)

The HSPF over-estimated and the PRMS under-estimated the mean monthly flow (Figure 5.19).

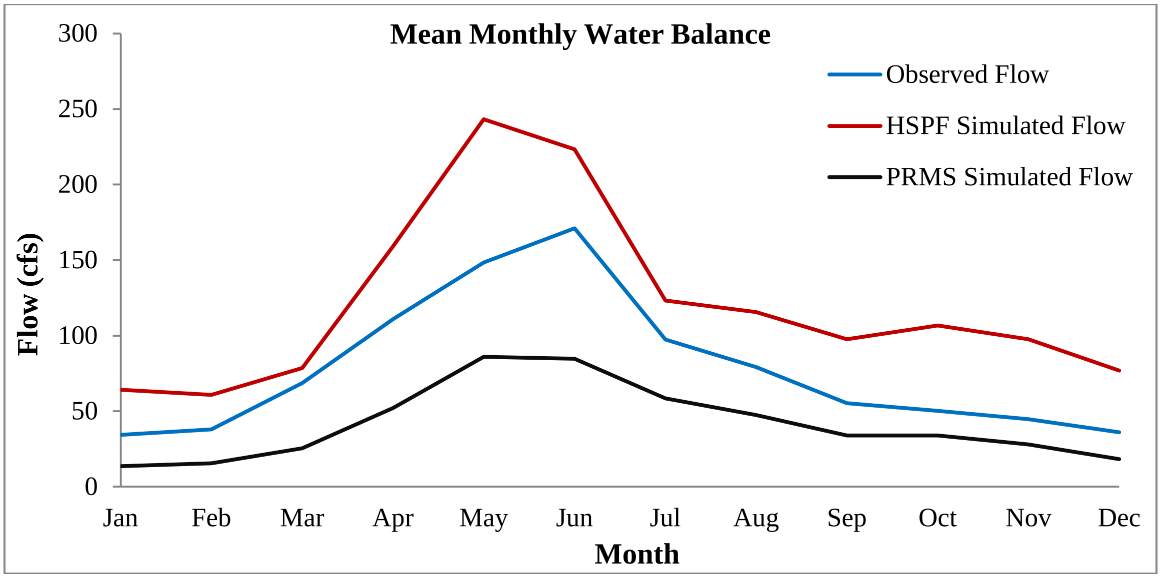

Figure 5.19 Comparison of observed and estimated mean monthly streamflow for HSPF and PRMS for validation period (1992-2002), (scenario 2, Rapid Creek watershed)

The HSPF continuously over-estimated and the PRMS continuously under-estimated the daily flow (Figure 5.20).

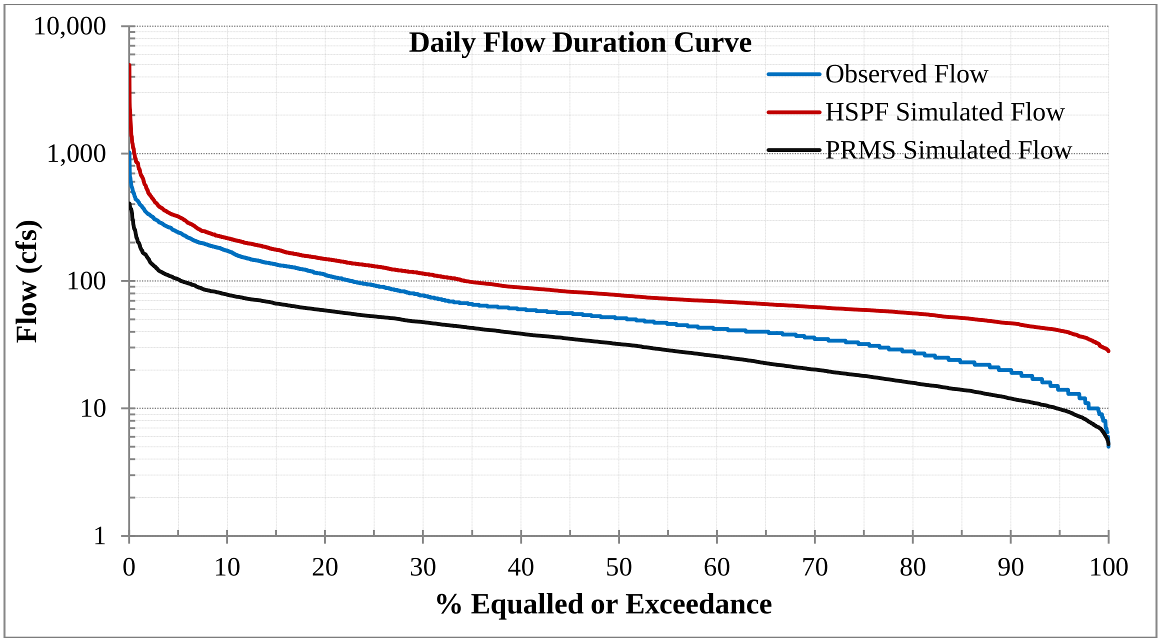

Figure 5.20 Comparison of observed and estimated daily streamflow duration curves for HSPF and PRMS for the validation period (1992-2002), (scenario 2, Rapid Creek watershed)

During the calibration period, the average volume errors for HSPF and PRMS annual flows were 66 and -38 percent respectively (Table 5-8). The NSE statistic of

PRMS annual flow (NSE = -0.47) was better than the HSPF (NSE = -0.52). The negative NSE value explained that the mean annual observed flow might estimate better flow than the model. The r and R^2 statistics of HSPF annual flow (r = 0.91 and $R^2 = 0.83$) were better than the PRMS (r = 0.84 and $R^2 = 0.70$). The average volume error for PRMS monthly mean flow (-34 percent) was better than the HSPF (88 percent). The NSE, r, and R^2 statistic of the PRMS monthly mean, mean monthly and daily flow were better than the HSPF.

Table 5-8 Comparison between HSPF and PRMS estimated streamflow for the validation period (1992-2002), (scenario 2, Rapid Creek watershed)

Items	Annual		Monthly Mean		Mean Monthly		Daily	
	HSPF	PRMS	HSPF	PRMS	HSPF	PRMS	HSPF	PRMS
Avg. % Error	66.36	-37.70	87.76	-33.85	66.18	-47.11	93.60	-32.02
PBIAS	54.96	-46.68	54.94	-46.74	54.94	-46.74	54.97	-46.68
NSE	-0.52	-0.47	-0.29	0.29	-0.18	0.06	-1.81	0.30
RSR	1.23	1.21	1.13	0.84	1.09	0.97	1.67	0.83
RMSE	48.00	47.08	79.25	58.80	47.45	42.27	135.36	67.47
r	0.91	0.84	0.79	0.86	0.95	0.97	0.62	0.77
R^2	0.83	0.70	0.63	0.74	0.90	0.93	0.39	0.60

5.9 Summary of Scenario 2 – Validation for Rapid Creek Watershed

The PRMS better estimated the annual and monthly mean flow than the HSPF for most of the dry and normal years. The HSPF better estimated the monthly mean flow than the PRMS for rainfall runoff events during most of the wet years. The PVE for the PRMS monthly mean flow was less than the HSPF except March and June. The HSPF over-estimated and the PRMS under-estimated the mean monthly and daily flow. Both models did not perform well for estimating daily flow. The NSE statistic for PRMS annual flow was better than the HSPF, however, r and R^2 statistics for HSPF annual flow were better than the PRMS. The NSE, r, and R^2 statistics for PRMS monthly and daily flow were better than the HSPF. In general, the PRMS performed better than the HSPF during the validation period (1992-2002).

5.10 Comparison of Scenario 1 and 2 for Rapid Creek Watershed

The comparison study of the HSPF and PRMS models for scenario 1 (wet models) and scenario 2 (dry models) are discussed in the following sections: 1) comparison of HSPF Wet and HSPF Dry models, 2) comparison of PRMS Wet and PRMS Dry models , and 3) Comparison of HSPF and PRMS models.

5.11 Comparison of HSPF Wet and HSPF Dry Models for Rapid Creek Watershed

The PVEs of the HSPF Wet model annual flow were less than the HSPF Dry model for 12 years and greater for 5 years during the entire simulation period (1992-2008) (Table 5-9). The average PVE of the HSPF Wet model annual flow (9 percent) was less than the HSPF Dry model (50 percent). The HSPF Wet model better estimated the annual flow (error: -0.2 to -8 percent) for wet years (1995 and 1998), a dry year (2002), and a normal year (2000). The HSPF Dry model better estimated the annual flow (error: -10 to 11 percent) for dry years (2006 and 2007) and a wet year (1997). The average volume errors in HSPF Wet model annual flow (-0.2 to 76 percent, average: 18 percent) were better than HSPF Dry model (-11 to 131 percent, average: 62 percent) for the wet period. The average volume errors of HSPF Wet model annual flow (-9 to -59 percent, average: -40 percent) were better than the HSPF Dry model (-9 to 119 percent, average: 45 percent) for the dry period.

Table 5-9 Comparison of observed and estimated annual streamflow for HSPF Wet and HSPF Dry models for the simulation period (1992-2008), (Rapid Creek watershed)

Wet Model	**Year**	**Observed Flow (cfs)**	**HSPF Wet (cfs)**	**HSPF Dry (cfs)**	**PVE HSPF Wet**	**PVE HSPF Dry**	**Dry Model**
Scenario 1 – Calibration	**1992**^{d}	26.3	46.3	60.7	76.1	130.7	**Scenario 2 - Validation**
	1993^{w}	64.4	94.0	127.7	45.9	98.3	
	1994	48.7	33.1	56.7	-32.1	16.5	
	1995^{w}	88.5	88.3	144.8	-0.2	63.7	
	1996^{w}	93.8	125.1	158.6	33.3	69.1	
	1997^{w}	137.4	110.6	152.1	-19.4	10.8	
	1998^{w}	135.3	129.2	177.3	-4.5	31.1	
	1999^{w}	125.5	156.6	210.3	24.8	67.6	
	2000	59.4	59.2	93.2	-0.4	56.9	
	2001	45.5	37.3	75.9	-17.9	66.9	
	2002^{d}	32.4	29.7	70.9	-8.5	118.5	
Scenario 1 – Validation	**2003**	39.0	32.1	58.8	-17.7	50.8	**Scenario 2 - Calibration**
	2004^{d}	22.6	15.1	37.7	-33.3	66.6	
	2005^{d}	20.4	13.5	32.8	-33.7	61.2	
	2006^{d}	29.9	10.3	26.5	-65.6	-11.1	
	2007^{d}	27.0	11.2	24.5	-58.6	-9.3	
	2008	55.4	34.3	36.5	-38.2	-34.0	
Average		61.8	60.3	90.9	-8.8	50.2	

Note: w- wet year, d- dry year, and PVE- percent volume error

The HSPF Wet model better estimated monthly mean than the HSPF Dry model flow for rainfall runoff events during wet years (1995 and 1999) (Figure 5.21). The HSPF Wet model better estimated monthly mean flow than the HSPF Dry model for rainfall runoff events during dry years (1992 and 2002) and normal years (2000 and 2003). The HSPF Dry model better estimated monthly mean flow for rainfall runoff events during a dry year (2007). The HSPF Wet model under-estimated monthly mean flow for dry years (2004 to 2007). The HSPF Dry model over-estimated the monthly mean flow for wet years (1995 and 1999). The HSPF Dry model over-estimated the monthly mean flow than the HSPF Wet model for base flow periods during most of the simulation period. The

HSPF Wet model better estimated the monthly mean flow than the HSPF Dry model for rainfall runoff events during most of the wet years, normal years, and few dry years.

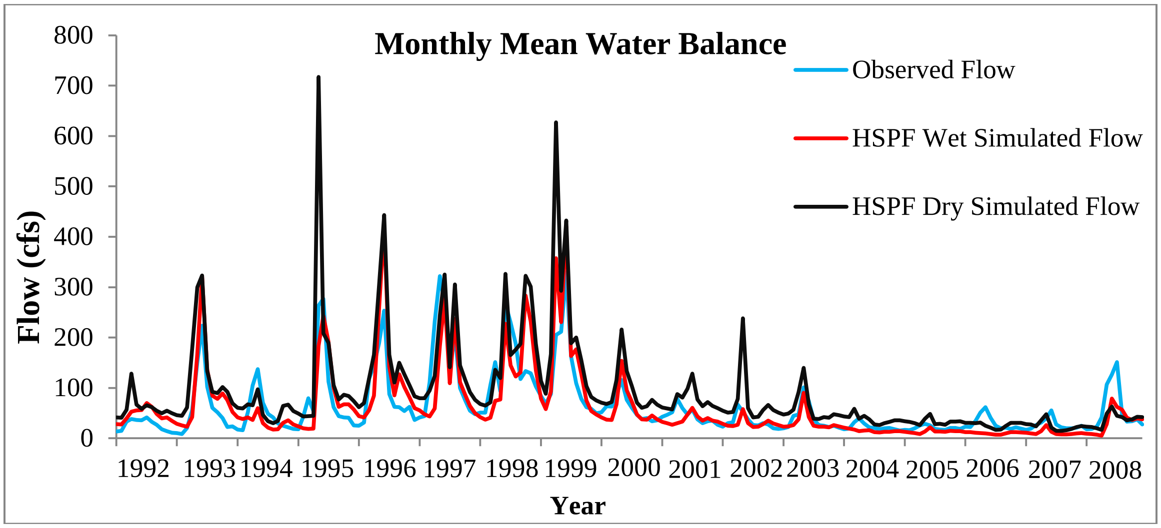

Figure 5.21 Comparison of estimated monthly mean flow for HSPF Wet and HSPF Dry models for the simulation period (1992-2008), (Rapid Creek watershed)

The average volume error of the HSPF Wet model annual and monthly mean flow was less than the HSPF Dry model during the calibration, validation, and entire simulation periods (Table 5-10). The NSE statistics for the HSPF Wet model annual and monthly mean flow were better than the HSPF Dry model for the calibration, validation, and entire simulation periods. The r and R^2 statistics of HSPF Wet model annual and monthly mean flow were better than the HSPF Dry model during the calibration period. The r and R^2 statistics of the HSPF Dry model annual and monthly mean flow were better than the HSPF Wet model during the validation period. The r and R^2 statistics for HSPF Wet model annual and monthly mean flow were better than the HSPF Dry model for the entire simulation period.

Table 5-10 Statistical comparison of HSPF Wet and HSPF Dry models for the calibration, validation and simulation periods, (Rapid Creek watershed)

Statistics	**Calibration Period**				**Validation Period**				**Simulation Period**			
	Annual		**Monthly Mean**		**Annual**		**Monthly Mean**		**Annual**		**Monthly Mean**	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Avg. PVE	8.83	20.69	21.96	32.99	-41.15	66.36	-35.98	87.76	-8.81	50.24	1.51	68.43
NSE	0.74	-0.35	0.57	0.17	-0.45	-0.52	0.26	-0.29	0.78	-0.04	0.60	-0.10
r	0.89	0.34	0.82	0.50	0.86	0.91	0.73	0.79	0.92	0.92	0.84	0.81
R^2	0.79	0.11	0.67	0.25	0.74	0.83	0.54	0.63	0.85	0.84	0.70	0.65

Note: calibration wet model (1992-2002), calibration dry model (2003-2008), validation wet model (2003-2008), validation dry model (1992-2002), simulation wet/dry model (1992-2008)

In general, the HSPF Wet model performed better than the HSPF Dry model for the calibration, validation, and entire simulation periods.

5.12 Comparison of PRMS Wet and PRMS Dry Models for Rapid Creek Watershed

The PVEs of the PRMS Wet model annual flow were less than the PRMS Dry model for 6 years, greater for 10 years, and similar for 1 year during the entire simulation period (1992-2008) (Table 5-11). The average PVE of the PRMS Dry model annual flow (-20 percent) was better than the PRMS Wet model (57 percent) for the entire simulation period. The PRMS Wet model better estimated the annual flow (error: 15 to 17 percent) than the PRMS Dry model (error: -41 to -57 percent) for wet years (1995, 1996, and 1997). The PRMS Dry model better estimated the annual flow (error: 5 to 14 percent) than the PRMS Wet model (error: 98 to 116 percent) for dry years (1992, 2007, and 2008). The PRMS Wet model better estimated the annual flow (error: -39 to 30 percent) than the PRMS Dry model (error: -30 to -68 percent) for the wet period. The PRMS Dry model better estimated the annual flow (error: -24 to 42 percent) than the PRMS Wet model (error: 48 to 171 percent) for the dry period.

Table 5-11 Comparison of observed and estimated annual streamflow for PRMS Wet and PRMS Dry models for the simulation period (1992-2008), (Rapid Creek watershed)

Wet Model	Year	Observed Flow (cfs)	PRMS Wet (cfs)	PRMS Dry (cfs)	PVE PRMS Wet	PVE PRMS Dry	Dry Model
Scenario 1 – Calibration	1992^d	26.3	56.8	29.5	116.0	12.2	Scenario 2 - Validation
	1993^w	64.4	83.9	44.9	30.3	-30.3	
	1994	48.7	88.1	36.6	80.9	-24.9	
	1995^w	88.5	101.7	47.2	15.0	-46.7	
	1996^w	93.8	107.2	55.0	14.2	-41.4	
	1997^w	137.4	160.6	59.7	16.9	-56.5	
	1998^w	135.3	102.9	56.4	-24.0	-58.4	
	1999^w	125.5	76.5	40.4	-39.0	-67.8	
	2000	59.4	55.9	28.8	-5.9	-51.5	
	2001	45.5	60.3	33.9	32.5	-25.5	
	2002^d	32.4	47.9	24.6	47.7	-24.0	
Scenario 1 – Validation	2003	39.0	55.9	33.4	43.6	-14.2	Scenario 2 - Calibration
	2004^d	22.6	45.8	24.7	102.5	9.2	
	2005^d	20.4	55.1	28.9	170.5	41.9	
	2006^d	29.9	71.8	38.3	140.4	28.5	
	2007^d	27.0	59.9	30.6	122.1	13.5	
	2008	55.4	109.6	57.9	97.9	4.6	
Average		61.8	78.8	39.5	56.6	-19.5	

Note: w – wet year, d – dry year, and PVE – percent volume error

The PRMS Wet model better estimated the monthly mean flow than the PRMS Dry model for rainfall runoff events during the wet period. The PRMS Dry model better estimated the monthly mean flow than the PRMS Wet model for rainfall runoff events during the dry period (Figure 5.22). The PRMS Wet model continuously over-estimated the monthly mean flow for rainfall runoff events during the dry period and the PRMS Dry model continuously under-estimated it for the wet period. Both PRMS Wet and Dry models estimated monthly mean flow for the base flow periods were similar during the entire simulation period.

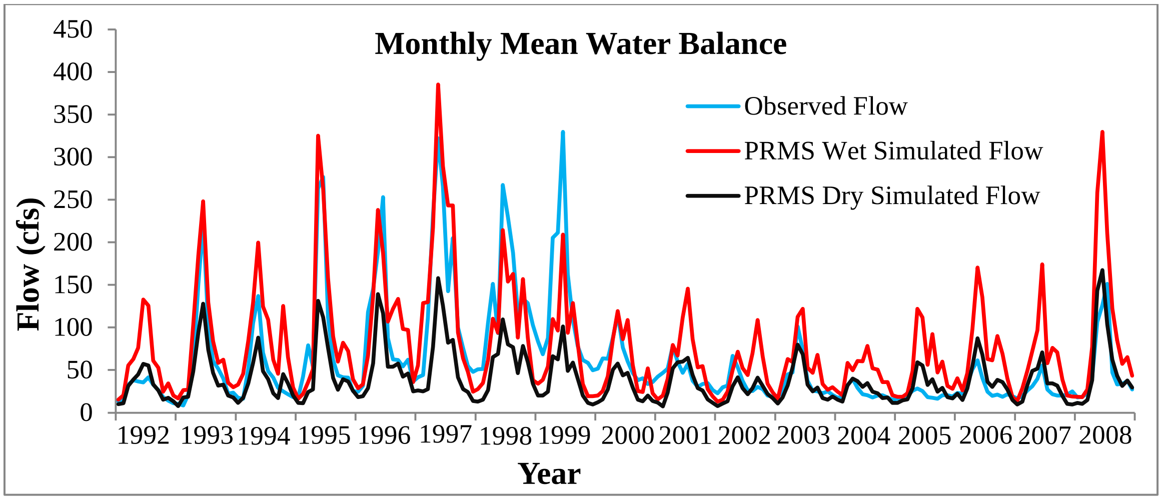

Figure 5.22 Comparison of estimated monthly mean flow for PRMS Wet and PRMS Dry models for the simulation period (1992-2008), (Rapid Creek watershed)

The average volume errors of the PRMS Dry model annual and monthly mean flow were less than the PRMS Wet model for the calibration, validation, and simulation periods (Table 5-12). The NSE, r and R^2 statistics for the PRMS Dry model annual and monthly mean flow were better than the PRMS Wet model for the calibration period. The NSE, r and R^2 statistics for the PRMS Wet model annual and monthly mean flow were better than the PRMS Dry model for the simulation period. The NSE statistic of the PRMS Wet model annual flow (NSE = -0.47) was better than the PRMS Wet model (NSE = -8.20) for the validation period. The negative NSE value explained that the mean annual observed flow might estimate better flow than the model. The r and R^2 statistics of the PRMS Wet model annual and monthly mean flow were similar to the PRMS Dry model for the validation period.

Table 5-12 Statistical comparison of PRMS Wet and PRMS Dry models for the calibration, validation and simulation periods, (Rapid Creek watershed)

Statistics	Calibration Period				Validation Period				Simulation Period			
	Annual		Monthly Mean		Annual		Monthly Mean		Annual		Monthly Mean	
	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY
Avg. PVE	25.87	13.90	32.44	10.83	112.81	-37.70	107.45	-33.85	56.56	-19.49	58.92	-18.08
NSE	0.54	0.76	0.66	0.69	-8.20	-0.47	-3.10	0.29	0.39	0.04	0.49	0.40
R	0.76	0.92	0.84	0.88	0.86	0.84	0.84	0.86	0.65	0.17	0.79	0.79
R^2	0.58	0.84	0.70	0.77	0.75	0.70	0.70	0.74	0.42	0.03	0.63	0.63

Note: calibration wet model (1992-2002), calibration dry model (2003-2008), validation wet model (2003-2008), validation dry model (1992-2002), simulation wet/dry model (1992-2008)

In general, the PRMS Wet model performed better than the PRMS Dry model for the wet period and the PRMS Dry model performed better than the PRMS Wet model for the dry period. The PRMS Wet and Dry models were found very sensitive for simulation of the wet vs. the dry periods. Based on NSE, r, and R^2 statistics, the PRMS Wet model performed better than the PRMS Dry model for the entire simulation period (1992-2008).

5.13 Comparison of HSPF and PRMS Models for Rapid Creek Watershed

The HSPF Wet model performed better than the HSPF Dry model for the calibration, validation, and entire simulation periods (see pp. 78-81, comparison of HSPF Wet and HSPF Dry models). The PRMS Wet model performed better than the PRMS Dry model for the wet period, the PRMS Dry model performed better than the PRMS Wet model for the dry period, and the PRMS Wet model performed better than the PRMS Dry model for the entire simulation period (see pp. 81-84, comparison of PRMS Wet and PRMS Dry models).

The comparisons between HSPF and PRMS models for the Rapid Creek watershed are discussed in the following sections: 1) comparison of HSPF Wet and

PRMS Wet models 2) comparison of HSPF Composite and PRMS Composite models. The HSPF Composite model was developed by calibrating the entire simulation period (1992-2008). The PRMS Composite model was developed by combining the PRMS Wet model (scenario 1 calibration) (1992-2002) and the PRMS Dry model (scenario 2 calibration) (2003-2008).

5.14 Comparison of HSPF Wet and PRMS Wet Models for Rapid Creek Watershed

During 17 year simulation period (1992-2008), the HSPF annual flow was better than the PRMS for 14 years (Table 5-13). The HSPF annual flow was better than the PRMS for the dry period, normal years, and 3 out of 6 wet years. The average PVE of HSPF annual flow (9 percent) was less than the PRMS (57 percent).

Table 5-13 Comparison of observed and estimated annual streamflow for HSPF Wet and PRMS Wet models for the simulation period (1992-2008), (Rapid Creek watershed)

	Year	**Observed Flow (cfs)**	**HSPF Wet (cfs)**	**PRMS Wet (cfs)**	**PVE HSPF Wet**	**PVE PRMS Wet**	
Simulation Period (1992-2008)	**1992**^{d}	26.3	46.3	56.8	76.1	116.0	**Calibration Period (1992-2002)**
	1993^{w}	64.4	94.0	83.9	45.9	30.3	
	1994	48.7	33.1	88.1	-32.1	80.9	
	1995^{w}	88.5	88.3	101.7	-0.2	15.0	
	1996^{w}	93.8	125.1	107.2	33.3	14.2	
	1997^{w}	137.4	110.6	160.6	-19.4	16.9	
	1998^{w}	135.3	129.2	102.9	-4.5	-24.0	
	1999^{w}	125.5	156.6	76.5	24.8	-39.0	
	2000	59.4	59.2	55.9	-0.4	-5.9	
	2001	45.5	37.3	60.3	-17.9	32.5	
	2002^{d}	32.4	29.7	47.9	-8.5	47.7	
	2003	39.0	32.1	55.9	-17.7	43.6	**Validation Period (2003-2008)**
	2004^{d}	22.6	15.1	45.8	-33.3	102.5	
	2005^{d}	20.4	13.5	55.1	-33.7	170.5	
	2006^{d}	29.9	10.3	71.8	-65.6	140.4	
	2007^{d}	27.0	11.2	59.9	-58.6	122.1	
	2008	55.4	34.3	109.6	-38.2	97.9	
Average		61.8	60.3	78.8	-8.8	56.6	

Note: w- wet year, d- dry year, and PVE- percent volume error

The HSPF better estimated monthly mean flow than the PRMS for rainfall runoff events during a dry year (2002) and a normal year (2003) (Figure 5.23). The PRMS better estimated monthly mean flow than the HSPF for rainfall runoff events during wet years (1993 and 1996). The PRMS over-estimated and HSPF under-estimated the monthly mean flow for most of the dry years. The HSPF better estimated the monthly mean flow than the PRMS for base flow periods during wet years (1998 and 1999) and a dry year (2002).

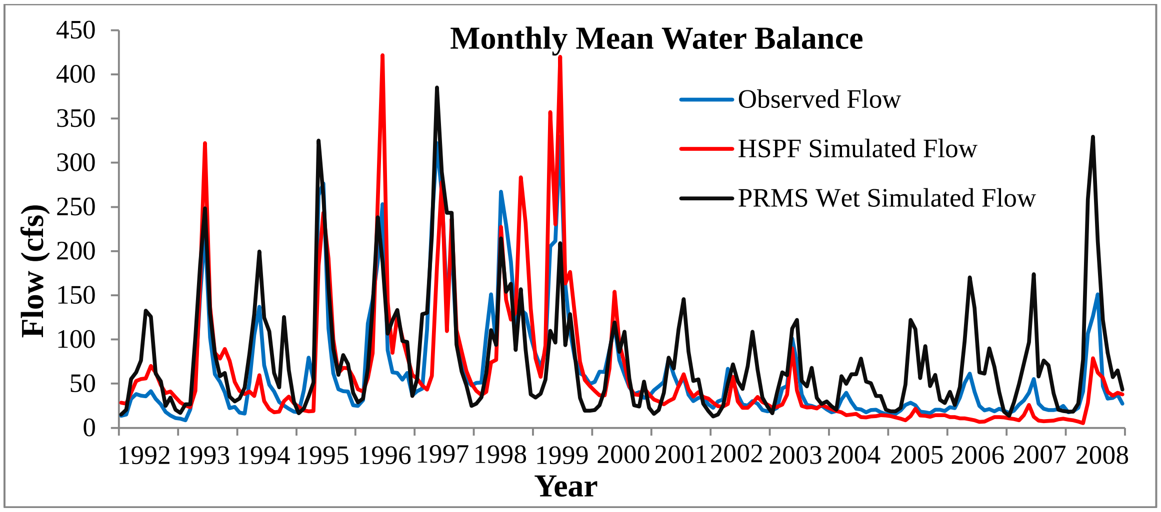

Figure 5.23 Comparison of estimated monthly mean flow for HSPF Wet and PRMS Wet models for the simulation period (1992-2008), (Rapid Creek watershed)

The NSE, r, and R^2 statistics of the HSPF annual flow were better than the PRMS and the same statistics of the PRMS monthly mean and daily flow were better than the HSPF for the calibration period (1992-2002) (Table 5-14). The NSE statistics for the HSPF annual, monthly mean and daily flow were better than the PRMS for the validation period (2003-2008). The r and R^2 statistics for the PRMS monthly mean and daily flow were better than the HSPF for the validation period. Both models did not perform well for the validation period as compared to the calibration period. The NSE, r, and R^2 statistics of the HSPF annual, monthly mean and daily flow were better than the PRMS for the entire simulation period (1992-2008).

Table 5-14 Statistical comparison of HSPF Wet and PRMS Wet models for the simulation period (1992-2008), (Rapid Creek watershed)

Scenario	**Statistics**	**Average PVE**		**NSE**		**r**		**R^2**	
		HSPF Wet	**PRMS Wet**	**HSPF Wet**	**PRMS Wet**	**HSPF Wet**	**PRMS Wet**	**HSPF Wet**	**PRMS Wet**
Calibration	**Annual**	9	26	0.74	0.54	0.89	0.76	0.79	0.58
	Monthly	22	32	0.57	0.66	0.82	0.84	0.67	0.70
	Daily	26	36	0.36	0.59	0.75	0.80	0.57	0.64
Validation	**Annual**	-41	113	-0.45	-8.20	0.86	0.86	0.74	0.75
	Monthly	-36	107	0.26	-3.10	0.73	0.84	0.54	0.70
	Daily	-34	109	0.22	-2.55	0.64	0.72	0.41	0.52
Simulation	**Annual**	-9	57	0.78	0.39	0.92	0.65	0.85	0.42
	Monthly	2	59	0.60	0.49	0.84	0.79	0.70	0.63
	Daily	5	61	0.41	0.42	0.77	0.76	0.59	0.57

Note: calibration period (1992-2002) and validation period (2003-2008)

In general, the HSPF better estimated the annual flow than the PRMS for the calibration and validation periods. The PRMS better estimated the monthly mean and daily flow than the HSPF for the calibration period. The HSPF better estimated the monthly mean flow than the PRMS for the validation period. The HSPF better estimated the annual, monthly mean, and daily flow than the PRMS for the entire simulation period.

5.15 Comparison of HSPF Composite and PRMS Composite Models for Rapid Creek Watershed

During 17 year simulation period (1992-2008), the PVEs of the HSPF annual flow were less than the PRMS for 9 years and greater for 8 years (Table 5-15). The HSPF better estimated annual flow than the PRMS for 3 out 6 wet years, 3 out of 6 dry years, and 3 out of 5 normal years. The average PVE of HSPF annual flow (2 percent) was less than the PRMS (22 percent).

Table 5-15 Comparison of observed and estimated annual streamflow for HSPF Composite and PRMS Composite models for the simulation period (1992-2008), (Rapid Creek watershed)

Year	Observed Flow (cfs)	HSPF Simulated Flow (cfs)	PRMS Simulated Flow (cfs)	PVE (HSPF)	PVE (PRMS)		
1992^d	26.31	55.21	56.83	109.82	115.98	**PRMS Wet Model**	**HSPF Composite Model/PRMS Composite Model**
1993^w	64.38	89.05	83.87	38.32	30.26		
1994	48.68	39.14	88.08	-19.60	80.94		
1995^w	88.49	85.80	101.75	-3.04	14.98		
1996^w	93.81	117.90	107.15	25.68	14.22		
1997^w	137.36	105.85	160.56	-22.94	16.89		
1998^w	135.32	127.19	102.90	-6.01	-23.96		
1999^w	125.49	142.72	76.54	13.73	-39.01		
2000	59.42	67.63	55.91	13.83	-5.90		
2001	45.46	44.77	60.26	-1.53	32.54		
2002^d	32.43	35.63	47.89	9.87	47.67	**PRMS Dry Model**	
2003	38.97	35.76	33.42	-8.24	-14.23		
2004^d	22.61	17.81	24.69	-21.23	9.18		
2005^d	20.36	15.49	28.88	-23.92	41.88		
2006^d	29.85	11.64	38.35	-61.02	28.45		
2007^d	26.96	12.42	30.62	-53.95	13.54		
2008	55.40	39.26	57.93	-29.14	4.56		
Average	61.84	61.37	67.98	-2.32	21.65		

Note: w- wet year, d- dry year, and PVE- percent volume error

The HSPF over-estimated the monthly mean flow for rainfall runoff events during wet years (1996 and 1999) and under-estimated it for normal years (1994 and 2008) (Figure 5.24). The HSPF was inconsistent in estimating monthly mean flow, it over-estimated one dry year (1992) and under-estimated others (2006 and 2007). The PRMS over-estimated monthly mean flow for rainfall runoff events during dry years (1992, 2002, 2005) and normal years (1994 and 2001) and under-estimated it for a wet year (1999). The PRMS better estimated the monthly mean flow than the HSPF for rainfall runoff events during wet years (1995 and 1996), dry years (2004, 2006 and 2007), and a normal year (2008). The HSPF better estimated the monthly mean flow than the PRMS for base flow periods during wet years (1998 and 1999).

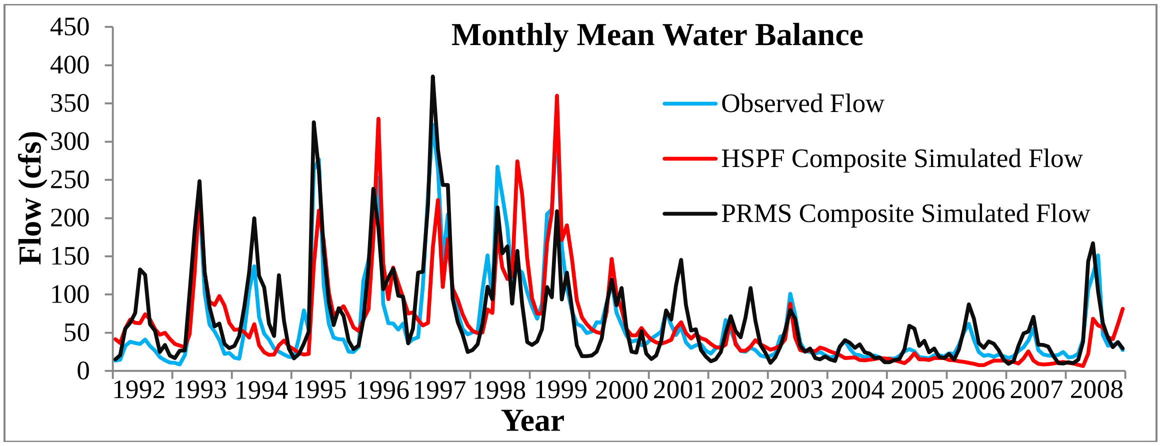

Figure 5.24 Comparison of estimated monthly mean flow for HSPF Composite and PRMS Composite models for the simulation period (1992-2008), (Rapid Creek watershed)

The NSE, r, and R^2 statistics of the HSPF annual flow were better than the PRMS Composite (Table 5-16). The NSE, r, and R^2 statistics of PRMS Composite monthly mean and daily flow were better than the HSPF Composite.

Table 5-16 Comparison of HSPF Composite and PRMS Composite models for the simulation period (1992-2008), (Rapid Creek watershed)

Statistics	**Annual**		**Monthly Mean**		**Daily**	
	HSPF Composite	PRMS Composite	HSPF Composite	PRMS Composite	HSPF Composite	PRMS Composite
Avg. PVE	-2.32	21.65	16.24	24.81	20.48	27.27
NSE	0.83	0.69	0.63	0.70	0.57	0.62
r	0.92	0.85	0.80	0.86	0.77	0.82
R^2	0.85	0.72	0.65	0.74	0.59	0.67

Note: Avg. PVE – Average percent volume error

In general, the HSPF Composite model better estimated the annual flow than the PRMS Composite model and the PRMS Composite model better estimated the monthly mean and daily flow than the HSPF Composite model for the entire simulation period (1992-2008).

5.16 Summary of Rapid Creek Watershed Results

The HSPF better estimated the annual water budget than the PRMS and the PRMS better estimated the monthly mean and daily water budgets than the HSPF during the calibration period of mostly wet years (see p. 62, summary of scenario 1 calibration). The HSPF better estimated all three of the water budgets (annual, monthly mean, and daily) than the PRMS during the validation period of mostly dry years (see p. 66, summary of scenario 1 validation).

The PRMS better estimated the three water budgets than the HSPF during the calibration period of mostly dry years (see p. 72, summary of scenario 2 calibration). The PRMS better estimated the three water budgets than the HSPF during the validation period of mostly wet years (see p. 77, summary of scenario 2 validation).

The HSPF Wet model (calibration period having mostly wet years) performed better than the HSPF Dry model (calibration period having mostly dry years) for the calibration, validation, and entire simulation periods (see pp. 78-81, comparison of HSPF Wet and HSPF Dry models).

The PRMS Wet model performed better than the PRMS Dry model for the wet period and the PRMS Dry model performed better than the PRMS Wet model for the dry period (see pp. 81-84, comparison of PRMS Wet and PRMS Dry models). The PRMS models (Wet and Dry) were found very sensitive for simulation of wet vs. dry periods. The PRMS Wet model performed better than the PRMS Dry model for the entire simulation period.

The HSPF Wet model better estimated the annual water budget than the PRMS Wet model for the calibration and the validation periods (see pp. 85-87, comparison of

HSPF Wet and PRMS Wet models). The PRMS Wet model better estimated the monthly mean and daily water budget than the HSPF Wet model for the calibration period and the HSPF Wet model better estimated the monthly mean and daily water budget than the PRMS Wet model for the validation period. The HSPF Wet model better estimated all three of the water budgets (annual, monthly mean, and daily) than the PRMS Wet model for the entire simulation period.

The HSPF Composite model better estimated the annual water budget than the PRMS Composite model and the PRMS Composite model better estimated the monthly mean and daily water budget than the HSPF Composite model for the entire simulation period 1992-2008 in Rapid Creek watershed (see pp. 87-89, comparison of HSPF Composite and PRMS Composite models).

5.17 Spring Creek Watershed Results

A combined calibration and validation period was used for the simulation of Spring Creek watershed above Sheridan Lake from 1993 to 2003. During the 11 year simulation period (1993 to 2003), the absolute volume error between observed and HSPF annual streamflow was less than 15 percent for 4 years, 15 to 30 percent for 4 years, and greater than 30 percent for 3 years (Table 5-17). The absolute volume error for PRMS annual streamflow was less than 15 percent for 4 years, 15 to 30 percent for 4 years, and greater than 30 percent for 3 years. The HSPF over-estimated the annual flow (1 to 21 percent) for 2 years and under-estimated it (2 to 60 percent) for 9 years. The PRMS over-estimated the annual flow (2 to 69 percent) for 6 years and under-estimated it (13 to 46 percent) for 5 years.

Table 5-17 Comparison of observed and estimated annual streamflow for HSPF and PRMS for the simulation period (1993-2003), (Spring Creek watershed)

Year	Observed Flow (cfs)	HSPF Flow (cfs)	PRMS Flow (cfs)	PVE (HSPF)	PVE (PRMS)
1993	27.30	26.03	23.61	-4.63	-13.49
1994^{d}	9.92	3.98	10.30	-59.89	3.87
1995^{w}	39.94	30.79	57.13	-22.92	43.02
1996^{w}	32.87	27.40	27.30	-16.62	-16.94
1997^{w}	43.34	52.61	44.14	21.38	1.83
1998^{w}	37.05	37.35	20.15	0.81	-45.61
1999^{w}	43.76	41.23	31.91	-5.77	-27.06
2000^{d}	10.97	6.32	9.22	-42.36	-15.96
2001^{d}	11.11	6.02	14.25	-45.84	28.20
2002^{d}	6.17	4.90	10.42	-20.45	68.93
2003^{d}	8.70	8.50	9.89	-2.34	13.59
Average	24.65	22.29	23.48	-18.06	3.67

Note: w- wet year and d- dry year

The HSPF under-estimated the annual flow during a wet year (1995) and 1 dry year (2001) (Figure 5.25). The PRMS over-estimated the annual streamflow during a wet year (1995) and a dry year (2001).

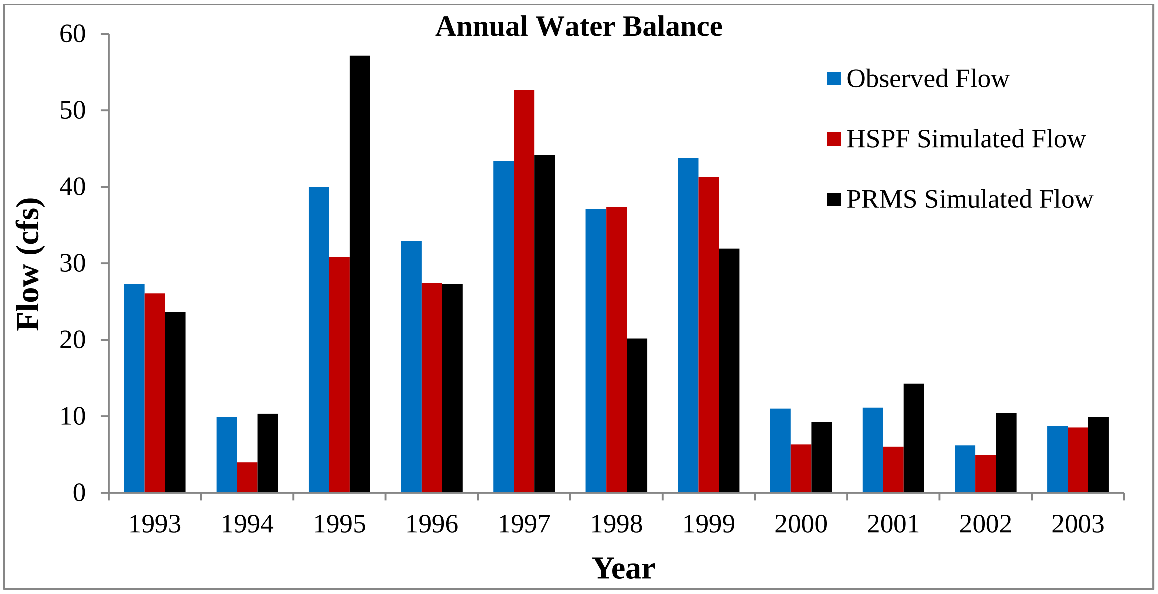

Figure 5.25 Comparison of observed and estimated annual streamflow for HSPF and PRMS for the simulation period (1993 – 2003), (Spring Creek watershed)

The HSPF under-estimated and the PRMS over-estimated the monthly mean flow for rainfall runoff events during a wet year (1995) and a dry year (2001) (Figure 5.26). Both models estimated better monthly mean flow for rainfall runoff events during wet years (1996, 1997, and 1999). The HSPF better estimated the monthly mean flow than the PRMS for base flow periods during wet years (1997 and 1998) and dry years (1994 and 2003).

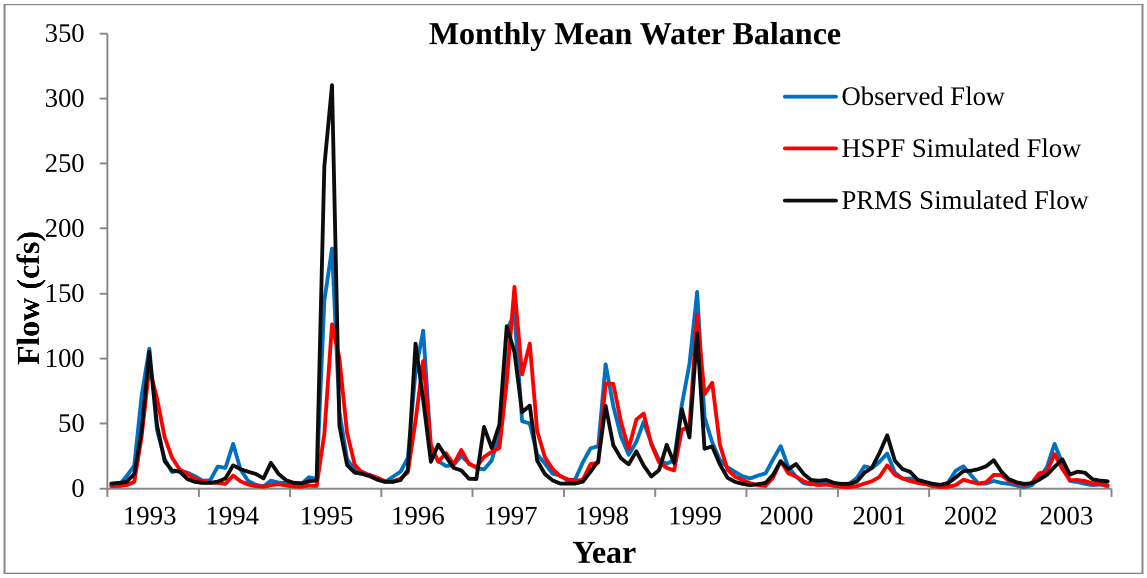

Figure 5.26 Comparison of observed and estimated monthly mean streamflow for HSPF and PRMS for the simulation period (1993 – 2003), (Spring Creek watershed)

The percent volume errors (PVEs) of the HSPF monthly mean flow were consistent throughout a year (Figure 5.27). The PVEs of the PRMS monthly mean flow varied from July to February. The PVEs of the PRMS monthly mean flow were high from July to September during dry years (1994, 2002, and 2003). The average PVEs of the HSPF monthly mean flow were less than PRMS from July to February.

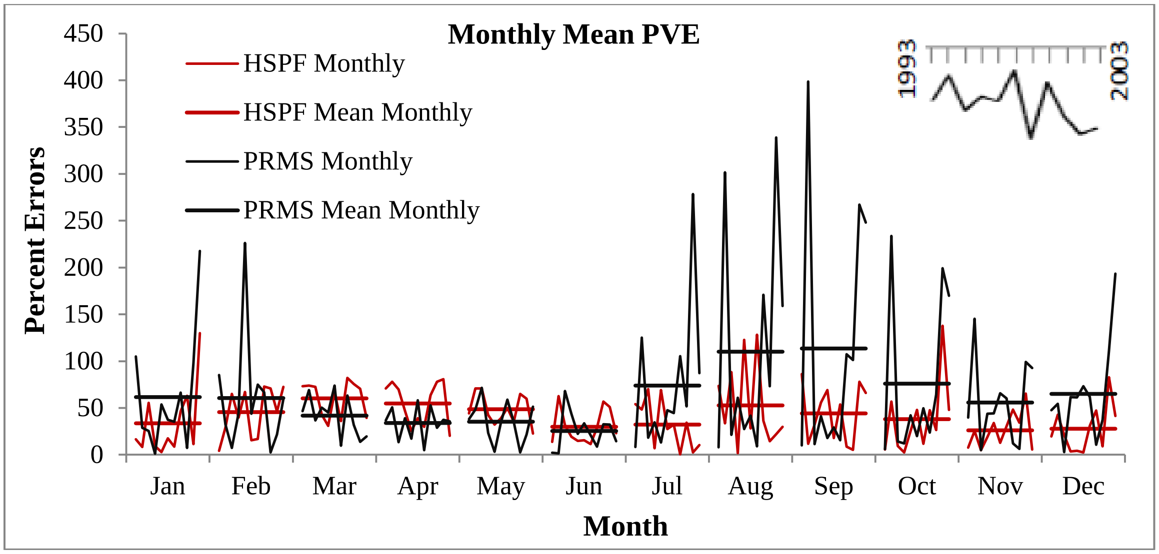

Figure 5.27 Comparison of percent volume error of HSPF and PRMS estimated monthly mean flow for the simulation period (1993-2003), (Spring Creek watershed)

The HSPF model under-estimated the mean monthly flow during early summer and over-estimated it during late summer (Figure 5.28). The PRMS better estimated the mean monthly flow than the HSPF from spring to early winter.

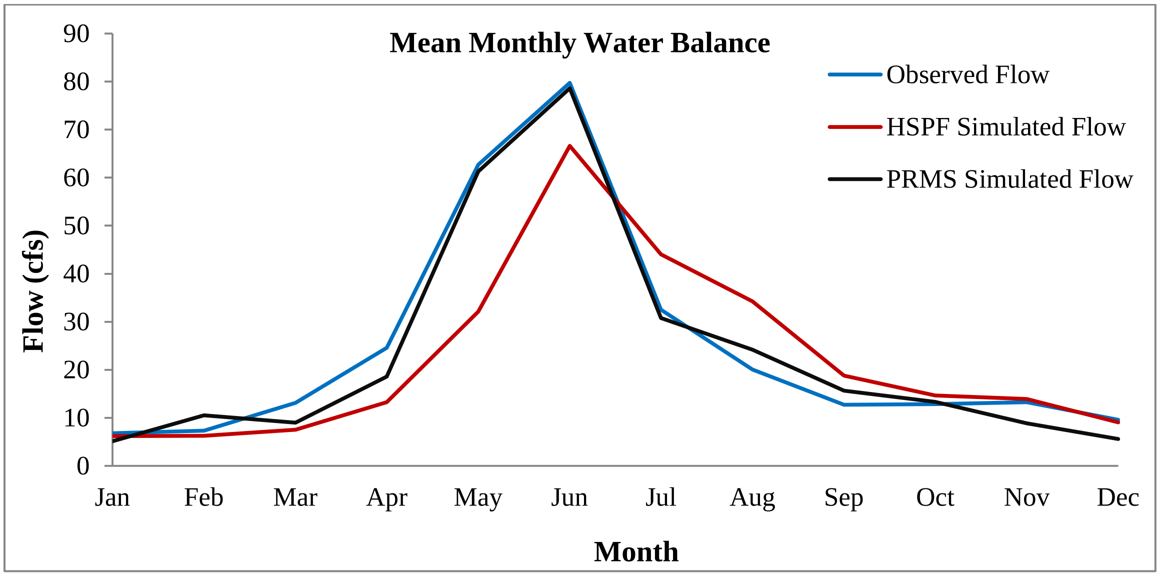

Figure 5.28 Comparison of observed and estimated mean monthly streamflow for HSPF and PRMS for the simulation period (1993-2003), (Spring Creek watershed)

The HSPF better estimated the daily flow than the PRMS for June month of a wet year (1999) and a dry year (2001) (Figure 5.29 and Figure 5.30).

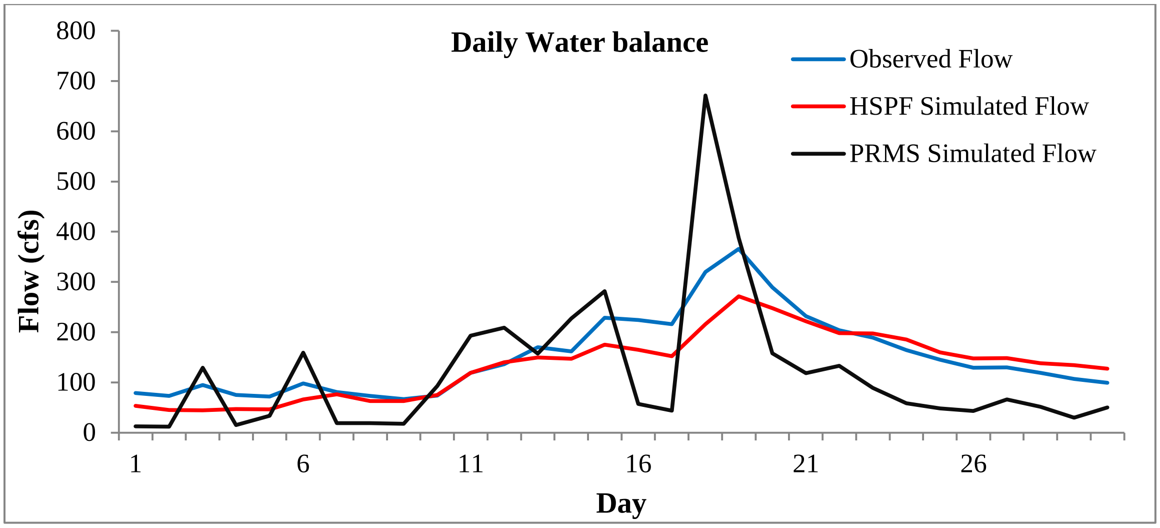

Figure 5.29 Comparison of HSPF and PRMS estimated daily flow for June 1999 (wet year), (Spring Creek watershed)

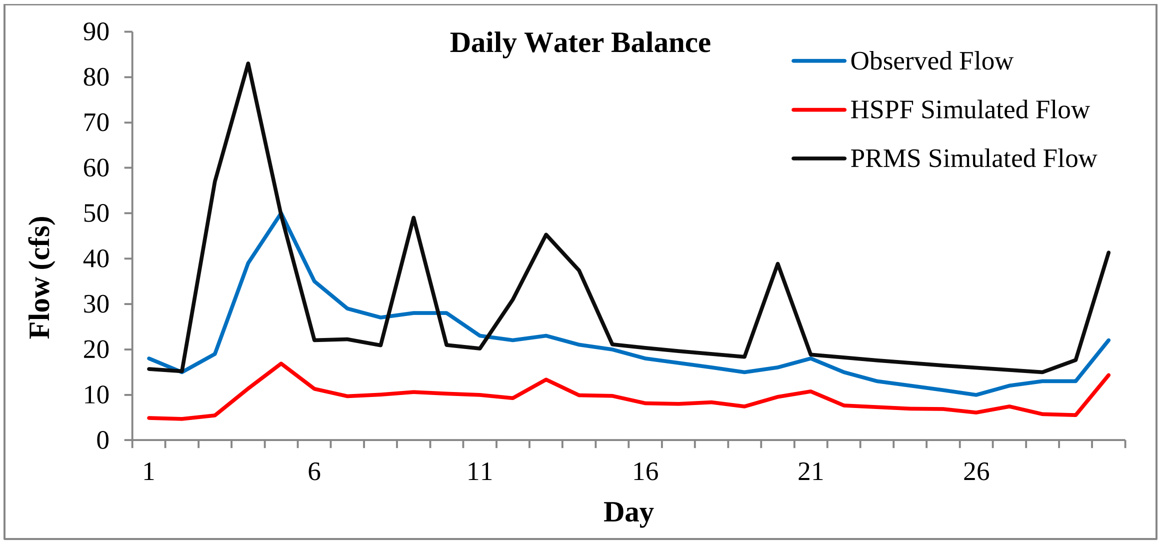

Figure 5.30 Comparison of HSPF and PRMS estimated daily flow for June 2001 (dry year), (Spring Creek watershed)

The flow duration curve showed that the HSPF better estimated the percentage of daily flow than the PRMS (Figure 5.31).

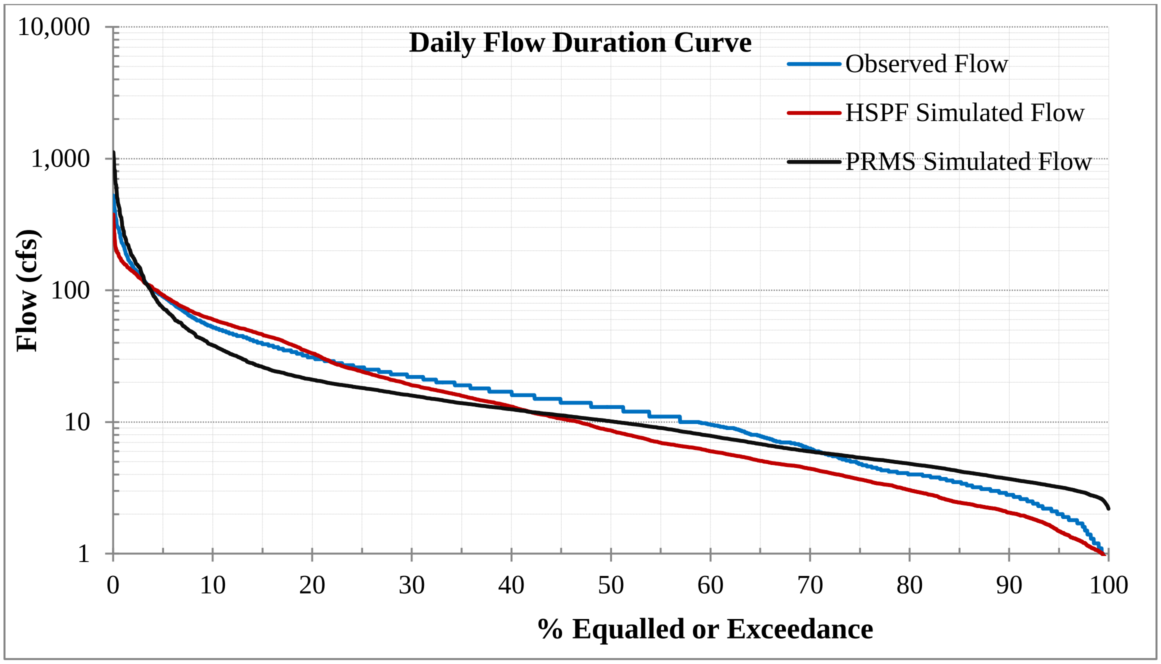

Figure 5.31 Comparison of observed and estimated daily streamflow duration curves for HSPF and PRMS for the simulation period (1993-2003), (Spring Creek Watershed)

During the simulation period, the average volume error of the HSPF and PRMS annual flow were -18 and 4 percent respectively (Table 5-18). The NSE, r, and R^2 statistics for the HSPF annual flow (NSE = 0.88, r = 0.96, and R^2 = 0.93) were better than the PRMS (NSE = 0.66, r = 0.84, and R^2 = 0.70). The average volume error of the HSPF monthly mean flow (-7 percent) was better than the PRMS (23 percent). The NSE statistic of HSPF monthly mean flow (NSE = 0.74) was better than the PRMS (NSE = 0.67). The r and R^2 statistics of the PRMS monthly mean flow (r = 0.88, and R^2 = 0.77) were better than the HSPF (r = 0.86, and R^2 = 0.74). The NSE, r, and R^2 statistics for the PRMS mean monthly flow (NSE = 0.98, r = 0.99, and R^2 = 0.98) were better than the HSPF (NSE = 0.72, r = 0.86, and R^2 = 0.74). The NSE, r, and R^2 statistics for the HSPF daily flow (NSE = 0.64, r = 0.80, and R^2 = 0.65) were better than the PRMS (NSE = 0.05, r = 0.78, and R^2 = 0.60).

Table 5-18 Comparison between HSPF and PRMS estimated streamflow for the simulation period (1993-2003), (Spring Creek Watershed)

Items	Annual		Monthly		Mean Monthly		Daily	
	HSPF	PRMS	HSPF	PRMS	HSPF	PRMS	HSPF	PRMS
Avg. % Error	-18.06	3.67	-7.20	23.17	-0.82	-6.09	-1.50	28.92
PBIAS	-9.58	-4.73	-9.65	-4.63	-9.66	-4.65	-9.59	-4.73
NSE	0.88	0.66	0.74	0.67	0.72	0.98	0.64	0.05
RSR	0.35	0.58	0.51	0.57	0.53	0.15	0.60	0.98
RMSE	5.15	8.52	17.00	18.93	11.70	3.34	24.62	40.27
r	0.96	0.84	0.86	0.88	0.86	0.99	0.80	0.78
R^2	0.93	0.70	0.74	0.77	0.74	0.98	0.65	0.60

5.18 Summary of Spring Creek Watershed Results

The HSPF better estimated annual flow (7 out of 11 years) than the PRMS during the simulation period (1993-2003). The HSPF monthly mean flow was better than the PRMS for rainfall runoff events during wet years (1995 and 1998) and one dry year (2003). The HSPF better estimated monthly mean flow than the PRMS for base flow periods during wet years (1997 and 1998) and dry years (1994 and 2003). The PRMS better estimated mean monthly flow than the HSPF from spring to early winter. The NSE statistics for HSPF annual, monthly mean, and daily flow were better than the PRMS. The r and R^2 statistics for HSPF annual and daily flow were better than the PRMS, however, the r and R^2 statistics for PRMS monthly mean flow were better than the HSPF. In general, the HSPF performed better than the PRMS for the simulation period (1993-2003) in Spring Creek watershed.

5.19 Temporal and Spatial Scale Issues in HSPF and PRMS Models

The study area of the Rapid Creek watershed (294 square miles) is 2.3 times bigger than the Spring Creek watershed (127 square miles). Both watersheds lie in the

Black Hills and are covered by about 90 percent forest and 10 percent rangeland area. Pactola, Buska, Stovho, and Mocmont soils are present in both watersheds. In general, both watersheds have similar physical characteristics. Temporal and spatial scale issues in HSPF and PRMS are discussed in the following sections. The simulation periods for Rapid Creek watershed (1992-2008) and Spring Creek watershed (1993-2003) were used for evaluating the effect of temporal scale on each model output. A common calibration/simulation period (1993-2002) was used for evaluating the effect of spatial scale on each model output.

5.20 Temporal Scale Issue in HSPF Model

Based on NSE, r, and R^2 statistics, the HSPF annual flow (NSE = 0.78, r = 0.92, and R^2 = 0.85) was better than the monthly flow (NSE = 0.60, r = 0.84, and R^2 = 0.70), and the monthly flow was better than the daily flow (NSE = 0.86, r = 0.96, and R^2 = 0.93) for the Rapid Creek watershed during the simulation period 1992-2008 (Table 5-19). The HSPF annual flow was better than the monthly flow, and the monthly flow was better than the daily flow for the Spring Creek watershed during the simulation period 1993-2003.

Table 5-19 HSPF statistical measure using temporal scale

	Rapid Creek watershed			**Spring Creek watershed**		
Item	**NSE**	**r**	**R^2**	**NSE**	**r**	**R^2**
Annual	0.78	0.92	0.85	0.88	0.96	0.93
Monthly	0.60	0.84	0.70	0.74	0.86	0.74
Daily	0.41	0.77	0.59	0.64	0.80	0.65

Note: Simulation period for the Rapid Creek 1992-2008, Spring Creek 1993-2003

The results indicate that the HSPF performance improved as the model output time step increased (e.g. from a daily interval to annual interval) for any watershed size.

5.21 Temporal Scale Issue in PRMS Model

Based on NSE, r, and R^2 statistics, the PRMS monthly flow (NSE = 0.49, r = 0.79, and R^2 = 0.63) was better than the daily flow (NSE = 0.42, r = 0.76, and R^2 = 0.57), and the daily flow was better than the annual flow (NSE = 0.39, r = 0.65, and R^2 = 0.42) for the Rapid Creek watershed during the simulation period 1992-2008 (Table 5-20). The PRMS monthly flow (NSE = 0.67, r = 0.88, and R^2 = 0.77) was better than the annual flow (NSE = 0.66, r = 0.84, and R^2 = 0.70), and the annual flow was better than the daily flow (NSE = 0.05, r = 0.78, and R^2 = 0.60) for the Spring Creek watershed during the simulation period 1993-2003.

Table 5-20 PRMS statistical measure using temporal scale

	Rapid Creek watershed			**Spring Creek watershed**		
Item	**NSE**	**r**	**R^2**	**NSE**	**r**	**R^2**
Annual	0.39	0.65	0.42	0.66	0.84	0.70
Monthly	0.49	0.79	0.63	0.67	0.88	0.77
Daily	0.42	0.76	0.57	0.05	0.78	0.60

Note: Simulation period for the Rapid Creek 1992-2008, Spring Creek 1993-2003

The results indicate that the PRMS estimates better flow for the monthly interval than the annual and daily intervals for any watershed size. The PRMS estimates better flow for the daily interval than the annual interval for a large watershed. The PRMS estimates better flow for the annual interval than the daily interval for a small watershed.

5.22 Spatial Scale Issue in HSPF Model

The NSE, r, and R^2 statistics of the HSPF annual flow for the Spring Creek watershed (NSE = 0.86, r = 0.96, and R^2 = 0.93) were better than the Rapid Creek watershed (NSE = 0.72, r = 0.89, and R^2 = 0.79) during the common simulation period 1993-2002 (Table 5-21). The NSE, r, and R^2 statistics of the HSPF monthly mean flow for the Spring Creek watershed (NSE = 0.73, r = 0.86, and R^2 = 0.74) were better than the

Rapid Creek watershed (NSE = 0.55, r = 0.82, and R^2 = 0.67). The NSE, r, and R^2 statistics of the HSPF daily flow for the Spring Creek watershed (NSE = 0.64, r = 0.80, and R^2 = 0.64) were better than the Rapid Creek watershed (NSE = 0.34, r = 0.75, and R^2 = 0.56). The statistical results illustrate that the HSPF model of the Spring Creek was better than the Rapid Creek watershed for estimating all three of the water budgets (annual, monthly mean, and daily).

Table 5-21 HSPF statistical measure using spatial scale

	Annual		**Monthly**		**Daily**	
Items	**Rapid Creek**	**Spring Creek**	**Rapid Creek**	**Spring Creek**	**Rapid Creek**	**Spring Creek**
NSE	0.72	0.86	0.55	0.73	0.34	0.64
r	0.89	0.96	0.82	0.86	0.75	0.80
R^2	0.79	0.93	0.67	0.74	0.56	0.64

Note: Rapid Creek watershed (294 sq. miles), Spring Creek watershed (127 sq. miles), common simulation period (1993-2002)

The percent volume errors (PVE) of the HSPF monthly mean flow for both watersheds (Spring Creek and Rapid Creek) were similar for June and July (Figure 5.32). The PVEs of the HSPF monthly mean flow for the Spring Creek watershed were less than the Rapid Creek watershed from October to February. The PVEs of the HSPF monthly mean flow for the Rapid Creek watershed were less than the Spring Creek watershed for March, May and August. The graphical results illustrate that the PVEs of the HSPF monthly mean flow varied between the watersheds.

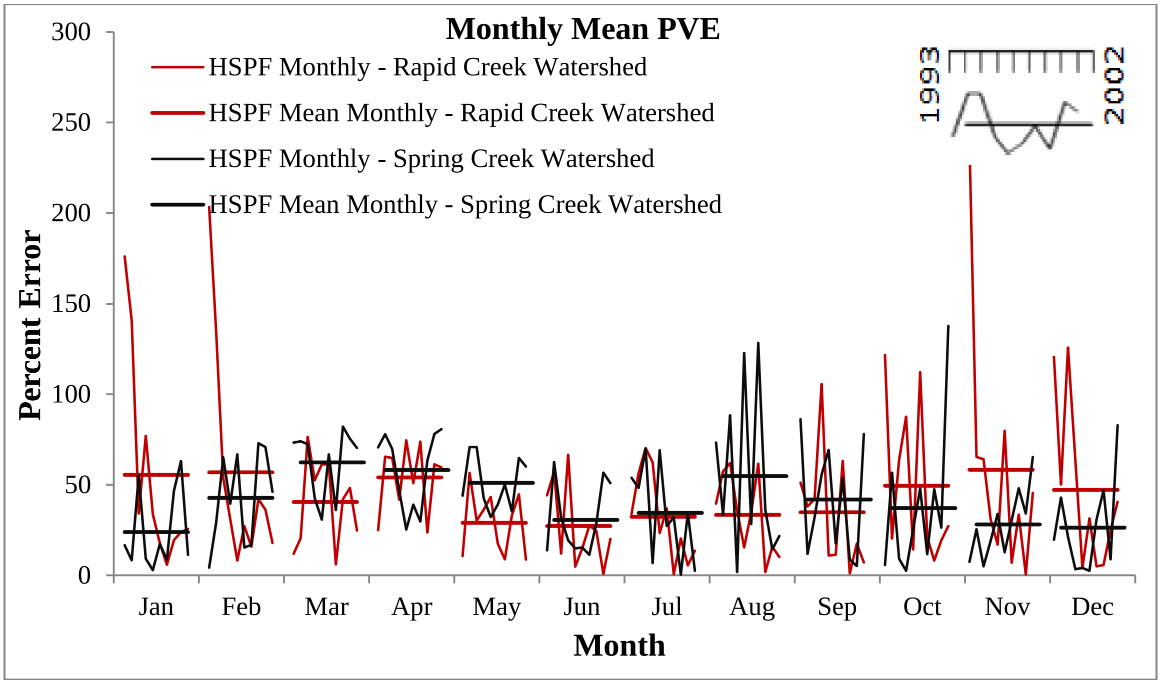

Figure 5.32 Comparison of percent volume error of HSPF estimated monthly flow for the Rapid Creek and Spring Creek watersheds during the common simulation period (1993-2002)

The results indicate that the HSPF performance for estimating all three of the water budgets improved as the watershed size decreased.

5.23 Spatial Scale Issue in PRMS Model

The NSE, r, and R^2 statistics of the PRMS annual flow for the Spring Creek watershed (NSE = 0.62, r = 0.82, and $R^2 = 0.68$) were better than the Rapid Creek watershed (NSE = 0.51, r = 0.73, and $R^2 = 0.54$) during the common simulation period 1993-2002 (Table 5-22). The NSE statistic of the PRMS monthly mean flow for the Rapid Creek watershed (NSE = 0.68) was better than the Spring Creek watershed (NSE = 0.66). The r and R^2 statistics of the PRMS monthly mean flow for the Spring Creek watershed (r = 0.88, and $R^2 = 0.77$) were better than the Rapid Creek watershed (r = 0.84, and $R^2 = 0.71$). The NSE, r, and R^2 statistics of the PRMS daily flow for the Rapid Creek watershed (NSE = 0.60, r = 0.80, and R^2 = 0.64) were better than the Spring Creek watershed (NSE = 0.03, r = 0.78, and R^2 = 0.60).

Table 5-22 PRMS statistical measure using spatial scale

Items	Annual		Monthly		Daily	
	Rapid Creek	Spring Creek	Rapid Creek	Spring Creek	Rapid Creek	Spring Creek
NSE	0.51	0.62	0.68	0.66	0.60	0.03
r	0.73	0.82	0.84	0.88	0.80	0.78
R^2	0.54	0.68	0.71	0.77	0.64	0.60

Note: Rapid Creek watershed (294 sq. miles), Spring Creek watershed (127 sq. miles), common simulation period (1993-2002)

The PVEs of the PRMS monthly mean flow for the Rapid Creek watershed were less than the Spring Creek watershed in August and September (Figure 5.33). The PVEs of the PRMS monthly mean flow for the Spring Creek watershed were less than the Rapid Creek watershed in February and October. The PVEs of the PRMS monthly mean flow for both watersheds were similar during the winter and the spring. The graphical results indicate that the PVEs of the PRMS monthly mean flow varied between the watersheds.

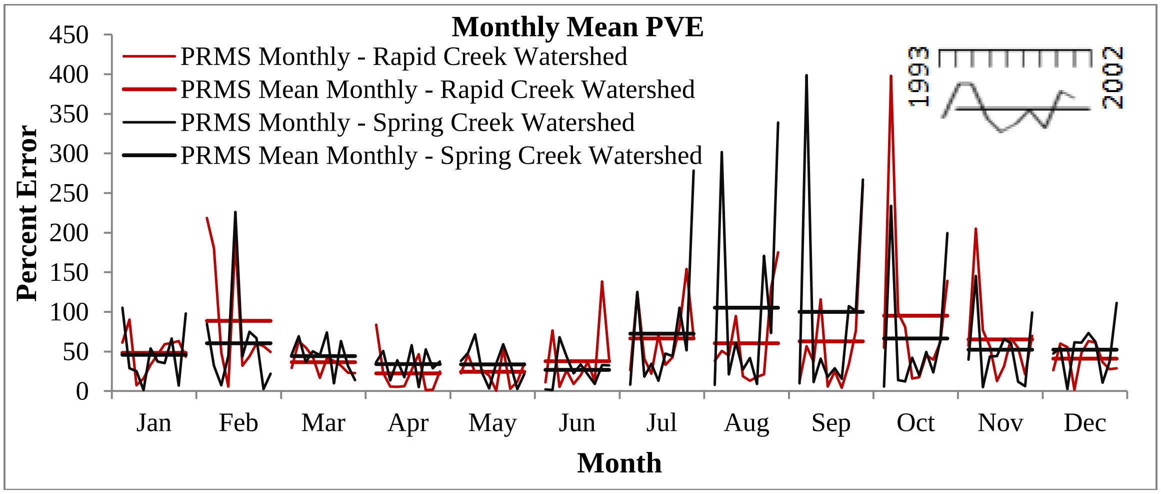

Figure 5.33 Comparison of percent volume error of PRMS estimated monthly mean flow for the Rapid Creek and Spring Creek watersheds during the simulation period (1993-2002)

The results indicate that the PRMS performance for estimating the annual water budget improved as the watershed size decreased. The PRMS performance for estimating the daily water budget reduced as the watershed size decreased. The PRMS performance for estimating the monthly water budget remained similar for any watershed size.

5.24 Summary of Temporal and Spatial Scale Issues in HSPF and PRMS Models

The HSPF performance improved as the model output time step increased (e.g. from a daily interval to annual interval) for a small and large watershed. The PRMS better estimated flow for the monthly interval than the annual and daily intervals for a small and large watershed. The PRMS better estimated flow for the daily interval than the annual interval for a large watershed. The PRMS better estimated flow for the annual interval than the daily interval for a small watershed.

The HSPF performance for estimating all three of the water budgets (annual, monthly mean, and daily) improved as the watershed size decreased. The PRMS performance for estimating the annual water budget improved as the watershed size decreased. The PRMS performance for estimating the daily water budget reduced as the watershed size decreased. The PRMS performance for estimating the monthly water budget remained similar for different watershed size.

The results indicate that The HSPF and PRMS model output were influenced by the temporal and spatial scale.

5.25 Sensitivity Analysis

Sensitivity analysis is used to find the most important parameters of a model. A relative percent sensitivity analysis was performed on the final calibrated parameters of the models (HSPF and PRMS) for both watersheds during their individual simulation period (Rapid Creek watershed: 1992-2008 and Spring Creek watershed: 1993-2003). The relative percent sensitivity is calculated as percent change in streamflow to percent change in parameter value (Fontaine and Jacomino, 1997).

The percent change in model estimated flow relative to 10 percent increase in parameter value was calculated. Two values of the HSPF parameter (AGWRC and DEEPFR) have upper limit of 1; therefore parameter values had to be reduced by 10 percent instead of increased by 10 percent. A PRMS parameter (gwsink_coef) was inactive during the calibration. The sensitivity of gwsink_coef was performed by changing its value from 0 to 0.01. Two PRMS parameters (tmax_cbh_adj and tmin_cbh_adj) for the Spring Creek watershed were inactive. The sensitivity of these parameters was performed by changing their value from 0 to 0.1. Both HSPF and PRMS parameters are described in chapter 4 Materials and Methods (see p. 41 HSPF Input files, see p. 51 PRMS calibration approach).

The snow adjustment factor (SNOWCF) was the most sensitive parameter in the HSPF during simulation of the Rapid Creek watershed (Table 5-23).

Table 5-23 Relative percent sensitivity of major calibration parameters of the HSPF model (Rapid Creek watershed)

Parameter	**Percent change**	**Percent change in avg. annual flow**		**Relative percent sensitivity**	
		HSPF Wet	**HSPF Dry**	**HSPF Wet**	**HSPF Dry**
SNOWCF^1	10.00	10.26	11.48	45.00	59.59
AGWRC	-10.00	4.46	2.39	19.55	12.43
DEEPFR^4	-10.00	3.38	1.05	14.84	5.48
LZETP^2	10.00	-2.90	-2.88	-12.70	-14.95
LZSN^3	10.00	-1.03	-0.58	-4.53	-3.02
INFILT^5	10.00	0.36	0.18	1.58	0.94
UZSN	10.00	-0.29	-0.65	-1.28	-3.39
CCFACT	10.00	0.11	-0.03	0.47	-0.13
INTFW	10.00	0.01	0.01	0.04	0.07
IRC	10.00	0.00	0.00	0.00	0.00

Note: The five HSPF parameters noted as 1, 2, 3, 4 & 5 are similar to PRMS parameters noted as 1, 2, 3, 4 & 5 respectively

The rain adjustment factor (rain_cbh_adj) was the most sensitive parameter in the PRMS during simulation of the Rapid Creek watershed (Table 5-24).

Table 5-24 Relative percent sensitivity of major calibration parameters of the PRMS model (Rapid Creek watershed)

Parameter	**Percent change**	**Percent change in avg. annual flow**		**Relative percent sensitivity**	
		PRMS Wet	**PRMS Dry**	**PRMS Wet**	**PRMS Dry**
rain_cbh_adj	10	13.39	9.00	43.67	29.93
snow_cbh_adj^1	10	5.35	8.34	17.44	27.74
pref_flow_den^5	10	4.90	7.63	15.98	25.39
gwsink_coef^4	0 to 0.01	-3.01	0.00	-9.82	0.00
soil_moist_max^3	10	-1.55	2.21	-5.04	7.34
tmax_cbh_adj^2	10	-1.53	1.35	-4.98	4.49
smidx_coef	10	0.41	1.26	1.32	4.20
soil_rechr_max	10	0.39	-0.05	1.27	-0.18
tmin_cbh_adj	10	-0.13	0.17	-0.43	0.55
gwflow_coef	10	0.00	0.00	0.02	0.00
fastcoef_sq	10	0.00	0.00	0.01	0.00
fastcoef_lin	10	0.00	0.02	0.01	0.06
ssr2gw_rate	10	0.00	0.00	0.00	0.00
slowcoef_lin	10	0.00	0.00	0.00	0.00

Parameter	Percent change	Percent change in avg. annual flow		Relative percent sensitivity	
		PRMS Wet	PRMS Dry	PRMS Wet	PRMS Dry
sat_thresold	10	0.00	0.00	0.00	0.00
soil2gw_max	10	0.00	0.00	0.00	0.00
slowcoef_sq	10	0.00	0.00	0.00	0.00
adjmix_rain_hru_mo	10	0.00	0.04	0.00	0.12

Note: The five PRMS parameters noted as 1, 2, 3, 4 & 5 are similar to HSPF parameters noted as 1, 2, 3, 4 & 5 respectively

The snow adjustment factor (SNOWCF) was the most sensitive parameter in the HSPF during simulation of the Spring Creek watershed (Table 5-25).

Table 5-25 Relative percent sensitivity of major calibration parameters of the HSPF model (Spring Creek watershed)

Parameter	Percent change	Percent change in avg. annual flow	Relative percent sensitivity
SNOWCF[1]	10	9.91	33.80
LZETP[2]	10	-9.47	-32.27
AGWRC	-10	4.94	16.83
LZSN[3]	10	-2.57	-8.76
DEEPFR[4]	-10	1.35	4.59
INFILT[5]	10	0.98	3.34
CCFACT	10	-0.08	-0.28
INTFW	10	-0.04	-0.14
IRC	10	0.00	0.00
UZSN	10	0.00	0.00

Note: The five HSPF parameters noted as 1, 2, 3, 4 & 5 are similar to PRMS parameters noted as 1, 2, 3, 4 & 5 respectively

The rain adjustment factor (rain_cbh_adj) was the most sensitive parameter in the PRMS during simulation of the Rapid Creek watershed (Table 5-26).

Table 5-26 Relative percent sensitivity of major calibration parameters of the PRMS model (Spring Creek watershed)

Parameter	**Percent change**	**Percent change in avg. annual flow**	**Relative percent sensitivity**
rain_cbh_adj	10	22.92	42.00
snow_cbh_adj[1]	10	22.81	41.80
pref_flow_den[5]	10	3.27	5.99
soil_moist_max[3]	10	-2.03	-3.73
smidx_coef	10	1.09	2.00
tmax_cbh_adj[2]	10	-0.90	-1.65
gwsink_coef[4]	0 to 0.01	-0.53	-0.97
soil_rechr_max	10	0.51	0.93
tmin_cbh_adj	10	-0.45	-0.82
adjmix_rain_hru_mo	10	0.06	0.12
fastcoef_sq	10	0.00	0.00
fastcoef_lin	10	0.00	0.00
soil2gw_max	10	0.00	0.00
slowcoef_sq	10	0.00	0.00
ssr2gw_rate	10	0.00	0.00
slowcoef_lin	10	0.00	0.00
gwflow_coef	10	0.00	0.00
sat_thresold	10	0.00	0.00

Note: The five PRMS parameters noted as 1, 2, 3, 4 & 5 are similar to HSPF parameters noted as 1, 2, 3, 4 & 5 respectively

The most sensitive HSPF and PRMS models parameters identified in this study are shown in the Table 5-27.

Table 5-27 Rank of the most sensitive parameters of the HSPF and PRMS models

Rank	HSPF			PRMS		
	Rapid Creek Watershed		Spring Creek Watershed	Rapid Creek Watershed		Spring Creek Watershed
	Wet	Dry	Mixed	Wet	Dry	Mixed
1	SNOWCF[1]	SNOWCF[1]	SNOWCF[1]	rain_cbh_adj	rain_cbh_adj	rain_cbh_adj
2	AGWRC	LZETP[2]	LZETP[2]	snow_cbh_adj[1]	snow_cbh_adj[1]	snow_cbh_adj[1]
3	DEEPFR[4]	AGWRC	AGWRC	pref_flow_den[5]	pref_flow_den[5]	pref_flow_den[5]
4	LZETP[2]	DEEPFR[4]	LZSN[3]	gwsink_coef[4]	soil_moist_max[3]	soil_moist_max[3]
5	LZSN[3]	UZSN	DEEPFR[4]	soil_moist_max[3]	tmax_cbh_adj[2]	smidx_coef
6	INFILT[5]	LZSN[3]	INFILT[5]	tmax_cbh_adj[2]	smidx_coef	tmax_cbh_adj[2]
7	UZSN	INFILT[5]	UZSN	smidx_coef	tmin_cbh_adj	gwsink_coef[4]

Note: The five HSPF parameters noted as 1, 2, 3, 4 & 5 are similar to PRMS parameters noted as 1, 2, 3, 4 & 5 respectively

5.26 Sensitive Parameters in Calibrated HSPF and PRMS Models and Model Accuracy

The most sensitive HSPF model parameters identified in this study are snow gage correction factor (SNOWCF), active ground-water recession coefficient (AGWRC), fraction of groundwater inflow to deep recharge (DEEPFR), index to lower zone evapotranspiration (LZETP), lower zone nominal soil moisture storage (LZSN), index to infiltration capacity (INFILT), and upper zone nominal soil moisture storage (UZSN).

The most sensitive PRMS model parameters identified in this study are rain adjustment factor (rain_cbh_adj), snow adjustment factor (snow_cbh_adj), preferential flow density (pref_flow_den), deep groundwater loss (gwsink_coef), maximum water holding capacity of soil recharge zone (soil_moist_max), maximum temperature adjustment factor (tmax_cbh_adj), and non-linear surface runoff contribution coefficient (smidx_coef).

The following section compares and discusses the top 7 parameters of both models to determine if any of the parameters are a potential source for the differences in the accuracy of model output.

PRMS model parameter rain_cbh_adj: This parameter in PRMS ranges from 0.5 to 1.5 and is corrective coefficient applied to model rainfall as determined from precipitation data. HSPF has no such parameter. For this research, the HSPF used observed NOAA climate station precipitation data while the PRMS used DAYMET precipitation data for model simulations. DAYMET precipitation dataset is an estimate (1km-grid) based upon interpolation and extrapolation techniques. This method generates daily meteorological data for large and complex terrain having less meteorological stations (Thornton et al., 1997).

Cross validation of DAYMET precipitation and NOAA precipitation data were performed using observed precipitation data from Community Collaborative Rain, Hail & Snow Network (CoCoRaHS) in the Rapid Creek watershed (see p.130, Appendix B). The DAYMET under-estimated CoCoRaHS precipitation during June and September (2 to 3 percent) and over-estimated it during other months (6 to 82 percent). The NOAA over-estimated CoCoRaHS precipitation during May to September (2 to 13 percent) and under-estimated it during other months (2 to 37 percent). For average annual precipitation, the DAYMET over-estimated CoCoRaHS by 16 percent and NOAA over-estimated it by 0.4 percent. This indicates that the DAYMET precipitation does not represent the precipitation during rainfall runoff events in the Black Hills very well, and PRMS can correct for this error by use and calibration of **rain_cbh_adj**.

In a first simulation in the Rapid Creek watershed, the PRMS used a **rain_cbh_adj** value of 1.15 to increase the DAYMET precipitation by 15 percent during wet period, which effectively adjusts DAYMET precipitation values closer to observed values at climate stations and CoCoRaHS (see p. 138, Appendix C). In a second simulation in the Rapid Creek watershed, the PRMS used a **rain_cbh_adj** value of 0.5 to decrease the DAYMET precipitation by 50 percent during dry period, which again effectively adjusts DAYMET precipitation values closer to observed value at climate stations and CoCoRaHS. This indicates that the **rain_cbh_adj** corrects the DAYMET data to simulated rainfall that are more similar to precipitation values used for HSPF. This also indicates that the PRMS rain adjustment parameter (rain_cbh_adj) may not be a potential source of error for differences in model output.

PRMS model parameter snow_cbh_adj and HSPF model parameter SNOWCF: The PRMS model parameter **snow_cbh_adj** ranges from 0.5 to 1.5. The HSPF model parameter **SNOWCF** ranges from 1 to 2. These parameters are the corrective coefficients applied to model snowfall as determined from precipitation data. Both HSPF and PRMS use this parameter to adjust precipitation value to account for poor catch efficiency of the gage during snow events. In an example simulation of the Rapid Creek watershed, the PRMS used a **snow_cbh_adj** value of 1.07 to increase the DAYMET precipitation by 7 percent and HSPF used a **SNOWCF** value of 1.15 to increase the NOAA climate station precipitation by 15 percent during snow events (pp. 134, 138, Appendix C). This indicates that the snow adjustment parameter in both models

(PRMS: snow_cbh_adj, HSPF: SNOWCF) is similar and may not be a potential source of error for differences in model output.

PRMS model parameter tmax_cbh_adj and tmin_cbh_adj: Both of these parameters in PRMS range from -5 to 5 and are corrective coefficients applied to model input DAYMET temperature data. HSPF has no such parameter. For this research, the HSPF used observed NOAA climate station temperature data while the PRMS used DAYMET temperature data for model simulations. Cross validation of DAYMET temperature data was performed using observed climate station temperature data from the USGS gage in the Rapid Creek watershed (see p. 131, Appendix B). The comparison showed that DAYMET continuously under-estimated aggregated maximum monthly temperature (9 to 17 percent) throughout a year. The DAYMET under-estimated aggregated monthly minimum temperature (1 to 5 percent) for 9 months except September, December, and January (over-estimated by 1 to 3 percent). The DAYMET under-estimated average monthly maximum temperature and average monthly minimum temperature by 12 and 2 percent respectively. The DAYMET average monthly maximum temperature and minimum temperature were less than 6 degree Fahrenheit (°F) and 1 °F as compared to USGS gage temperature respectively. In an example simulation in the Rapid Creek watershed, the **tmax_cbh_adj** ranged from 5 to 7 °F and the **tmin_cbh_adj** ranged from 0 to 1 °F. These PRMS calibrated parameter values are added to DAYMET temperature which effectively adjusts DAYMET temperature values closer to observed values at climate stations. This indicates that the **tmax_cbh_adj** and **tmin_cbh_adj** correct the DAYMET data to simulated temperature that are more similar to observed climate stations temperature data. This also indicates that the PRMS temperature adjustment parameters (tmax_cbh_adj and tmin_cbh_adj) may not be a potential source of error for differences in model output.

HSPF model parameter LZETP: This parameter in HSPF ranges from 0.1 to 0.9 and affects evapotranspiration from the lower soil zone (primary soil moisture storage and root zone of soil profile). In an example simulation in the Spring Creek watershed, **LZETP** value was 0.75 for forest land use and 0.55 for rangeland land use. The study indicates that the **LZETP** value is higher for forest land use than the other land uses. The **LZETP** controls evapotranspiration during dry periods and is calibrated for runoff simulation. PRMS calibrates the ET parameter **jh_coef** (Jansen Haise coefficient) to meet the target observed potential ET. PRMS does not calibrate ET parameter (jh_coef**)** during water balance calibration but it calibrates the **tmax_cbh_adj** parameter. During water balance calibration, this PRMS parameter **tmax_cbh_adj** adjusts temperature which affects ET. This study indicates that the different parameters (HSPF: LZETP and PRMS: tmax_cbh_adj) have similar roles in runoff simulations, which indicates that the **LZETP** parameter in HSPF and the **tmax_cbh_adj** parameter in PRMS may not be a potential source of error for differences in model output.

PRMS model parameter soil_moist_max and HSPF model parameter LZSN: The PRMS model parameter **soil_moist_max** ranges from 1 to 10. The HSPF model parameter **LZSN** ranges from 2 to 15. These parameters represent soil moisture storage depth and are related to maximum field capacity of the soil. In an example simulation of the Spring Creek watershed , PRMS used a **soil_moist_max** value of 6.2 and HSPF used a **LZSN** value of 9.4. This study indicates that the soil moisture storage parameter in both models (PRMS: soil_moist_max, HSPF: LZSN) is similar and may not be a potential source of error for differences in model output.

PRMS model parameter gw_sink_coef and HSPF model parameter DEEPFR: The PRMS model parameter **gw_sink_coef** ranges from 0 to 1.0. The HSPF model parameter **DEEPFR** ranges from 0 to 0.5. These parameters represent the fraction of groundwater inflow to the deep recharge. These parameters are also known as the coefficient of groundwater loss or sink loss. In an example simulation of the Spring Creek watershed, the PRMS used a **gw_sink_coef** value of 0 (no loss from groundwater to deep aquifers) and HSPF used a **DEEPFR** value of 0.15 for forest land use (15 percent loss of groundwater to deep aquifers). This study indicates that the soil groundwater loss parameter in both models (PRMS: gw_sink_coef, HSPF: DEEPFR) is similar and may not be a potential source of error for differences in model output.

HSPF model parameter INFILT and PRMS model parameter pref_flow_den: This parameter in HSPF ranges from 0.001 to 0.5 and divides available moisture from precipitation (except interception) into surface, subsurface and soil moisture storage components. The low value of **INFILT** results in high overland flow and interflow runoff; high value of **INFILT** results high base flow to the stream. The **INFILT** parameter is neither a maximum rate nor an infiltration capacity term. Typical **INFILT** values are less than the infiltration rate. The initial **INFILT** value can be taken from SCS hydrologic soil groups and adjusted during the calibration process. In an example simulation in the Spring Creek watershed, the INFILT value was 0.45 for forest land use and 0.1 to 0.45 for rangeland land use. The study indicates that the **INFILT** value for forest land use is higher than the other land uses.

The **pref_flow_den** parameter in PRMS ranges from 0 to 0.1 and divides the amount of precipitation, snowmelt, and Hortonian surface runoff (sum of surface runoff due to infiltration excess and exceeding impervious storage capacity) between the capillary and the preferential-flow reservoirs. The capillary reservoir represents water held in the soil by capillary forces. The preferential reservoir represents the amount of soil moisture between field capacity and saturation, which is available for fast interflow through large openings in the soil. In an example simulation in the Rapid Creek watershed, the maximum value of the **pref_flow_den** parameter (0.1) occurred during the wet and dry calibration period. The study indicates that the different parameters (HSPF: INFILT and PRMS: pref_flow_den) have similar roles in runoff simulations, which indicates that the **INFILT** parameter in HSPF and the **pref_flow_den** parameter in PRMS may not be a potential source of error for differences in model output.

HSPF model parameter AGWRC: This parameter in HSPF ranges from 0.85 to 0.999 and is the groundwater recession rate or ratio of current groundwater discharge to earlier groundwater discharge at a specific time interval. PRMS has no such parameter. The **AGWRC** controls base flow that contributes to streamflow. The **AGWRC** value varied with land use type. In general, the initial value ranges from 0.971 for grassland and 0.996 for high-density forest. The optimal values of AGWRC for different land uses are obtained through the calibration process. In an example simulation in the Rapid Creek watershed, **AGWRC** values ranged from 0.995 to 0.999 for forest and from 0.985 to 0.999 for rangeland land use. The study indicates that **AGWRC** value for forest land use is higher than the other land uses. This study also indicates that this HSPF parameter (AGWRC) may be a potential source of error for differences in model output.

HSPF model parameter UZSN: This parameter in HSPF ranges from 0.05 to 2.0 and is the upper zone nominal soil moisture storage, which will be available for evapotranspiration. PRMS has no such parameter. The initial **UZSN** value can be estimated using LZSN (0.06 * LZSN for steep slopes, limited vegetation; 0.08 * LZSN for moderate slopes, moderate vegetation; 0.14 * LZSN for heavy forest). The **UZSN** value changes over the growing season. It is more sensitive during the summer than the winter. The optimal **UZSN** value is obtained through the calibration process. In an example simulation in the Spring Creek watershed, the **UZSN** values ranged from 0.7 to 0.95. The study indicates that the **UZSN** values for different land uses are close. The study also indicates that this HSPF parameter (UZSN) may be a potential source of error for differences in model output.

PRMS model parameter (smidx_coef): This parameter in PRMS ranges from 0.001 to 0.06, which computes the Hortonian surface runoff using the contributing-area concept. HSPF has no such parameter. The **smidx_coef** is a coefficient in the nonlinear contributing area algorithm. This parameter controls the overland flow that enters to the streams. In an example simulation in the Rapid Creek watershed, the **smidx_coef** value was 0.004. The study indicates that the **smidx_coef** value varies with the calibration scenarios (wet vs. dry climates). The study also indicates that this PRMS parameter (smidx_coef) may be a potential source of error for differences in model output.

5.27 Model Uncertainties

A hydrologic model is an approximate representation of a natural earth system. Models introduce error or uncertainty in the output, as they cannot truly represent the natural system. The description of model uncertainty aims to help users to minimize the error of model output. The major sources of modeling uncertainties identified in this study are physical characteristics of the watershed, input data, modeler decision, and the model capability.

The Black Hills area of South Dakota lies in semi-arid region. Flash floods and debris flows due to heavy rains and intense thunderstorms occur in the Black Hills. This makes a unique challenge for a modeler to accurately simulate runoff and streamflow.

Precipitation is a driving factor behind any hydrologic model. A single rainfall station (SD 396427) located below Pactola Reservoir was used to distribute the rainfall for the Rapid Creek watershed. A single rainfall station (SD 393868) was used to distribute the rainfall for 90 percent of the Spring Creek watershed. The comparison between NOAA climate station precipitation and CoCoRaHS precipitation indicates that a single NOAA climate station does not represent the precipitation in the entire study area very well. Rainfall distribution from a single climate station to the entire drainage area may be the biggest factor for potential source of error in HSPF simulation.

The PRMS used DAYMET data for daily precipitation, minimum and maximum temperature as input. The DAYMET estimates 1 kilometer by 1-kilometer gridded data using approximately 10 to 20 NOAA stations near the watershed to create input meteorological data for the site. The study indicates that DAYMET does not represent the precipitation in the Black Hills very well. This may be the biggest factor for potential source of error in PRMS simulation.

Both HSPF and PRMS models used GIS methods to characterize the watershed. The GIS uses a digital elevation model, national land cover dataset and soil data to calculate parameter values. The NLCD 2006 land use map was used for the entire HSPF simulations and the NLCD 2001 land use map was used for the entire PRMS simulations. The single land use map for the entire HSPF and PRMS simulations may introduce error in the model output.

The user plays a vital role in deciding the number of sub-basins to use, the initial parameter value, in defining calibration and validation periods, calibration technique, and when to decide that the calibration is complete. Because of this, an inexperienced user may unknowingly misrepresent the model.

The model capability is also a factor in determining the model output. The HSPF model uses hourly data as an input and the PRMS model uses daily data as input. In general, the HSPF better estimated daily flow than the PRMS. The HSPF used solar radiation and potential evapotranspiration as an input. The PRMS calibrated the solar radiation and potential evapotranspiration. This may introduce error in PRMS model output.

5.28 Discussion of Advantages and Limitations of Each Model

The HSPF model can simulate basin hydrology, sediment processes, and water quality and the PRMS model simulates basin hydrology. The developed HSPF rainfall runoff model of this study can be used for additional sediment and water quality studies. The HSPF can have a minimum time step of 1 minute while the model PRMS can have a minimum time step of 1 day. For this research, HSPF simulations used an hourly time step and PRMS simulations used a daily time step. This is congruent with end user application.

The HSPF used extensive hourly time series data (precipitation, air temperature, potential evapotranspiration, wind speed, solar radiation, cloud cover, and dew point) from National Oceanic and Atmospheric Administration (NOAA) stations. For this research, the hourly meteorological data of NOAA stations were obtained in Watershed Data Management (WDM) file from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) system of the U.S. EPA. The BASINS data were available up to 2008 at the time of this study. The HSPF requires great time and effort to prepare a new dataset from the NOAA website (e.g. finding, downloading, filling the gaps, and adding each time series to the WDM file). The PRMS model used significantly less daily time series data (precipitation, minimum temperature, and maximum temperature) from DAYMET and the data were up to date at the time of this study.

The initial HSPF model input parameter values were estimated using Arc GIS 10.0, Arc Hydro 2.0 and EPA Basins Technote 6. The HSPF requires a skilled user and more time for preparing the input files. The HSPF provides flexibility to users to characterize the watershed to meet the user objectives (e.g. number of subbasins, land segments, meteorological zones).

The PRMS models were developed from a preliminary version of a national data set, referred to as the Geospatial Fabric for the National Hydrologic Model (NHM) being developed by USGS. The NHM provides preprocessed input data to users, so users do not need to spend a lot of time for preparing the model input files. The NHM data has a coarse scale and fixed resolution, so the users have less flexibility for characterizing the watershed as needed. The users can utilize GIS Weasel to characterize the watershed for developing PRMS input files (GIS Weasel requires advanced ArcGIS license in the computer). High-resolution PRMS model development requires skilled user, time effort, and better computer capability.

The HSPF used the standard manual approach to calibrate the models. This study calibrated 10 HSPF parameters. The HSPF does not allow users to adjust the input data with a parameter except the snow gage catch correction factor (SNOWCF). Ground water loss coefficient (DEEPFR) for open water (recharge) land segment in the HSPF model of this study used higher value (1) than the "BASINS EPA Technote 6" recommended values (0 to 0.2). The time required to calibrate HSPF depends on resolution of the watershed (e.g. number of land segments) and calibration points (subbasins). The calibration of the HSPF model for the Rapid Creek watershed (4 subbasins) used 4 times as much time than the Spring Creek watershed (no subbasin). In general, the HSPF calibration time and effort increases with increasing size of a watershed.

The PRMS used an automated calibration procedure developed by the PRMS model development team. This study calibrated 26 PRMS parameters. The PRMS calibrated input data (precipitation: rain_cbh_adj, snow_cbh_adj, and temperature: tmax_cbh_adj, tmin_cbh_adj). The automated calibration for the Spring Creek watershed extremely adjusted the parameter values to find the best match between observed and simulated flow. The study indicates that the DAYMET data does not represent the small watershed in the Black Hills very well. The calibration of PRMS for the Rapid Creek watershed used less time and effort than the Spring Creek watershed. In general, the PRMS model calibration time and effort decreases with increasing size of a watershed.

The HSPF output results are well managed using the WDM file and the users can get organized output data with graphs. The PRMS output needs extra time for formatting and plotting graphs because the output file is not well organized.

The users may find more difficulties to understand the PRMS parameters as compared to the HSPF parameters because the PRMS model is not as well documented as the HSPF model.

Sometimes users may find technical issues while installing the HSPF software. The PRMS users may struggle running the model if they move the dataset from one computer to another (relative path vs. absolute path location in the PRMS control file). If users use absolute path, then they need to specify the new location of model executable, input, and output files within the PRMS control file while they change PRMS file from one computer to other.

The HSPF model is more stable and has a longer history versus the PRMS model. The PRMS developer changed their parameters name and calibration techniques on a regular basis during this study period and the users may find difficulties dealing with such issues. The users may find difficulties starting with PRMS model at the present time because the PRMS developer have not officially launched the NHM data to the public yet.

5.29 Summary of Results, Discussions and Conclusions

One of the primary applications of this research is to help common end users to select the more appropriate hydrologic model, Hydrologic Simulation Program Fortran (HSPF) or Precipitation Runoff Modeling System (PRMS), when working with a specific size of watershed. The study was conducted to evaluate the influence of the temporal and spatial scale on the accuracy of rainfall runoff simulation model output. The study was conducted in the Rapid Creek watershed above Pactola Reservoir (294 square miles) and the Spring Creek watershed above Sheridan Lake (127 square miles). Both watersheds lie in the central Black Hills of western South Dakota.

The HSPF used extensive hourly time series data (precipitation, air temperature, potential evapotranspiration, wind speed, solar radiation, cloud cover, and dew point) from National Oceanic and Atmospheric Administration (NOAA) stations. The PRMS used minimum daily time series data (precipitation, minimum temperature, and maximum temperature) from DAYMET. The area weighted DAYMET data were retrieved from USGS geodata portal. Both models used U.S. Geological Survey (USGS) streamflow gage data during the model calibration and validation periods.

The HSPF used Arc GIS 10.0 and Arc Hydro 2.0 tools to define the watershed area utilizing National Hydrography Dataset Plus (NHDPlus) and National Hydrography Dataset (NHD). National Land Cover Dataset (2006) was used to characterize the watersheds in the HSPF. The HSPF used Theissen polygon method to define meteorological zones. The PRMS models were developed from a preliminary version of a national data set, referred to as the Geospatial Fabric for the National Hydrologic Model (NHM) being developed by the USGS. The NHM applies methods established in the GIS Weasel software to the NHDPlus data and necessary spatial data to describe the parameters for PRMS simulation.

The HSPF used the standard calibration approach, which includes 3 steps: calibrating first the annual water balance, then the monthly water balance and finally the specific rainfall runoff events. The PRMS utilized an automated procedure for calibration. The PRMS calibration was performed in six steps: 1) mean monthly solar radiation 2) mean monthly potential evapotranspiration 3) water balance configurations 4) daily flow components 5) daily high flow, and 6) daily low flow.

Separate calibration and validation periods were used for simulation of the Rapid Creek watershed. The HSPF better estimated the annual and daily water budget than the PRMS and the PRMS better estimated the monthly water budget than the HSPF for the calibration period. The HSPF better estimated all three of the water budgets (annual, monthly mean, and daily) than the PRMS for the validation period. Both models performed better in the calibration period as compared to the validation period.

The study recalibrated both models using a new calibration period of mostly dry years, a validation period of mostly wet years and ran supplemental simulations for the Rapid Creek watershed. The PRMS better estimated the three water budgets than the HSPF for the calibration and validation periods. The HSPF and PRMS simulations were influenced by the selection of calibration/validation period (e.g. wet vs. dry periods).

Results indicate that the HSPF better simulates the streamflow when the calibration period includes a wet period as compared to a dry period. The PRMS better simulates the streamflow when the calibration period includes a wet period as compared to a dry period.

A combined calibration and validation period was used for the simulation of the Spring Creek watershed. The HSPF better estimated the three water budgets than the PRMS for the entire simulation period.

The HSPF performance increased as the model output time step increased (e.g. from a daily interval to an annual interval). The PRMS estimated better flow for a monthly interval than an annual and a daily interval. The PRMS better estimated flow for a daily interval than an annual interval for the large watershed. The PRMS better estimated flow for a annual interval than a daily interval for the small watershed.

The HSPF performance for estimating all three of the water budgets (annual, monthly mean, and daily) improved as the watershed size decreased. The PRMS performance for estimating the annual water budget improved as the watershed size decreased. The PRMS performance for estimating the daily water budget reduced as the watershed size decreased. The PRMS performance for estimating the monthly water budget remained similar for different watershed size. The HSPF and PRMS performances were influenced by the temporal and spatial scale.

Results indicate that the HSPF better estimated annual, monthly, and daily water budget than the PRMS for a small watershed. The HSPF better estimated annual water budget than the PRMS for a large watershed. The PRMS better estimated monthly and daily water budget than the HSPF for a large watershed when wet and dry periods were calibrated individually.

The results indicate that the temporal and spatial scale variability influences the accuracy of HSPF and PRMS model simulations. The study also indicates that an appropriate selection of a model for a specific size of a watershed should be based on a specific hydrologic question that a user is seeking to answer.

5.30 Alternative Studies

The HSPF and PRMS models for the study areas were developed by focusing on common end users. The model results can be improved further by providing better meteorological data. For example, Schmitz (2011) improved the HSPF results for the Spring Creek watershed utilizing Next Generation Radar (NEXRAD) precipitation data over the historical rain gage station data in his MS thesis on “Scaling Issues in Watershed Modeling for Water Quality, MS Thesis”. The HSPF and PRMS model performances change with different calibration scenarios (wet vs. dry calibration periods). The modeling effort should continue in developing dynamic parameters to represent the change in physical characteristic of the watershed over the period of time. The parameter values differ for various calibration scenarios and changing one parameter may affect the other. The parameter correlation methods should be further explored to understand the better streamflow modeling.

6. References

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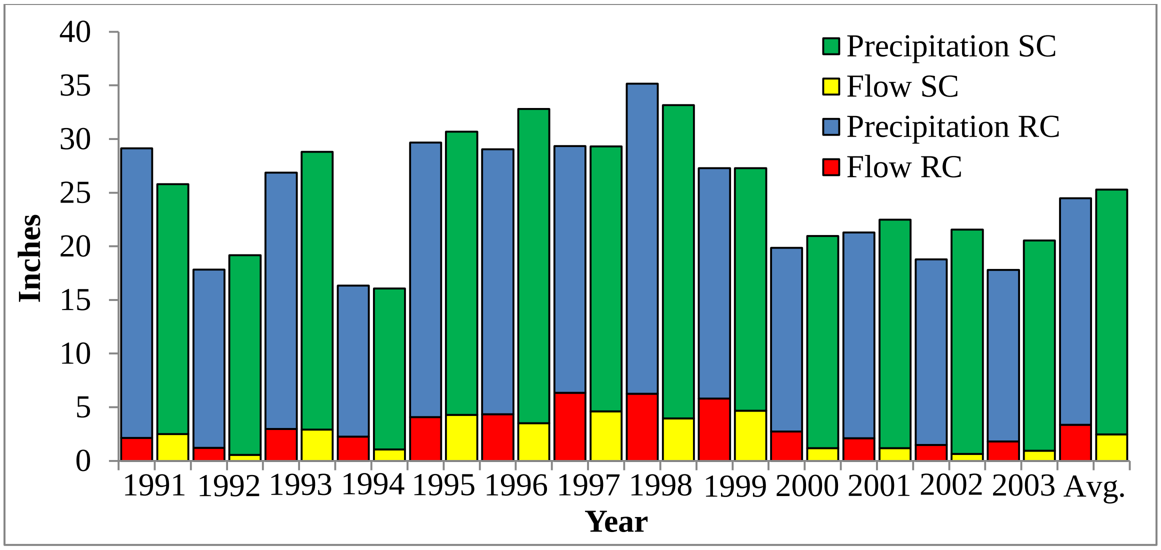
Appendix A

Year	Rapid Creek Watershed			Spring Creek Watershed		
	Streamflow (in/yr)	**Precipitation(in/yr)**	**Runoff Efficiency (%)**	**Streamflow (in/yr)**	**Precipitation(in/yr)**	**Runoff Efficiency (%)**
1991	2	27	8	2	23	11
1992	1	17	7	1	19	3
1993	3	24	12	3	26	11
1994	2	14	16	1	15	7
1995	4	26	16	4	26	16
1996	4	25	18	4	29	12
1997	6	23	28	5	25	19
1998	6	29	22	4	29	14
1999	6	22	27	5	23	21
2000	3	17	16	1	20	6
2001	2	19	11	1	21	6
2002	1	17	9	1	21	3
2003	2	16	11	1	20	5
Avg.	**3**	**21**	**15**	**2**	**23**	**10**



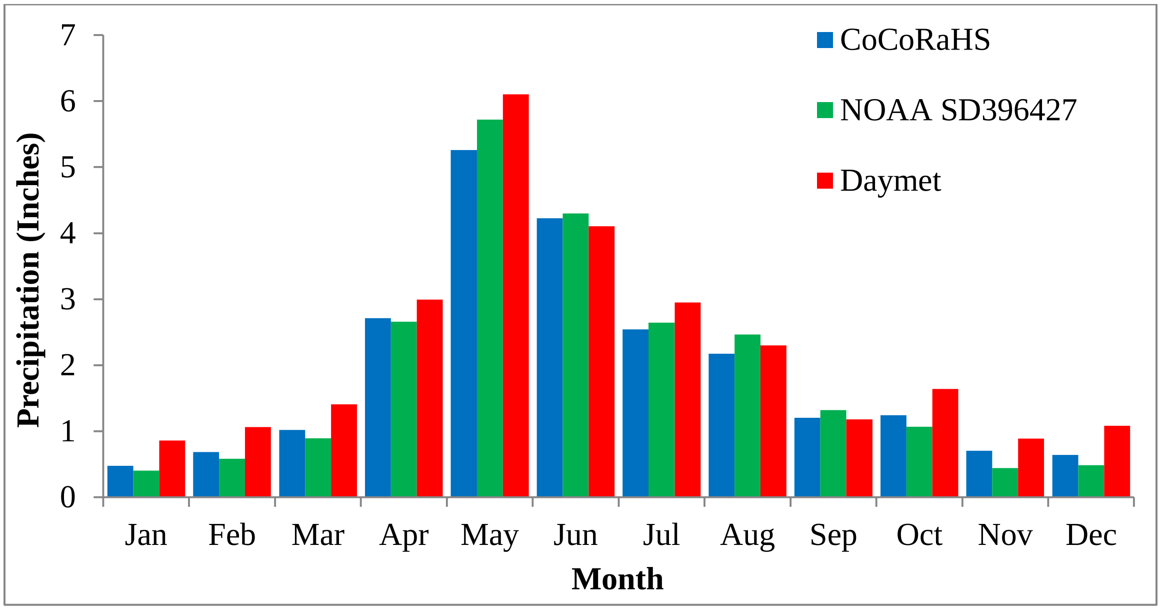
Note: SC – Spring Creek above Sheridan Lake, RC – Rapid Creek above Pactola Dam

Appendix B

Comparison of DAYMET, NOAA and CoCoRaHS Precipitation Data

Average Monthly Precipitation (Inches)					
Month	**CoCoRaHS**	**NOAA SD396427**	**DAYMET**	**% Error NOAA**	**% Error DAYMET**
Jan	0.47	0.40	0.86	-15.38	81.85
Feb	0.69	0.58	1.06	-15.13	54.83
Mar	1.02	0.89	1.41	-12.30	38.09
Apr	2.71	2.66	2.99	-1.97	10.26
May	5.26	5.72	6.10	8.80	16.06
Jun	4.23	4.30	4.10	1.68	-2.88
Jul	2.54	2.65	2.95	4.12	16.11
Aug	2.17	2.46	2.30	13.41	5.81
Sep	1.20	1.32	1.18	9.86	-2.12
Oct	1.24	1.07	1.64	-14.22	32.04
Nov	0.70	0.44	0.89	-37.14	26.20
Dec	0.64	0.48	1.08	-24.52	69.41
Sum	22.87	22.97	26.56	0.43	16.12

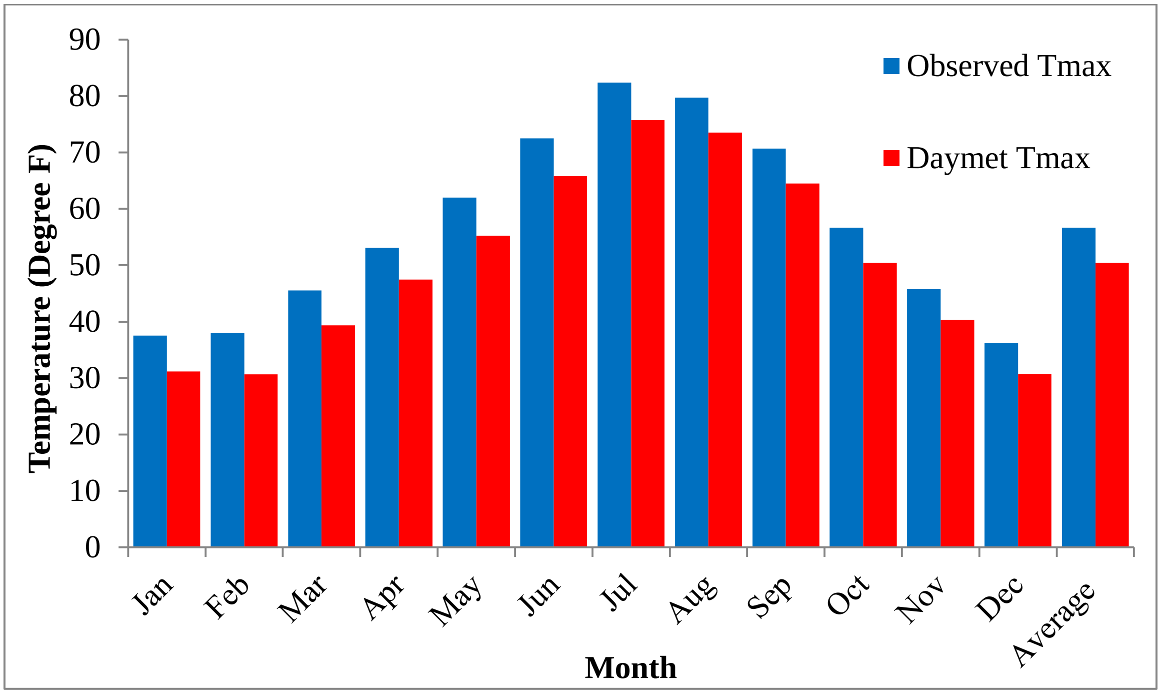
Note: Data from October 2007 to December 2011

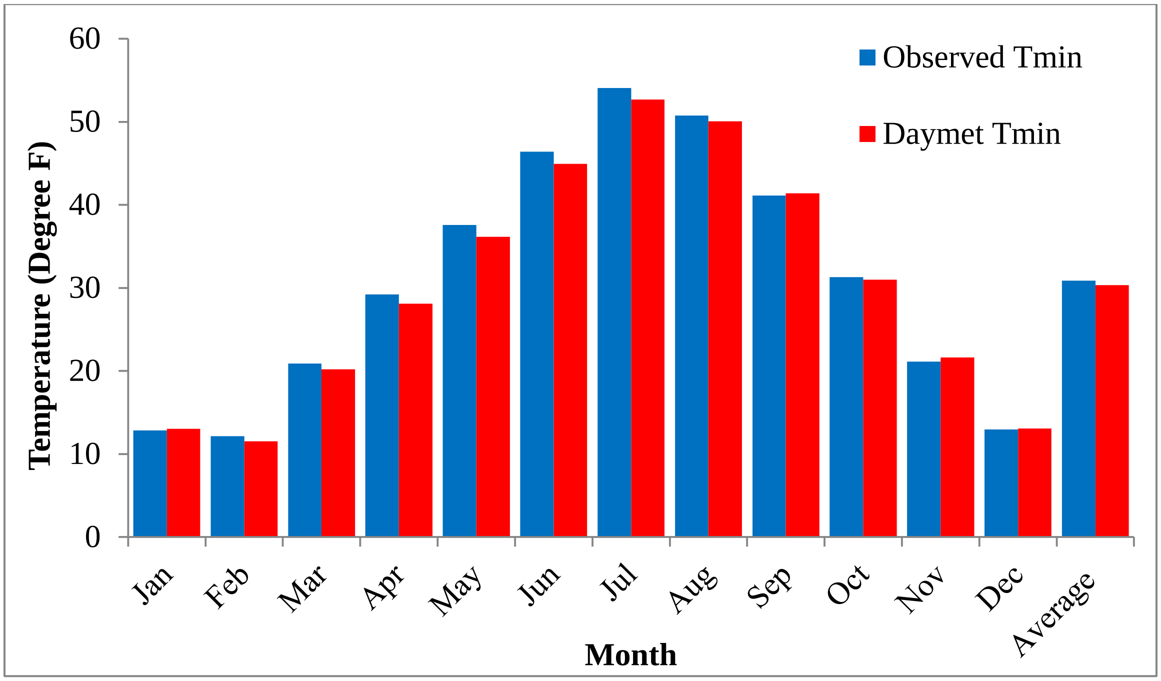


Comparison of DAYMET temperature and observed USGS gage temperature

Average Monthly Temperature (Degree Fahrenheit)						
Month	**Observed Tmax**	**DAYMET Tmax**	**% Error DAYMET Tmax**	**Observed Tmin**	**DAYMET Tmin**	**% Error DAYMET Tmin**
Jan	37.6	31.2	-17.0	12.8	13.0	1.7
Feb	38.0	30.6	-19.4	12.1	11.5	-5.0
Mar	45.5	39.3	-13.6	20.9	20.2	-3.3
Apr	53.1	47.4	-10.6	29.2	28.1	-3.9
May	62.0	55.2	-10.9	37.6	36.2	-3.7
Jun	72.5	65.8	-9.2	46.4	44.9	-3.1
Jul	82.4	75.7	-8.1	54.1	52.7	-2.6
Aug	79.7	73.5	-7.7	50.8	50.0	-1.4
Sep	70.7	64.5	-8.8	41.1	41.4	0.7
Oct	56.7	50.4	-11.0	31.3	31.0	-1.1
Nov	45.8	40.3	-11.9	21.1	21.6	2.5
Dec	36.2	30.7	-15.1	13.0	13.1	0.9
Average	56.7	50.4	-11.9	30.9	30.3	-1.5

Note: Data from October 2007 to December 2011 (Observed Temperature: USGS gage 06410500)




Temperature (Degree F)
60
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Average
Month
Observed Tmin
Daymet Tmin

Appendix C

HSPF Calibrated Parameters by Land Cover for the Rapid Creek Watershed						
Parameter	**Land Cover**	**Initial Estimate**	**HSPF Wet calibrated value**	**HSPF Dry calibrated value**	**HSPF Composite calibrated value**	**Range**
LZSN	Open Water	8.0	8.0	11.0	8.0	2.0-15.0
	Forest	8.0	8.0-15.0	11.5	8.0-15.0	
	Rangeland	7.0	7.0-15.0	10.1	7.0-15.0	
AGWRC	Open Water	0.990	0.990	0.997	0.990	0.85-0.999
	Forest	0.995	0.995-0.999	0.999	0.995-0.999	
	Rangeland	0.985	0.985-0.999	0.995	0.985-0.999	
LZETP	Open Water	0.75	0.75	0.64	0.75	0.1-0.9
	Forest	0.70	0.70	0.56	0.70	
	Rangeland	0.50	0.50	0.40	0.50	
INFILT	Open Water	0.350	0.350	0.350	0.455	0.001-0.5
	Forest	0.250	0.25-0.5	0.250	0.325-0.5	
	Rangeland	0.100	0.1-0.5	0.100	0.13-0.5	
INTFW	Open Water	3.0	3.0	2.8	3.3	1.0-10.0
	Forest	2.0	2.0	2.5	2.2	
	Rangeland	2.5	2.5	3.0	2.8	
IRC	Open Water	0.80	0.80	0.88	0.85	0.3-0.85
	Forest	0.60	0.60	0.66	0.85	
	Rangeland	0.70	0.70	0.77	0.85	
UZSN	Open	1.00	1.00	0.50	1.80	0.05-2.0

HSPF Calibrated Parameters by Land Cover for the Rapid Creek Watershed						
Parameter	**Land Cover**	**Initial Estimate**	**HSPF Wet calibrated value**	**HSPF Dry calibrated value**	**HSPF Composite calibrated value**	**Range**
	Water					
	Forest	1.00	1.00	0.50	1.80	
	Rangeland	1.00	1.00	0.50	1.80	
DEEPFR	Open Water	1.00	1.00	1.00	1.00	0.0-0.5
	Forest	0.20	0.20-0.35	0.10	0.20-0.35	
	Rangeland	0.20	0.20-0.35	0.10	0.20-0.35	
KVARY	Open Water	1.5	Not Calibrated		1.0	0.0-5.0
	Forest	1.5			1.0	
	Rangeland	1.0			1.0	
SNOWCF	ALL	1.15	1.00	1.15	1.00	1.0-2.0
CCFACT	ALL	0.30	0.50	0.30	3.00	0.5-8.0

HSPF Calibrated Parameters by Land Cover for the Spring Creek Watershed				
Parameter	**Land Cover**	**Initial Estimate**	**Calibrated Value**	**Possible Range**
LZSN	Open Water	8.5	6.2	2.0-15.0
	Forest	8.5	6.2	
	Rangeland	8.5	6.2	
	Urban	8.5	6.2	
	Barren	8.5	6.2	
AGWRC	Open Water	0.990-0.992	0.985-0.987	0.85-0.999
	Forest	0.990-0.992	0.975-0.985	
	Rangeland	0.980-0.985	0.980-0.987	
	Urban	0.980-0.985	0.975-0.980	
	Barren	0.980-0.985	0.975-0.985	

HSPF Calibrated Parameters by Land Cover for the Spring Creek Watershed				
Parameter	**Land Cover**	**Initial Estimate**	**Calibrated Value**	**Possible Range**
LZETP	Open Water	0.70	0.70	0.1-0.9
	Forest	0.75	0.75	
	Rangeland	0.55	0.55	
	Urban	0.50	0.50	
	Barren	0.35	0.35	
INFILT	Open Water	0.450	0.450	0.001-0.5
	Forest	0.350	0.350	
	Rangeland	0.1-0.450	0.1-0.450	
	Urban	0.1-0.2	0.1-0.2	
	Barren	0.1-0.450	0.1-0.450	
INTFW	Open Water	3.0-4.0	3.0-4.0	1.0-10.0
	Forest	3.0-4.5	3.0-4.5	
	Rangeland	3.0-3.5	3.0-3.5	
	Urban	2.5-3.5	2.5-3.5	
	Barren	2.0	2.0	
IRC	Open Water	0.7-0.75	0.7-0.75	0.3-0.85
	Forest	0.75	0.7-0.75	
	Rangeland	0.55	0.65	
	Urban	0.65	0.65	
	Barren	0.35	0.55	
UZSN	Open Water	0.7-0.95	0.7-0.95	0.05-2.0
	Forest	0.7-0.95	0.7-0.95	
	Rangeland	0.7-0.95	0.7-0.95	
	Urban	0.7-0.95	0.7-0.95	
	Barren	0.7-0.95	0.7-0.95	
DEEPFR	Open Water	1.00	1.00	0.0-0.5

HSPF Calibrated Parameters by Land Cover for the Spring Creek Watershed

Parameter	Land Cover	Initial Estimate	Calibrated Value	Possible Range
	Forest	0.15-0.25	0.15	
	Rangeland	0.25	0.10	
	Urban	0.05-0.1	0.05-0.1	
	Barren	0.10	0.50	
KAVARY	Open Water	0.5-1.0	Not Calib.	0.0-5.0
	Forest	0.5-1.0		
	Rangeland	0.0-0.5		
	Urban	0-0.5		
	Barren	0.5		
SNOWCF	ALL	1.15	1.15	1.0-2.0
CCFACT	ALL	0.30	0.30	0.5-8.0

HSPF Calibrated Parameters by Land Cover for the Spring Creek Watershed

Parameter	Land Cover	Initial Estimate	Calibrated Value	Possible Range
LZSN	Open Water	8.5	6.2	2.0-15.0
	Forest	8.5	6.2	
	Rangeland	8.5	6.2	
	Urban	8.5	6.2	
	Barren	8.5	6.2	
AGWRC	Open Water	0.990-0.992	0.985-0.987	0.85-0.999
	Forest	0.990-0.992	0.975-0.985	
	Rangeland	0.980-0.985	0.980-0.987	
	Urban	0.980-0.985	0.975-0.980	
	Barren	0.980-0.985	0.975-0.985	
LZETP	Open Water	0.70	0.70	0.1-0.9
	Forest	0.75	0.75	
	Rangeland	0.55	0.55	

HSPF Calibrated Parameters by Land Cover for the Spring Creek Watershed				
Parameter	**Land Cover**	**Initial Estimate**	**Calibrated Value**	**Possible Range**
	Urban	0.50	0.50	
	Barren	0.35	0.35	
INFILT	Open Water	0.450	0.450	0.001-0.5
	Forest	0.350	0.350	
	Rangeland	0.1-0.450	0.1-0.450	
	Urban	0.1-0.2	0.1-0.2	
	Barren	0.1-0.450	0.1-0.450	
INTFW	Open Water	3.0-4.0	3.0-4.0	1.0-10.0
	Forest	3.0-4.5	3.0-4.5	
	Rangeland	3.0-3.5	3.0-3.5	
	Urban	2.5-3.5	2.5-3.5	
	Barren	2.0	2.0	
IRC	Open Water	0.7-0.75	0.7-0.75	0.3-0.85
	Forest	0.75	0.7-0.75	
	Rangeland	0.55	0.65	
	Urban	0.65	0.65	
	Barren	0.35	0.55	
UZSN	Open Water	0.7-0.95	0.7-0.95	0.05-2.0
	Forest	0.7-0.95	0.7-0.95	
	Rangeland	0.7-0.95	0.7-0.95	
	Urban	0.7-0.95	0.7-0.95	
	Barren	0.7-0.95	0.7-0.95	
DEEPFR	Open Water	1.00	1.00	0.0-0.5
	Forest	0.15-0.25	0.15	
	Rangeland	0.25	0.10	
	Urban	0.05-0.1	0.05-0.1	
	Barren	0.10	0.50	

HSPF Calibrated Parameters by Land Cover for the Spring Creek Watershed

Parameter	Land Cover	Initial Estimate	Calibrated Value	Possible Range
KAVARY	Open Water	0.5-1.0	Not Calib.	0.0-5.0
	Forest	0.5-1.0		
	Rangeland	0.0-0.5		
	Urban	0-0.5		
	Barren	0.5		
SNOWCF	ALL	1.15	1.15	1.0-2.0
CCFACT	ALL	0.30	0.30	0.5-8.0

PRMS Calibrated Parameters for the Rapid Creek Watershed

Parameter name	Initial Estimate	PRMS Wet calibrated value	PRMS Dry calibrated value	Possible values	
				min	max
dday_intcp	-10.61- -32.16	-0.707- -25.851	-0.707- -25.851	-60	10
dday_slope	0.38-0.46	0.327-0.608	0.327-0.608	0.2	0.9
jh_coef	0.014	0.006-0.024	0.006-0.024	0.005	0.09
rain_cbh_adj	1	1.147	0.501	0.6	1.4
snow_cbh_adj	1	1.493	1.073	0.6	1.4
adjmix_rain	1	0.939	1.131	0.6	1.4
cecn_coef	5		7.036	2	10
emis_noppt	0.757	0.844	0.961	0.757	1
free2ho_cap	0.05	0.013	0.011	0.01	0.2
potet_sublim	0.5	0.682	0.662	0.1	0.75
slow_coef_lin	0.005	0.002	0.296	0.001	0.5
soil_moist_max	2.72-4.08	6.043-7.713	8.092-9.952	1	10
soil_rechr_max	1.89-2.47	3.581-4.24	1.512-2.08	0.25	5
tmax_allrain	32	33.966	36.201	30	40
tmax_allsnow	32	39.437	30.496	30	40
tmax_cbh_adj	0	5.427-7.361	-3.525	-5	5
tmin_cbh_adj	0	-0.122-1.456	-3.24	-5	5
fast_coef_lin	0.01	0.022	0.029	0.001	0.8
pref_flow_den	0	0.1	0.1	0	0.1

PRMS Calibrated Parameters for the Rapid Creek Watershed

Parameter name	Initial Estimate	PRMS Wet calibrated value	PRMS Dry calibrated value	Possible values	
				min	max
sat_thresold	10	5.988	8.283	1	15
smidx_coef	0.01	0.001	0.004	0.001	0.06
gwflow_coef	0.005	0.019	0.499	0.001	0.5
soil2gw_max	0.1	0	0.301	0	0.5
ssr2gw_rate	0.301-0.305	0.05-0.084	0.523-0.557	0.05	0.8
slowcoef_sq	0.1	0	0.032	0	1
fastcoef_sq	0.8	0.059	0	0	1

PRMS Calibrated Parameters for the Spring Creek Watershed

Parameter name	Initial Estimate	Calibrated value	Possible values	
			min	max
dday_intcp	-7.06- -34.23	-30.183-0.06	-60	10
dday_slope	0.29-0.464	0.246-0.46	0.2	0.9
jh_coef	0.014	0.001-0.019	0.005	0.09
rain_cbh_adj	1	1.059-1.209	0.6	1.4
snow_cbh_adj	1	1.062	0.6	1.4
adjmix_rain	1	0.612	0.6	1.4
cecn_coef	5	2.637	2	10
emis_noppt	0.757	0.863	0.757	1
free2ho_cap	0.05	0.017	0.01	0.2
potet_sublim	0.5	0.322	0.1	0.75
slow_coef_lin	0.005	0.022	0.001	0.5
soil_moist_max	2.72-4.08	9.263-9.721	1	10
soil_rechr_max	1.776-2.416	3.74-3.97	0.25	5
tmax_allrain	32	49.95	30	40
tmax_allsnow	32	39.084	30	40
tmax_cbh_adj	0	Not Calib.	-5	5
tmin_cbh_adj	0	Not Calib.	-5	5
fast_coef_lin	0.01	0.002	0.001	0.8
pref_flow_den	0	0.045	0	0.1
sat_thresold	100	83.616	1	15
smidx_coef	0.01	0.001	0.001	0.06
gwflow_coef	0.005	0.303	0.001	0.5
soil2gw_max	0.1	0.161	0	0.5

PRMS Calibrated Parameters for the Spring Creek Watershed				
Parameter name	**Initial Estimate**	**Calibrated value**	**Possible values**	
			min	**max**
ssr2gw_rate	0.301-0.305	0.756	0.05	0.8
slowcoef_sq	0.1	0.05	0	1
fastcoef_sq	0.8	0.054	0	1

Appendix D (CD-ROM)

The appendix D folder on the CD-ROM contains the following input and output HSPF and PRMS files for the Rapid Creek and Spring Creek watersheds.

HSPF Model:

Appendix D\Rapid Creek Watershed

HSPF_Wet_Model: Contains input and output files for HSPF model for the Rapid Creek watershed, calibrated with mostly wet years (scenario 1)

HSPF_Dry_Model: Contains input and output files for HSPF model for the Rapid Creek watershed, calibrated with mostly dry years (scenario 2)

HSPF_Composite_Model: Contains input and output files for HSPF Composite model for the Rapid Creek watershed, calibrated for entire simulation period

Appendix D\Spring Creek Watershed\HSPF: Contains input and output files for HSPF model for the Spring Creek watershed

The following describes the file extensions.

.uci HSPF executable UCI file.

.wdm Watershed Data Management file containing the input and output time series.

.out Text file containing the output state variables for different time steps

.ech Echo file used for troubleshooting the model execution.

rch.hbn Binary file containing same reach outputs as .out

wshd.hbn Binary file containing same watershed outputs as .out

baseline.uci HSPF executable UCI file (before calibration).

PRMS Model:

Appendix D\Rapid Creek Watershed

PRMS_Wet_Model: Contains input, output, and control files under respective folder name for PRMS model for the Rapid Creek watershed, calibrated with mostly wet years (scenario 1)

PRMS_Dry_Model: Contains input, output, and control files under same folder name for PRMS model for the Rapid Creek watershed, calibrated with mostly dry years (scenario 2)

Appendix D\Spring Creek Watershed\PRMS: Contains input, output, and control files under respective folder name for PRMS model for the Spring Creek watershed

The following describes the file extensions under input folders:

.wpar PRMS executable input parameter file

gage_data.prms PRMS flow data for calibration

precip.prms PRMS input precipitation file

tmax.prms PRMS input maximum temperature

tmin.prms PRMS input minimum temperature

SR Monthly Solar Radiation data for calibration of SR

PE Monthly Solar Radiation data for calibration of PE

Subdivide High flow and low flow data (disaggregation of gage_data.prms) for calibration of water balance

baseline.wpar PRMS executable input parameter file (before calibration)

The following describes the file extensions under output folders:

.statvar Text file containing output of the model in daily time step

.txt text file containing surface water and energy budgets

The following describes the file extensions under control folders:

.control Text file containing control parameters related to model input, output, and initial condition

Note: The PRMS Composite model for Rapid Creek watershed was developed by combining the simulation results of PRMS Wet (scenario 1) and PRMS Dry (scenario 2) Models.

Both HSPF and PRMS models developed for this study are archived in the USGS South Dakota Water Science Center, Rapid City, SD.

Vita

Dol Raj Chalise was born on December 27, 1986, in Chitwan, Nepal. He graduated from Amrit Science Campus in July 2004. Dol Raj received the Nepal Aid Fund scholarship from the government of India for pursuing a bachelor’s degree at the National Institute of Technology Tiruchirappalli in India. He earned a Bachelor of Technology Degree in Civil Engineering in August 2009, with honor. He was a member of the National Sports Organization of India and Isha Yoga community.

Dol Raj started his professional career as a design engineer in November 2009 in Hydro Solutions Pvt. Ltd., Nepal. He became a project manager in July 2011 in Energy Engineering Pvt. Ltd., Nepal. He left his position in July 2012 to attend graduate school in Rapid City, South Dakota, USA. Dol Raj started working for the South Dakota School of Mines and Technology as a teaching and research assistant in August 2012. He received an opportunity to work with U.S. Geological Survey (USGS) South Dakota Water Science Center as a Cooperative Ecosystem Studies Unit (CESU) student in August 2012. He worked as a teaching and research assistant until December 2013. Dol Raj is a member of the Nepal Engineering Council (NEC) and the American Society of Civil Engineers (ASCE).