Technical Note

Comparison of *HSPF* and *PRMS* Model Simulated Flows Using Different Temporal and Spatial Scales in the Black Hills, South Dakota

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Abstract: The hydrological simulation program Fortran (*HSPF*) [*Hydrological Simulation Program Fortran version 12.2* (Computer software). USEPA, Washington, DC] and the precipitation runoff modeling system (*PRMS*) [*Precipitation Runoff Modeling System version 4.0* (Computer software). USGS, Reston, VA] models are semidistributed, deterministic hydrological tools for simulating the impacts of precipitation, land use, and climate on basin hydrology and streamflow. Both models have been applied independently to many watersheds across the United States. This paper reports the statistical results assessing various temporal (daily, monthly, and annual) and spatial (small versus large watershed) scale biases in *HSPF* and *PRMS* simulations using two watersheds in the Black Hills, South Dakota. The Nash-Sutcliffe efficiency (NSE), Pearson correlation coefficient (r), and coefficient of determination (R^2) statistics for the daily, monthly, and annual flows were used to evaluate the models' performance. Results from the *HSPF* models showed that the *HSPF* consistently simulated the annual flows for both large and small basins better than the monthly and daily flows, and the simulated flows for the small watershed better than flows for the large watershed. In comparison, the *PRMS* model results show that the *PRMS* simulated the monthly flows for both the large and small watersheds better than the daily and annual flows, and the range of statistical error in the *PRMS* models was greater than that in the *HSPF* models. Moreover, it can be concluded that the statistical error in the *HSPF* and the *PRMS* daily, monthly, and annual flow estimates for watersheds in the Black Hills was influenced by both temporal and spatial scale variability. **DOI: 10.1061/(ASCE)HE.1943-5584.0001596.**

Description of Study Area

The study areas consisted of two watersheds: (1) the Rapid Creek watershed upstream of Pactola Reservoir, South Dakota, a large watershed for the Black Hills with a drainage area of 759 km^2; and (2) the Spring Creek watershed upstream of Sheridan Lake, South Dakota, a small watershed with a drainage area of 326 km^2 (Fig. 1) (USGS National Water Information System 2013). Both watersheds are covered primarily by a heavy forest of ponderosa pine, with approximately 10% of the basin used as rangeland (Homer et al. 2012; National Land Cover Database 2006). The forested areas include a layer of duff (partially decayed vegetation and other organic matter) on the forest floor.

The presence and thickness of the duff layer can significantly affect the runoff in the forest areas of the Black Hills (Chalise 2013). Both watersheds experience high runoff rates and amounts, or flashy flows, due to the fine-grained soils underlain by fractured rock. Similarities in land cover, land use, soils, and geology may contribute to the similarity in runoff characteristics for the two watersheds (Table 1). The study areas lie in a continental semiarid climate, with extreme variability of the precipitation and temperature. Hot summers and cold winters are common. The majority of rainfall occurs from April through August in the form of high-intensity thunderstorms. The snowpack generally develops from December to March, and the majority of the snowmelt occurs in May. The snowmelt runoff and groundwater recharge contribute to the flows in Rapid Creek and Spring Creek. The average annual potential evaporation generally exceeds the average annual precipitation in the study areas. The average pan evaporation or free water surface evaporation for April through October is approximately 30 in., measured at Pactola Reservoir (Driscoll et al. 2002).

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Models and Input Data

The *HSPF* and *PRMS* models for this study were constructed on the basis of the standard guidelines provided by the developer of each model (Bicknell et al. 2005; Markstrom et al. 2015). The *HSPF* user manual (Bicknell et al. 2005) and *PRMS* user manuals (Leavesley et al. 1983; Markstrom et al. 2015) provided detailed information about each model and the approach to calibration. For this investigation, the *HSPF* simulations used an hourly time step and the *PRMS* simulations used a daily time step.

The input data used to drive the *HSPF* model streamflow simulations were the precipitation, potential evapotranspiration, air temperature, solar radiation, wind, cloud cover, and dew point temperature. These data were downloaded from the U.S. Environmental Protection Agency (EPA) Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) meteorological database for January 1, 1990 to December 31, 2008 (Table 2) (USEPA 2015). The watershed data management (WDM) files, which are the time series input data files for the *HSPF*, were created for Rapid Creek (January 1, 1990 to December 31, 2008) and for Spring Creek (January 1, 1991 to December 31, 2003) using the BASINS

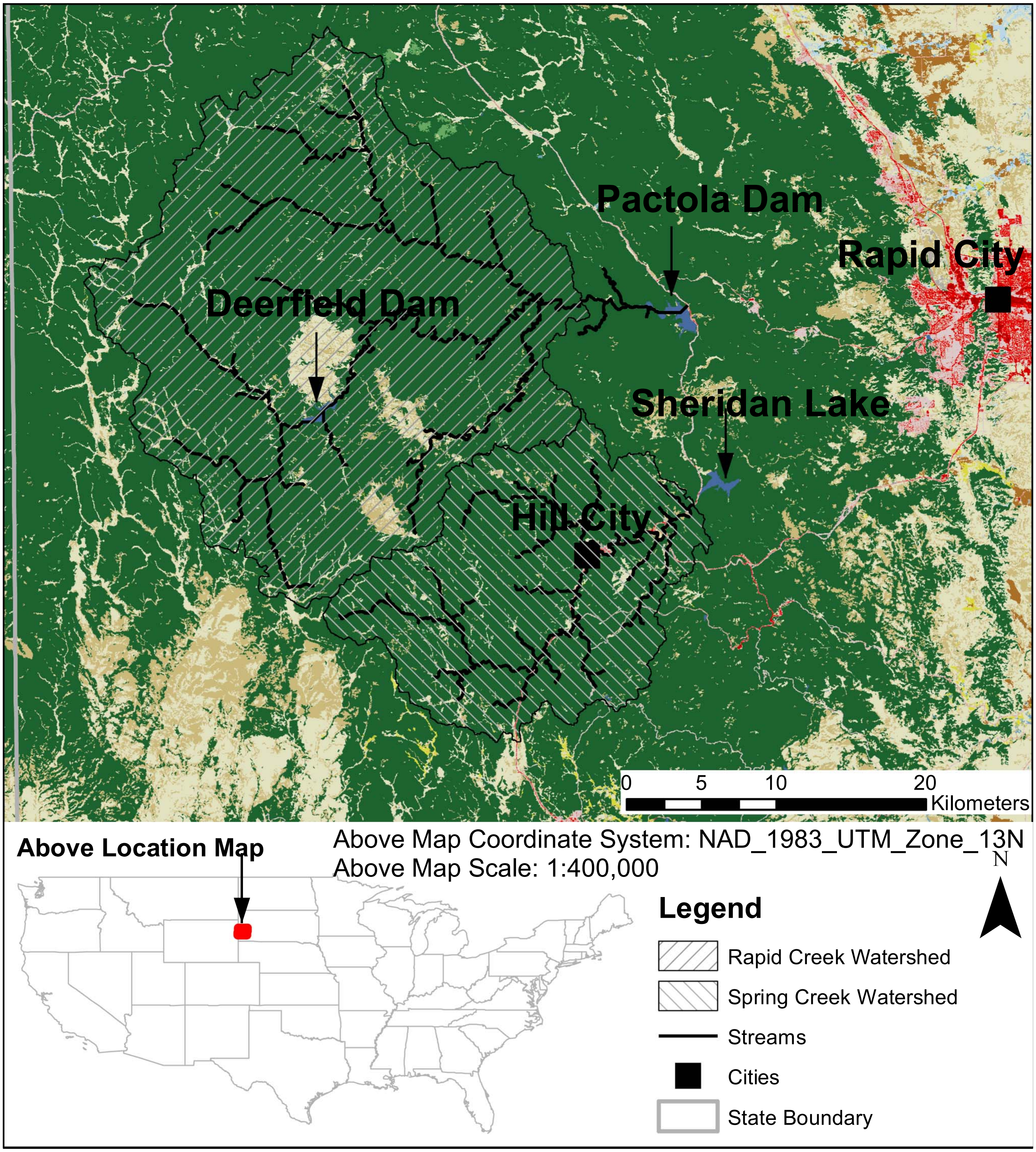

Fig. 1. Study area

system (Table 2). The discrepancy in the time series start and end dates for the two basins was due to data availability.

The *PRMS* simulations of the streamflow were driven by the 1-km-gridded daily surface weather data (Daymet) for the precipitation, minimum temperature, and maximum temperature (Daymet 2012; Thornton et al. 1997). The gridded Daymet data for each basin were averaged (area weighted) and retrieved using the USGS geodata portal from January 1, 1990 to December 31, 2008 for the Rapid Creek watershed and from January 1, 1991 to December 31, 2003 for the Spring Creek watershed (USGS Center for Integrated Data Analytics 2013).

Watershed Delineation and Characterization

For the *HSPF*, the *ArcGIS* and *Arc Hydro* tools were used to define the watershed areas. *Arc Hydro* requires a digital elevation model (DEM) raster file and a shapefile containing the stream segments to

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Table 1. Runoff Characteristic in Rapid Creek and Spring Creek Watersheds (Data from Chalise 2013)

	Rapid Creek watershed			Spring Creek watershed		
Year	Streamflow (in./year)	Precipitation (in./year)	Runoff efficiency (%)	Streamflow (in./year)	Precipitation (in./year)	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
Average	3	21	15	2	23	10

Table 2. National Oceanic and Atmospheric Administration Meteorological Stations Located in the Study Areas (Data from NCDC 2013)

Station identifier	Station name	Hourly data	Use
SD 396427	Pactola Dam	Precipitation	Rapid creek watershed
SD 396427	Pactola Dam	Air temperature	Rapid creek watershed
SD 396427	Pactola Dam	Potential ET	Both watersheds
SD 396937	Rapid City RAP	Wind speed	Both watersheds
SD 396937	Rapid City RAP	Solar radiation	Both watersheds
SD 396937	Rapid City RAP	Cloud cover	Both watersheds
SD 396937	Rapid City RAP	Dew point	Both watersheds
SD 393868	Hill City	Precipitation	Spring creek watershed
SD 392087	Custer	Precipitation	Spring creek watershed
SD 392088	Custer	Air temperature	Spring creek watershed

Note: ET = evapotranspiration; RAP = Rapid City Airport; SD = South Dakota.

designate a watershed. The DEM was obtained from the National Hydrography Dataset Plus (NHDPlus) for the Upper Missouri drainage basin (drainage area: MS, vector unit: 10U, and raster processing unit: 10f) (Horizon Systems Corporation 2013). The stream segments shapefile was acquired from the National Hydrography Dataset (NHD) through the National Map Viewer (USGS 2013). The location of the streamflow-gauging station (gauge) at the outlet was used to assign the watershed boundary during the *Arc Hydro* processing. The subbasins were defined using available the USGS gauges (Fig. 2). A single climate station (SD 396427) was used to distribute the precipitation data for the Rapid Creek watershed. Two climate stations (SD 393868 and SD 392087) were used to distribute the precipitation data for the Spring Creek watershed by developing a meteorological zone using the Thiessen polygon method (Singh 1992) (Fig. 3). The Rapid Creek watershed was characterized with 3 land use categories and 4 hydrozones (subbasins), producing 9 pervious land segments (PERLNDs). In the *HSPF*, a PERLND is defined as an area with similar hydrologic characteristics. 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 the watershed characterization of the Rapid Creek and Spring Creek watersheds.

In the *PRMS*, a watershed is discretized into a network of land surfaces, referred to as the hydrologic response units (HRUs). The *PRMS* models for the Rapid Creek and Spring Creek watersheds were created from a preliminary version of a national data set, referred to as the Geospatial Fabric for the National Hydrologic Model (NHM) (Viger and Bock 2014). The NHM aggregates the catchment and flowlines defined in the NHDPlus data set into HRUs and stream segments (Viger and Bock 2014; Haj et al. 2014). The NHM applies the methods established in the *GIS Weasel* user's manual to these features and necessary spatial data to describe the parameters for the *PRMS* simulation (Viger and Leavesley 2007). The USGS gauge 06410500 at Rapid Creek above Pactola Dam, South Dakota, for the Rapid Creek watershed, and the USGS gauge 06406920 at Spring Creek above Sheridan Lake, South Dakota, for the Spring Creek watershed were used as points of interest (POIs) to obtain the model parameters. Eighteen HRUs were used for the simulation of the Rapid Creek watershed (Fig. 4). Ten HRUs were used for the simulation of the Spring Creek watershed (Fig. 5).

Input Files

The *HSPF* input files consist of a user control interface (UCI) file and a time series WDM file. The WDM file for the Rapid Creek watershed (except the gauge at Deerfield Dam, South Dakota) and the Spring Creek watershed were created using the *BASINS* system (USEPA 2015). The Deerfield Dam outlet flow data (DFR SD) were later appended to the existing WDM file of the Rapid Creek watershed (U.S. Bureau of Reclamation 2013). For this investigation, the UCI file was prepared manually, and *ArcGIS* and BASINS Technical Note 6 (USEPA 2000) were used to compute the parameter values for each PERLND and its stream segments (the RCHRES module). The hydrologic engineering center river analysis system (*HEC-RAS*) was applied to create parameter values in the function tables (FTABLES) (USACE 2016). The cross-section data from the DEM (Castle Creek above Deerfield Dam, and Rapid Creek near Rochford) and the field survey data (Rapid Creek near Silver City) were used as input for *HEC-RAS*.

The *PRMS* input files consisted of a control, the data, and the parameter files (Markstrom et al. 2008, 2015). The selected modules in the control file used in the simulations were ddsolrad_hru_mo, muskingum, transp_tindex, potet_jh_hru_mo_ws, srunoff_smidx, soilzone, and climate_hru_mo. The data file information are provided in the preceding section, Models and Input Data. The parameter files were extracted from the initial version of a national data set called the Geospatial Fabric (Viger 2014).

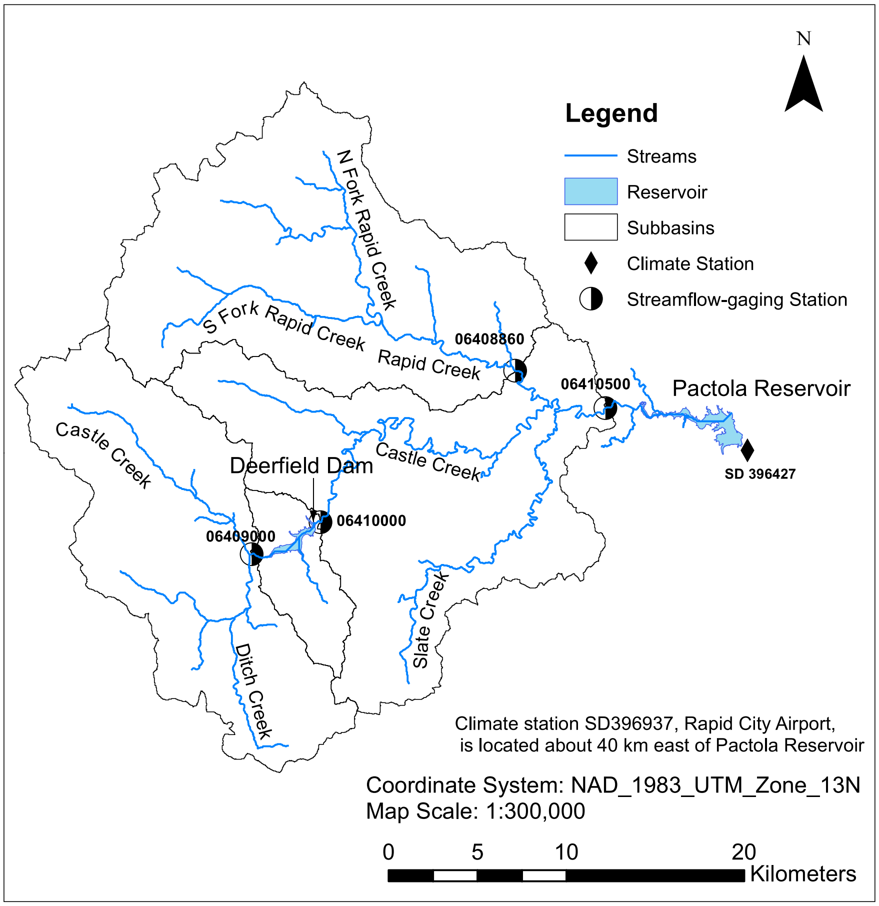

Fig. 2. Characterization of Rapid Creek watershed for *HSPF*

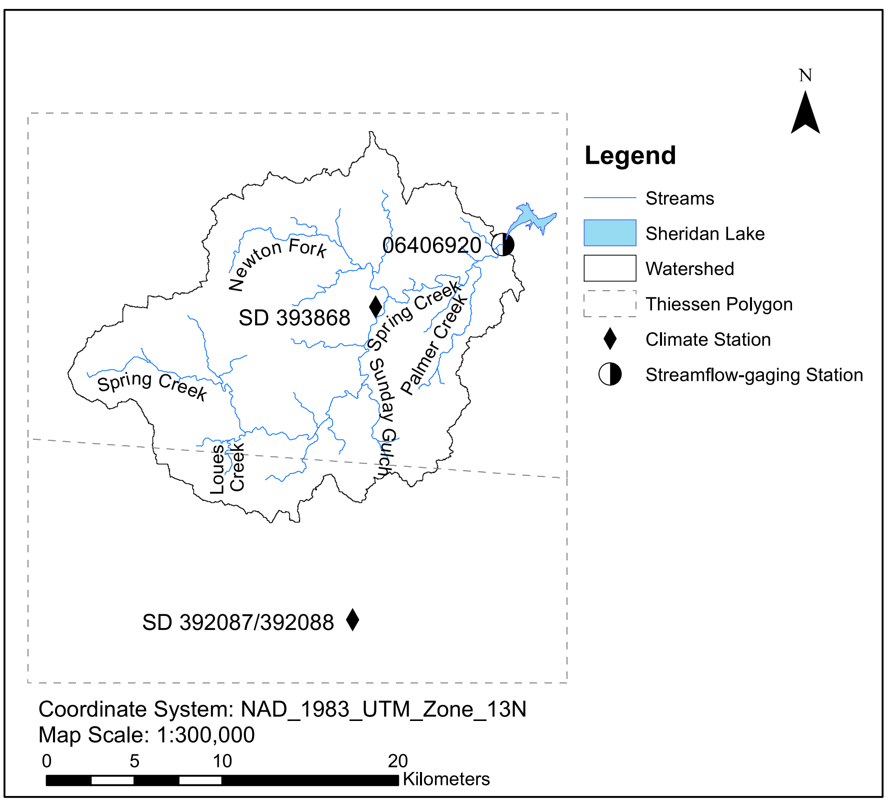

Fig. 3. Characterization of the Spring Creek watershed for *HSPF*

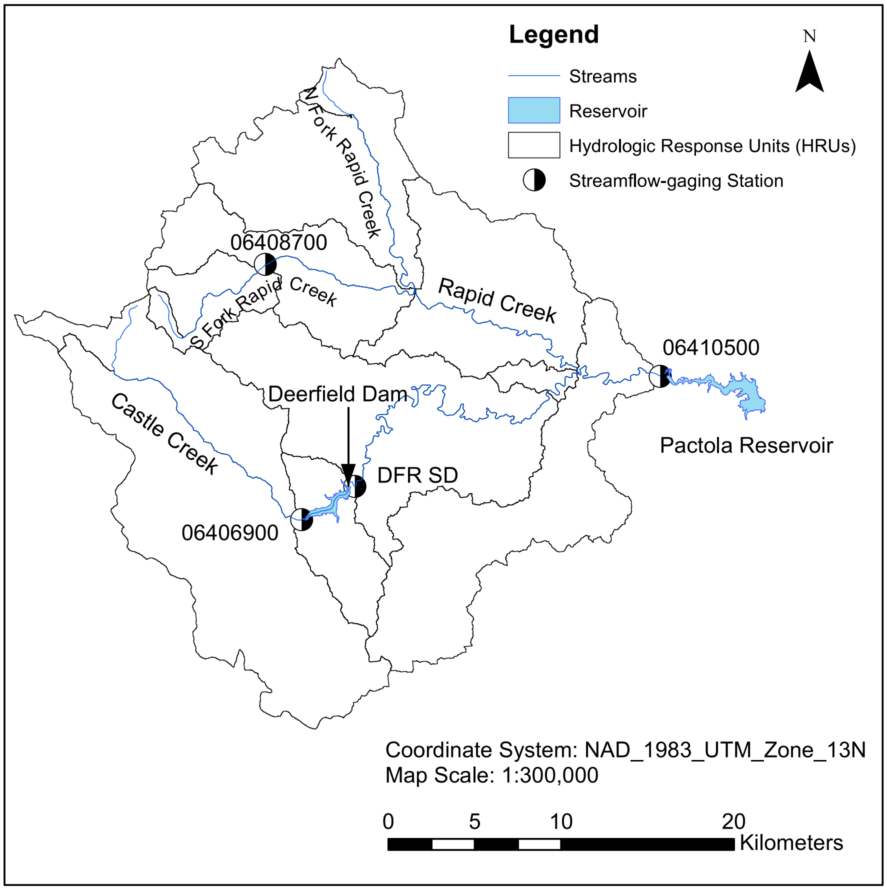

Fig. 4. Characterization of the Rapid Creek watershed for *PRMS*

Model Calibration, Validation, and Evaluation

Both models used the standard calibration approaches given in the user manuals. The manual approach, as described in Bicknell et al. (2005), was used for the *HSPF* model calibration. The Let Us Calibrate (*LUCA*) tool, an automatic approach, was used for the *PRMS* model calibration (Hay and Umemoto 2006). The daily streamflow obtained from the USGS National Water Information System (USGS National Water Information System 2013; U.S. Bureau of Reclamation 2013) (Table 3) was used for the model calibration and validation.

For the Rapid Creek watershed, the *HSPF* and *PRMS* models were used to simulate the flow from 1990 to 2008. The first 2 years of record (1990–91) were assigned for the initial model period. The next 11 years of record (1992–2002) were used for the calibration, and the remaining 6 years of record (2003–2008) were used for the validation period. Both the calibration and the validation period results were used to evaluate the models' performance.

For the Spring Creek watershed, both the *HSPF* and the *PRMS* models were simulated from 1991 to 2003. The first 2 years of records (1991–92) were assigned for the initial model period. The remaining 11 years of record (1993–2003) were used as a calibration period. There was no separate validation period in the Spring Creek watershed due to the lack of available data; the model calibration period results were used to evaluate the model performance.

The model performance was measured by comparing the simulated flows at the gauge locations to the measured streamflow. The Nash-Sutcliffe efficiency (NSE), the Pearson correlation coefficient (r), and the coefficient of determination (R^2) statistics were used to evaluate the performance of the models (Moriasi et al. 2007).

Results

Statistical results showed that both the *HSPF* and the *PRMS* were influenced by temporal and spatial scale variability. Performance results from the *HSPF* models for the Rapid Creek watershed, which is a large watershed, and the Spring Creek watershed, which is a small watershed, showed that overall the *HSPF* simulated flows rather well for both the basins at most temporal scales. The simulated annual flow was more accurate than the monthly and daily flows for both watersheds, with the lowest performance in the simulations of daily flows (Table 4). In addition, the *HSPF* consistently performed better for simulating the daily, monthly, and annual flows for the small watershed, as compared with the large watershed.

The performance results from the *PRMS* models for the Rapid Creek and Spring Creek watersheds show that the simulated monthly streamflows were more accurate than the daily and annual flows for both watersheds (Table 5). The accuracy of the simulated annual flow was higher than that of the daily flow for Spring Creek, the small watershed. However, the accuracy of the simulated annual flow was lower than that of the daily flow for Rapid Creek, the large watershed. The *PRMS* performance for estimating the daily and annual flows for both watersheds was variable.

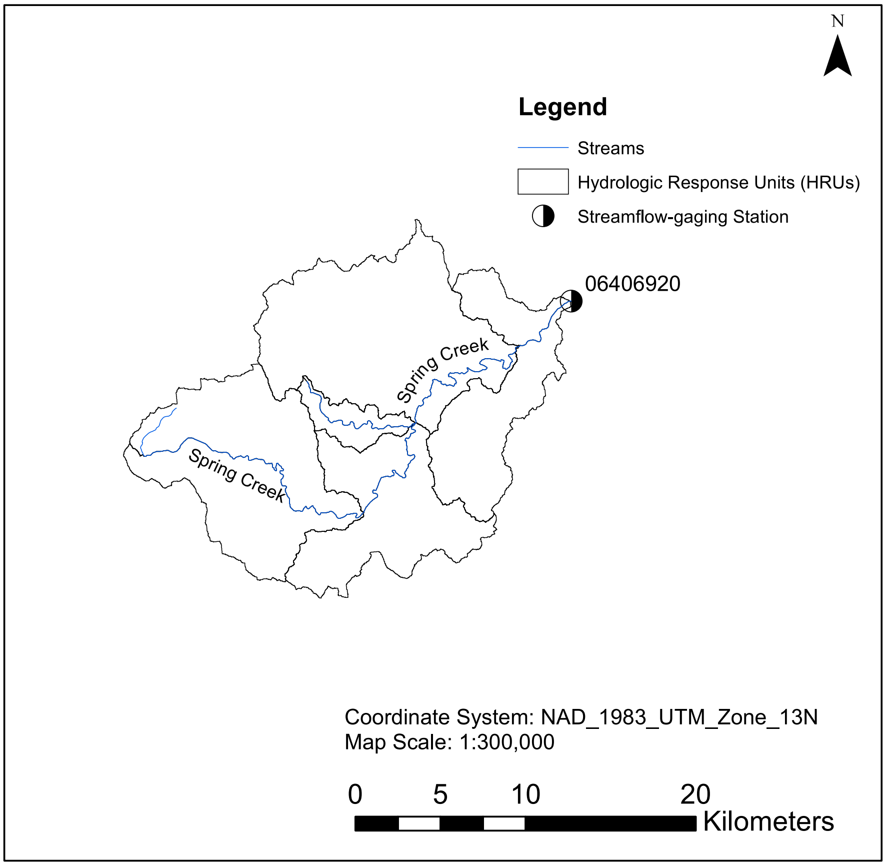

Fig. 5. Characterization of the Spring Creek watershed for *PRMS*

Table 3. Daily Flow Gauge Station Located in the Study Areas

Station identifier	Station name	Use
06409000	Castle Creek above Deerfield Dam, South Dakota	Rapid Creek watershed
DFR SD	Deerfield Dam, South Dakota	
06408860	Rochford, South Dakota	
06410500	Rapid Creek above Pactola Dam, South Dakota	
06406920	Spring Creek above Sheridan Lake, South Dakota	Spring Creek watershed

Table 4. Hydrological Simulation Program Fortran (*HSPF*) Statistical Measure Using Temporal and Spatial Scale

Temporal scale	Rapid Creek watershed			Spring Creek watershed		
	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, and for the Spring Creek 1993–2003. NSE = Nash-Sutcliffe efficiency; r = Pearson correlation coefficient; R^2 = coefficient of determination.

Discussion and Conclusions

Both the *HSPF* and the *PRMS* models had lower performance when simulating flows at daily time scales. The precipitation events in the Black Hills occur daily as intense and geographically limited thunderstorms. These localized storms are often not recorded by a climate station network, due to the spacing of climate stations. When a thunderstorm event was captured by a climate station, the extent of the event was overestimated by the *HSPF*'s rainfall distribution methods, resulting in an overestimation of rainfall for the event. Although the version of *PRMS* in this study used the Daymet precipitation data as input, those data were also derived from the climate stations and may have reflected a similar bias. The lower performance of the models with a larger spatial scale may have resulted from the increased number of events, which were either not recorded or were overestimated, in a larger basin area. This bias may be lessened at the longer time scales (monthly and annual), as the unrecorded and overestimated events balance in the water budget over longer intervals of time. Overall, the *HSPF* models outperformed the *PRMS* models, albeit slightly, for nearly all the temporal scales (Tables 4 and 5). This difference in performance may be due to the HSPF models' use of an hourly time step, as compared with the use of a daily time step in the *PRMS*. The smaller time step of the *HSPF* model may better capture, calibrate to, and simulate the flows of these flashy systems.

Table 5. Precipitation-Runoff Modeling System (*PRMS*) Statistical Measure Using Temporal and Spatial Scale

Temporal scale	Rapid Creek watershed			Spring Creek watershed		
	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, and for the Spring Creek 1993–2003. NSE = Nash Sutcliffe efficiency; r = Pearson correlation coefficient; R^2 = coefficient of determination.

Future Research Direction

Due to the limited number of watersheds in the Black Hills region, the two selected basins (Spring Creek: 326 km^2, and Rapid Creek: 759 km^2) represent the largest watershed and a small gauged watershed with similar runoff characteristics. In future investigations, the model performances could be further evaluated using multiple watersheds with significantly different runoff characteristics. For this investigation, both the *HSPF* and the *PRMS* models used precipitation data derived either from the historical climate station data or from Daymet. The authors suggest that for the Black Hills area, model simulations using high-resolution meteorological data, such as the Next Generation Radar (NEXRAD) precipitation data, could yield better performance results (Kitzmiller et al. 2013). Additionally, both the *HSPF* and the *PRMS* model performance could be evaluated for different climate scenarios (wet versus dry calibration periods) and changes in physical characteristics of the watersheds over time, (land-use change or land-cover change from the effects of pine beetle infestation and/or from fire).

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