THESIS

ASSESSING FLOW ALTERATION AND CHANNEL ENLARGEMENT DUE TO DAM MANAGEMENT AT HOG PARK CREEK, WYOMING

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2016

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ABSTRACT

ASSESSING FLOW ALTERATION AND CHANNEL ENLARGEMENT DUE TO DAM MANAGEMENT AT HOG PARK CREEK, WYOMING

As part of a complex water exchange agreement, Little Snake River water is piped through the Continental Divide and released into Hog Park Creek to replace over-appropriated North Platte River piped to Cheyenne, Wyoming. The Little Snake River water, in addition to native flows, has used Hog Park Creek as a conduit since the 1960s. As a result, Hog Park Creek has continued to enlarge. This study assesses flow alterations and channel enlargement at Hog Park Creek due to dam management.

To assess flow alterations at Hog Park Creek without a pre-dam daily flow record, the Precipitation-Runoff Modeling System (PRMS) simulated natural flows from 1995 to 2015. A regionalization technique transferred calibrated parameters to Hog Park Creek model parameterization from Encampment River model parameterization. Along with the simulated natural flows, reference flows were used to compare to the post-dam flow record. All comparisons indicate the greatest flow alterations were winter and spring monthly flows and low flows. The April median flows and 7-day low flows more than tripled. To a lesser degree of deviation, significant flow alterations included peak flow alterations such as greater magnitude, longer duration, increased frequency, earlier peak flow timing, and faster fall rates.

In addition, flow alterations due to climate were assessed. The climate trends reflect warmer-wetter climate change with a shift to earlier peak flows. However, these flow alterations are minor compared to those by dam management. The climate projections compared historic (1980-

1999) and future (2040-2059) PRMS simulated natural flows using warmer-wetter and -drier scenarios. Both scenarios project more frequent, flashier peak flows. The warmer-wetter scenario also projects a shift to earlier peak flows. This projected shift of peak flows to mid-May is earlier than the current artificial peak flows in late-May and the natural peak flows in early June.

Channel enlargement measured at Hog Park Creek is consistent with qualitative channel response for increased flows and sediment loads less than sediment transport capacity. Stream surveys from 2006 and 2015 measured irregular channel widening and bed degradation. The riffle cross-sections (XSs) measured little change while pool XSs at the maximum point of scour measured extensive widening (+ 3.6 m). Ecologic implications of continued channel enlargement were evaluated by modeling changes in water surface elevations using the Hydrologic Engineering Center River Analysis System (HEC RAS). Between 2006 and 2015, modeling indicated a decrease in water surface elevation by 3 cm per decade and a decrease in flood inundation area of 70 m^2 per 1 m of stream length per decade.

Additionally, the hydraulic modeling results support the theory that alluvial channel form is most influenced by bankfull flow, which in this case is the 1.5-year flood. Based on this agreement, modeling indicated channel enlargement began near a pre-dam bankfull flow of 3.8 $m^3\ s^{-1}$ (135 $ft^3\ s^{-1}$) and has since increased to 5.5 $m^3\ s^{-1}$ (195 $ft^3\ s^{-1}$) in 2015. A possible trajectory of channel enlargement is to a bankfull flow of 5.8 $m^3\ s^{-1}$ (205 $ft^3\ s^{-1}$), which is based on the 1.5-year flood since dam enlargement in the 1980s. However, without a stable flow regime, a stable channel form is not possible.

Thus, to improve aquatic and riparian habitat, a stable flow regime and channel form will be necessary. For this reason, recommendations for a modified flow regime based on the findings of this study are developed and can be used as guidance for adaptive management.

ACKNOWLEDGEMENTS

Without the help of my advisor, committee members, coworkers, friends, and family, I could not have succeeded with this study. Thank you for your encouragement, guidance, expertise, and patience. I hope to continue our partnership on this and many more studies.

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1. INTRODUCTION

The growth of Front Range cities fueled a boom of large-scale dam and trans-basin diversion projects throughout the Southern Rocky Mountains. Though environmental analyses for these projects were completed to minimize potential environmental impacts, some effects were difficult to predict and persist many decades later (Williams and Wolman, 1984). Consequently, numerous opportunities exist to reanalyze how dam management influences adverse environmental effects.

In the 1960s, the Front Range city of Cheyenne, Wyoming constructed a large-scale water collection and storage system and enlarged it in the 1980s. This system allows the exchange of Little Snake River water for over-appropriated North Platte River water. To work, this exchange must occur in advance of or during snowmelt, when the North Platte River water is captured. The exchange water from the Little Snake River is collected by 126 diversion structures and piped through the Continental Divide to Hog Park Reservoir. Based on the increased flow capacity, the environmental analysis anticipated initial channel erosion (USDA, 1981). However, channel enlargement below Hog Park Reservoir continues many decades later (Gilliam, 2011).

Trans-basin diversions are common across the world. Examples include the Twin Lakes Tunnel in Colorado, Snowy-Murray in Australia, and Nechako-Kemano in British Columbia (Dominick and O'Neill, 1998; Maheshwari *et al.*, 1995; Kellerhals *et al.*, 1979). However, past trans-basin diversion case studies relating to the unique exchange scenario at Hog Park that also examine flow alterations with channel enlargement are less common. These case studies each found increased flows and downstream channel enlargement, but the types and degree of flow alterations and magnitude of downstream channel response differ.

The earliest case studies involving systems with increased flows from trans-basin diversion found minor change to peak flows. In the Kemano River, which receives water from the Nechako River, the increased annual flow volume reflected increases in low and intermediate flows (Kellerhals *et al.*, 1979). A similar flow alteration was observed at the Milk River in Montana, which receives water from the St. Mary River in Ontario (Bradley and Smith, 1984). Similarly, a 10-fold increase in low flows was observed at the River Ter, UK, which receives water from groundwater pumped to Leighs Reservoir (Petts and Pratt, 1983). These studies indicate increased low and intermediate flows play a role in channel enlargement.

More recent case studies involving increased flows demonstrate peak flows play a role in channel enlargement and riparian resource degradation. At the Owens River in California, which receives water from the nearby Mono Basin, increases in flood magnitude, frequency, and duration were found to decrease annual growth rates of willows (Stromberg and Patten, 1992). Moreover, the best willow growth rates were observed for floods in the high range of natural flooding or low range of the combined natural and diverted flooding (Stromberg and Patten, 1992). Similarly, Lake Creek and Lake Fork of the Arkansas River, which receive water from the Colorado River headwaters, indicated a substantial decrease in riparian cover area due to 50 years of channel enlargement (Dominick and O'Neill, 1998). Additionally, La Poudre Pass Creek of the Poudre River, which receives water from the Colorado River headwaters, has recorded increased peak flows and decreased low flows that are contributing to channel enlargement (Wohl and Dust, 2012). These studies indicate peak flows play a role in channel enlargement.

Similarly, a previous case study at Hog Park Creek found increased low and intermediate flows as well as peak flow magnitude, frequency, and duration. Additional flow alterations included earlier peak flows, faster fall rates, and reduced flow variability (Gilliam, 2011). This previous study suggests continued channel enlargement at Hog Park Creek is influenced by a suite of flow attributes.

Building on the previous Hog Park case study, this study seeks to provide additional insight into contemporary flow alterations and channel enlargement. The previous study provided an assessment of flow alterations using regional regression and reference stream comparison. The lack of a pre-dam flow record precluded a pre- vs post- dam comparison at Hog Park Creek. Regional regression equations provided estimates of natural peak flows such as the 1.5-year flood (Miller, 2003). These estimates have high standard error, especially for the 1.5-year flood (56%). A reference stream (*e.g.*, similar location, climate, drainage area, and elevation) allowed direct comparison to the altered flow record which provided estimates of flow alterations such as timing, rates of change, magnitudes, frequencies, and durations. However, for this system, the reference flow record represents only a short period of time (1958-1963) which limits statistical analysis. Therefore, an alternative method to estimate natural flows at Hog Park Creek over a longer, contemporary period is needed.

A more rigorous assessment of flow alteration can be conducted using runoff Prediction in Ungauged Basin (PUB) theory. PUB regionalizes hydrologic process knowledge to understand hydrologic response in ungauged basins which can also be applied in gauged basins where a pre-dam flow record does not exist (Hratchowitz *et al*., 2013). For example, natural hydrologic processes in a surrogate watershed can be applied or transferred to the altered study watershed based on spatial proximity and physical similarity (Merz and Blöschl, 2004). Treating the Hog Park Creek watershed as an 'ungauged' basin allows comparing the estimated natural and post-dam flows during the same time period. One PUB method is to parameterize a hydrologic model of the altered study watershed and simulate a natural flow record (Maheshwari *et al*., 1995). A Hog Park Creek hydrologic model is parameterized using a regionalization technique which transfers calibrated parameters from the modeling of an adjacent natural basin, in this case the Encampment River. An improved understanding of contemporary flow alterations facilitates identification of a stable flow regime.

Similarly, assessment of an enlarging channel can be improved through hydraulic modeling. Stream survey data is available to parameterize hydraulic models at Hog Park Creek. Two hydraulic models (2006 and 2015) at Hog Park Creek allow assessing the progress of channel enlargement as well as the effects of channel enlargement to water surface elevations and flood inundation. Though it is not practical to return Hog Park Creek to its natural channel capacity, it is realistic to establish stable channel form based on a projected channel capacity and modified flow regime. Thus, the objectives of this study are to 1) assess flow alteration and how it is influenced by dam management and 2) assess channel enlargement and how it is influenced by attributes of the flow regime and aspects of dam management.

Together, hydrologic and hydraulic assessments are used to address the question of how channel enlargement is influenced by dam management. By doing so, this study identifies attributes of a stable flow regime essential to future channel stability at Hog Park Creek. After the conclusion of this document, recommendations are delivered for dam management to better integrate aquatic and riparian resource protection with their critical water supply objectives.

2. STUDY SITE

Following orogeny of the Sierra Madre Range in the Southern Rocky Mountains, glacial processes helped shape the landscape of the Hog Park area. Precambrian fractured rock aquifers of igneous and metamorphic geology are overlain by moderate to deep, loamy-skeletal soils (Bauer *et al.*, 1989). Steep hillslopes are forested with stands of *Abies lasiocarpa*, *Picea engelmannii*, and *Pinus Contorta*. And presently, fluvial processes under existing climate and dam management continue to shape the Hog Park area.

The climate of the Hog Park area consists of cold winters and cool summers. The bulk of precipitation falls as snow in the winter. With an average annual precipitation of 1080 mm, median peak snow water equivalent (SWE) is 760 mm (Whiskey Park SNOTEL) <wcc.nrcs.usda.gov>. Snowmelt is controlled by shortwave radiation in the alpine and longwave radiation in the sub-alpine, which yields a snow dominated hydrograph (Bales *et al*., 2006).

The snow dominated hydrograph under free-flowing conditions has a wet period in the spring during snowmelt and a dry period from late summer through winter. The Encampment River flows freely from the Mount Zirkel Wilderness in Colorado to the Encampment Wilderness in Wyoming. On the Encampment River above its confluence with Hog Park Creek, a USGS flow gage is operated as part of a hydrologic benchmark network, due to its long-term, unregulated flow record (Figure 1). Here, peak flow typically occurs in June and the average annual runoff is 550 mm. This gage serves as an unregulated flow reference for Hog Park Creek.

In contrast, the Hog Park Creek flow gage has only a regulated flow record which began in 1969 after dam construction. Since the 1960s, flows native to Hog Park Creek have increased by diverted Little Snake River water impounded in Hog Park Reservoir (Figure 1). After enlarged in the 1980s, the main dam stands nearly 36 m (120 ft) tall and has a capacity of about 3.08 x 10^7 m^3 (25,000 ac-ft). This makes it one of 3,200 major dams in the US and one of 350 on National Forest lands (<http://nid.usace.army.mil>). The purpose of this system is to use the Little Snake River water to simultaneously replace water in the North Platte River stored in Rob Roy Reservoir during snowmelt. Due to operational constraints, Little Snake River water cannot always be released at the same time and rate as water is captured from the North Platte River by Rob Roy Reservoir during snowmelt. So stored water may also be released prior to snowmelt.

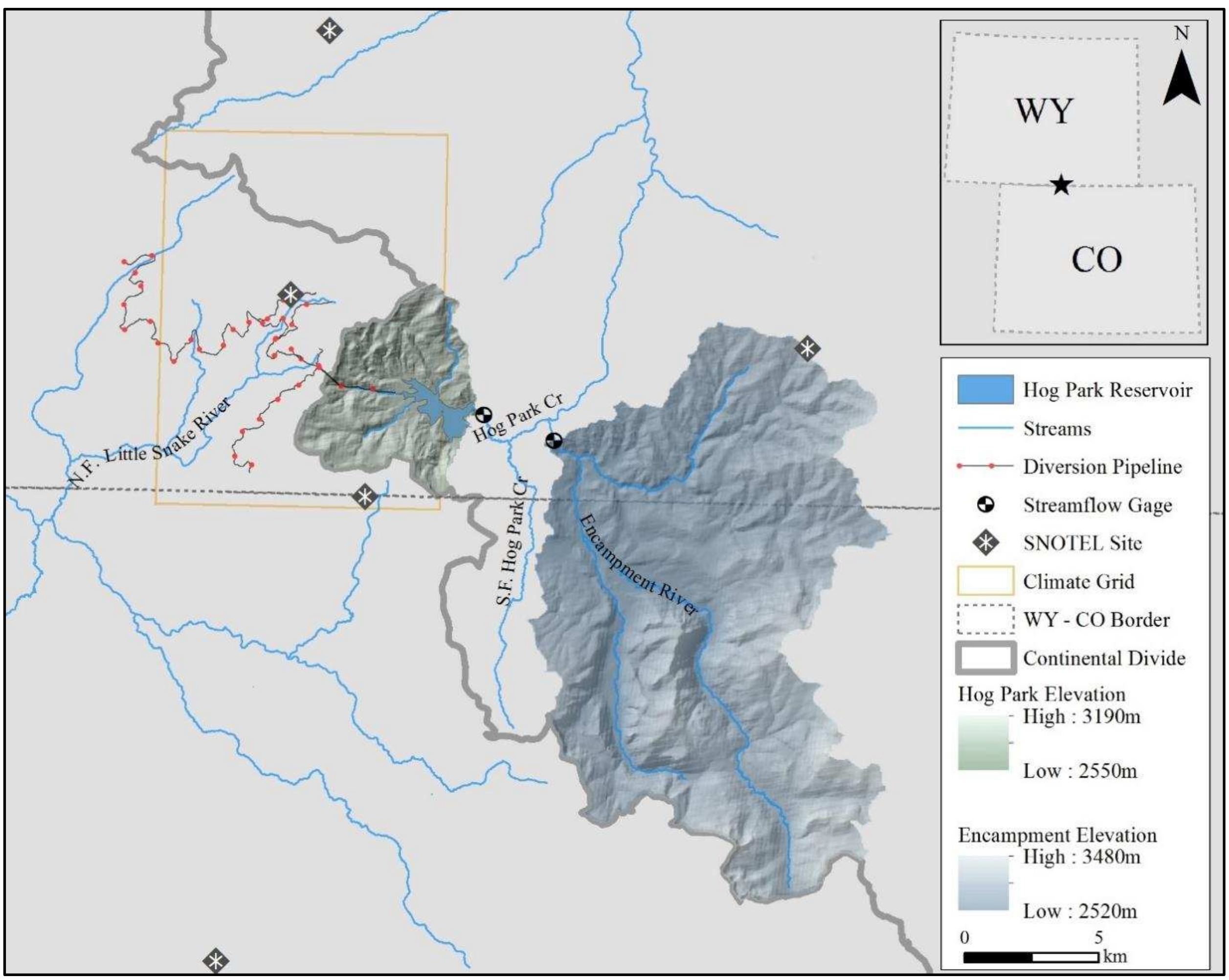

Figure 1: The Hog Park study area. A trans-basin diversion conveys water from the Little Snake River through the Continental Divide to Hog Park Reservoir. Diverted water released below the dam adds to native flows in Hog Park Creek. This added water replaces upstream North Platte River water piped to Cheyenne, Wyoming. The free-flowing Encampment River is used as a reference. (Hydrography and elevation data source: USGS, 2015).

Apart from the state water rights and exchange agreement, aspects of existing dam management to consider are the easement and advanced payback storage contract. In the original easement, a 0.42 m^3s^{-1} (15 ft^3 s^{-1}) minimum flow was required as part of a settlement with the Wyoming Wildlife Federation (WWF). Separately, the easement stipulated maximum flows through the outlet works should not exceed 5.7 m^3s^{-1} (200 ft^3 s^{-1}) except to release natural flows when higher. This precaution was an attempt to limit channel enlargement by reducing the number of artificially- high peak flows during naturally- average and dry years. Recognizing the potential limitation in the amount of water that could be exchanged during peak flows, an advanced payback storage contract was developed to capture more water. This contract allows releasing Little Snake River exchange water ahead of snowmelt if temporarily stored further downstream in Seminoe Reservoir. A new easement allows increasing the maximum outflow to 9.2 m^3s^{-1} (325 ft^3 s^{-1}). These examples show the compounding aspects of dam management that affect native Hog Park Creek flows.

Examples of flow alterations influenced by dam management are apparent in daily flow depth hydrographs of the Encampment River and Hog Park Creek (Figure 2). Though geospatially similar watersheds, a key difference is the time of concentration, or the time needed for runoff to flow from the top of the watershed to its pour point. Times for the Encampment River are greater due to its larger drainage area of 188 km^2 compared to 32 km^2 at Hog Park Creek. Additionally, the Hog Park Creek watershed has more east- than west- facing aspect, more area distributed lower in elevation (2,500 - 3,000 m), and a larger percentage of open water (5-10% of its area). Despite these differences, flow alterations apparent in the two hydrographs are higher peak flows and low flows since the 1980s. Also, there is indication of reduced peak flow variability (*e.g.*, 1995-2000) and earlier releases in the spring (*e.g,* 1992-1998).

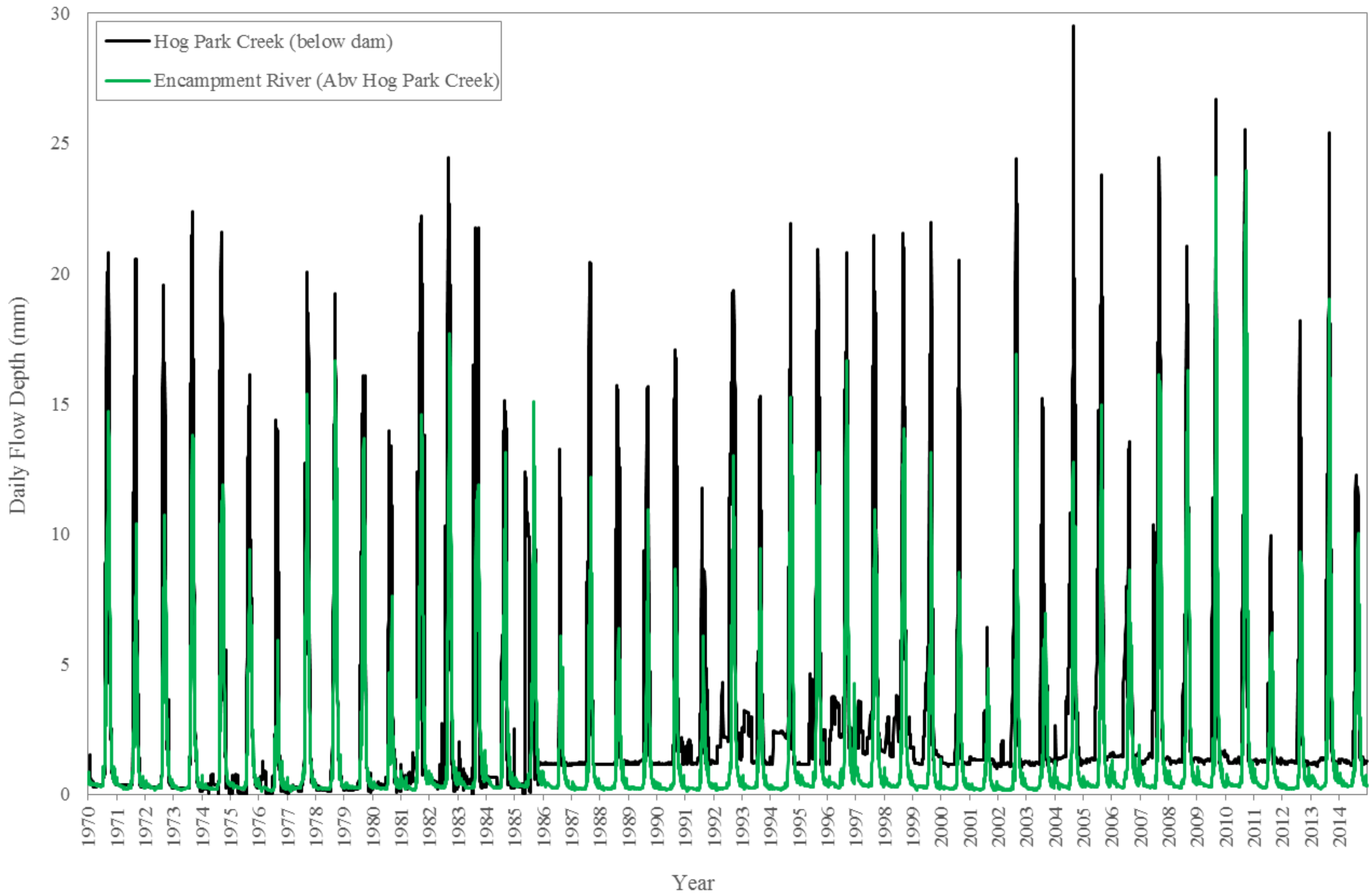

Figure 2: Daily flow depths at the Encampment River and Hog Park Creek (1970-2015). Dam enlargement occurred in the 1980s and a minimum flow was required. Notable differences include higher peaks and low flows. Also indicated are the early releases (*e.g.*, 1992-1998) and reduced peak flow variability (1995-2000).

3. METHODS

3.1 FLOW ALTERATIONS DUE TO DAM MANAGEMENT

To simulate natural flow at Hog Park Creek, the deterministic, distributed-parameter, physically-based Precipitation-Runoff Modeling System (PRMS) was selected. This model distributes parameters over sub-watersheds called hydrologic response units (HRUs). HRUs assume homogenous hydrologic response and are delineated from the stream network and other unique watershed characteristics. For each HRU, PRMS balances energy and water budgets of the snowpack, plant canopy, and soil zone to simulate hydrologic processes including snowmelt, sublimation, interception, infiltration, evapotranspiration, interflow, groundwater flow, and surface runoff (Leavesley *et al.*, 1983).

Key input variables distributed at each HRU include temperature, precipitation, solar radiation (SR), and evapotranspiration (ET). Temperature and precipitation data come from individual SNOTEL stations and are quality checked (Serreze *et al.*, 1999). The distribution technique is a 3-D, multiple-linear regression based on latitude, longitude, and elevation (Hay *et al.*, 2006). Daily clear-sky shortwave SR is estimated by a degree-day relation (Leaf and Brink, 1973). The estimates are adjusted at each HRU using daylight hours, days with precipitation, and potential SR based on slope, aspect, and latitude (Leavesley *et al.*, 1983). Daily actual ET is estimated using the modified Jensen-Haise method and distributed based on plant cover, soil properties, and potential ET (Jensen and Haise, 1963; Leavesley *et al.*, 1983).

Climate variables are used to simulate snowpack processes at each HRU. Snowpack processes conceptualized include: 1) water and energy balance changes due to rain, snow, or mixed precipitation; 2) snow covered area; 3) albedo; 4) water and energy balance changes due to radiant, convective, and convective fluxes; and 5) sublimation and evaporative loss. When the snowpack warms to isothermal, subsequent snowmelt becomes free water to fill pore space or exits into the soil zone (Markstrom *et al.*, 2015).

The soil and recharge zones for each HRU are conceptualized as three main reservoirs: capillary (soil zone when soil-water content is between field capacity and wilting point), gravity (soil zone when soil-water content exceeds field capacity), and groundwater (recharge zone from capillary and gravity reservoirs). Daily flow in and out of the soil-zone has the following general sequence: 1) route excess soil infiltration from snowmelt, rain throughfall, and upslope runoff that exceeds the maximum storage capacity of the capillary reservoir to the gravity and groundwater reservoirs; 2) route excess inflow that exceeds the maximum storage capacity of the gravity reservoir as slow interflow and groundwater recharge; and 3) compute the evaporation and transpiration losses from the capillary reservoir (Markstrom *et al.*, 2015). When soil infiltration exceeds antecedent soil-moisture content in the capillary zone, potential surface runoff is computed. Surface runoff computations are based on the non-linear, variable-source-area concept where contributing areas of runoff vary in space and time based on maximum infiltration rates and soil saturation capacity (Hewlett and Nutter, 1970).

Additionally, each HRU has unique geospatial parameter values that are extracted from zone maps (*e.g.*, stream network, land cover, canopy density, soils, elevation, slope, aspect, and radiation planes) using the *GIS Weasel* program (Viger and Leavesley, 2007). Since there is no natural streamflow record at Hog Park Creek, a regionalization method is used to complete parameterization of the Hog Park Creek model. The regionalization technique allows the transfer of calibrated parameters from the surrogate Encampment River watershed based on its close spatial proximity and physical similarity (Merz and Blöschl, 2004; Chang and Jung, 2010).

To parameterize the surrogate Encampment River model, ten year calibration (2005-2014) and evaluation (1995-2004) periods and an eight year run-in (1987-1994) period were selected. The water years 2005-2014 were chosen for the calibration period because there is more interest in these years. The ten year time period is a sufficient amount of time to capture hydrologic variability of average, dry, and wet water years (Yapo et al., 1996). Parameterization involved 6 rounds of 6 steps of the LUCA multiple-objective, stepwise calibration method (Hay *et al*., 2006). LUCA (Let Us Calibrate) is an automated sensitivity and optimization tool for PRMS (Hay and Umemoto, 2007). LUCA calibrates intermediate (*e.g.*, ET, SR) and final (*e.g.*, monthly, daily, low, and high flows) variables against a measured dataset. Measured datasets include global horizontal irradiance from the SUNY satellite solar radiation model available through the National Renewable Energy Laboratory (NREL) Solar Prospector Map <http://maps.nrel.gov/prospector>; actual ET from the Simplified Surface Energy Balance Model available at the USGS Geo Data Portal <http://cida.usgs.gov/gdp/>; and flows from the Encampment River USGS gage <http://waterdata.usgs.gov/nwis>.

During calibration, objective functions are used to measure accuracy by comparing statistics of PRMS model simulations (SIM) to measured (MSD) data using mean (MN) annual, monthly (m), and daily intervals (n). The two objective functions, listed below, are sum of the absolute difference in logarithms (SADL) and normalized root mean square error (NRMSE) (Hay *et al.*, 2006). A step continues until no improvement in accuracy is made after a series of iterations. After step 6, a new round begins with new parameter values from the previous round. Final parameter values are established after 6 rounds of 6 steps. The final Encampment River PRMS model performance is evaluated using Nash-Sutcliffe Efficiency (NSE) and Percent Bias (PBIAS) (Nash and Sutcliffe, 1970; Moriasi *et al.*, 2007).

$$\text{SADL} = \left(\sum_{n=1}^{nstep}(MSD(n) - SIM(n))^2 \Big/ \sum_{n=1}^{nstep}(MSD(n) - MN)^2\right)^{1/2} \tag{1}$$

$$\text{NRMSE} = \sum_{m=1}^{12} \text{abs}\left[\frac{(MSD_m - SIM_m)}{MSD_m}\right] \tag{2}$$

Using the parameter values transferred from the surrogate Encampment River model, natural flows are simulated at Hog Park Creek. Simulated natural flows are compared to the measured flows for overlapping 21-years (1995-2015). The flow alteration statistics are evaluated using the Indicators of Hydrologic Alteration (IHA) software (Richter *et al.*, 1996).

IHA statistics are non-parametric (*e.g.*, percentiles and medians) to better describe central tendencies of the flow data. To parameterize an IHA analysis, thresholds are needed to ensure IHA algorithms properly evaluate flood, low flow, and high flow attributes. Thresholds were set by visually setting values that worked for both simulated natural and measured hydrographs. For example, the minimum flood threshold was set to 3.8 m^3 s^{-1} (135 ft^3 s^{-1}) so it is high enough to exclude high flow pulses from measured flows and low enough to capture smaller floods of simulated natural flows. Similarly, thresholds were set at 0.28 m^3 s^{-1} (10 ft^3 s^{-1}) for low flows and 0.62 m^3 s^{-1} (22 ft^3 s^{-1}) for high flow pulses. When flows were between these two magnitudes, high flows began by a daily increase of 15% and ended by a daily decrease of 3%.

The flow attributes calculated by IHA include monthly magnitudes, magnitude and duration of annual extremes, timing of annual extremes, frequency and duration of pulse flows, rate and frequency changes, and snowmelt period flood characteristics (*e.g*., peak, duration, rise and fall rates). The flood characteristics calculate flow attributes specific to the snowmelt period from rising to falling limbs of the hydrograph. To indicate the relative degree of alteration amongst the calculated flow alterations, deviation factor (DF) is computed. The DF is the simulated minus measured flow attribute value divided by the simulated attribute value. Significance is evaluated by an algorithm that shuffles the simulated natural and measured flow data to recalculate new random DF values 1000 times. The fraction of the 1000 new random DFs that are greater than the original DF is the significance value, with values that range from zero to one. A flow alteration with a significance value of zero is highly significant.

3.2 FLOW ALTERATIONS DUE TO CLIMATE

Trends and projections are evaluated for the Encampment River and Hog Park Creek flows. Measured flow trends at the Encampment River are influenced by climate (*e.g.*, warming temperatures), but could also have other natural (*e.g.*, beetle epidemic, wildfire) or human (*e.g.*, logging, roads, trails) influences. The measured flow trends are used as a baseline for assessing possible flow alterations influenced climate change at Hog Park Creek.

Two future scenarios of flow alterations are based on the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model ensemble data archived at <http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/>. These are the climate data that informed the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) completed in 2014 (IPCC, 2014; Reclamation, 2013; Reclamation, 2014). The AR5 climate projections depend on relative concentration pathways (RCPs) which estimate greenhouse gas concentrations based on radiative forcing values. RCPs based on the 4.5 W m^{-2} and 8.5 W m^{-2} radiative forcing values represent intermediate (RCP 4.5) or no (RCP 8.5) mitigation efforts to constrain GHGs (Taylor *et al.*, 2007).

Climate projections for the Hog Park area are downscaled to a 1/8° x 1/8° latitude–longitude grid [(41.0 to 41.125) x (-107.0 to -106.875)] (Figure 1) (Maurer, *et al.*, 2006). This covers an area of approximately145 km^2. Two General Circulation Models (GCMs) are selected to represent two climate projection scenarios. Can-ESM2 (RCP 8.5) represents a warmer-wetter scenario and INM-CM4 (RCP 8.5) represents a warmer-drier scenario (Records *et al*., 2014). Using the climate data for the two scenarios, flows for historic (1980-1999) and mid-century (2040-2059) periods are simulated using the Hog Park Creek PRMS hydrologic model.

3.3 CHANNEL ENLARGEMENT

The evolution of channel enlargement at Hog Park Creek is quantified by tracking the changes in bankfull flow dimensions. As a channel enlarges to accommodate more flow, the bankfull flow dimensions enlarge over time. Due to the difficulty in assessing bankfull flow in an unstable channel using only ocular field indicators (*e.g.*, changes in vegetation type, breaks in elevation), other methods were needed for comparison. These include 1.5-year recurrence intervals, effective discharge, and wetted perimeter-flow curves. By quantifying the past and present changes in channel dimensions, the progression and implications of continued channel enlargement can be determined.

To understand the progression of changes in bankfull flow dimensions, the Hydrologic Engineering Center River Analysis System (HEC RAS) was used to simulate 1-D steady water surface elevations at Hog Park Creek (USACE, 2006). The Hog Park Creek HEC RAS model utilizes stream survey data from a reach located immediately below the dam.

The input data for hydraulic modeling include slope, cross-sectional (XS) geometry, channel and floodplain Manning's n estimates, and flows. Total station surveys from 2006 and 2015 provided slope, XS geometry, and reach lengths from XS to XS. In between XSs, longitudinal profile data were used to capture hydraulic grade controls along the study reach. The average bed slope of 0.00527 is used to approximate the energy slope and is set as the downstream boundary condition. Estimates of Manning's n within the active channel is computed using an empirical equation which is a function of grain size and flow depth (Limerinos, 1970). Additional roughness was added to the grain size roughness to account for channel irregularities (Arcement and Schneider, 1989). Estimates of Manning's n within the floodplain are from table values of winter and summer, medium-to-dense brush (Chow, 1959). These final Manning's n values were 0.038 for the channel and 0.1 for the floodplain. For flow inputs, the limited XS distance into the floodplain meant the highest flow that could be simulated was a 20-year flood. Since low flow validation data were not collected in this study, the lowest flow selected was a 1-year flood.

Hydraulic simulations that provide insight to the progression of channel enlargement are wetted perimeter-flow curves for each XS in the upper study reach. Conceptually, as flow increases the corresponding wetted perimeter gradually increases while the channel begins to fill. Once a channel is full enough, it spills into the floodplain and the corresponding wetted perimeter value immediately becomes larger. When a range of wetted perimeter values are plotted against their corresponding flows, this discontinuity or breakpoint can be seen. The flow value of this breakpoint provides an estimate of the geomorphic bankfull flow. In addition to bankfull flow estimates, hydraulic simulations provide insight to the implications of channel change. For example, changes to channel form can have effects on water surface elevation and flood inundation. This joint assessment of flows and channel change is made to understand how aspects of dam management influences channel enlargement (Figure 3).

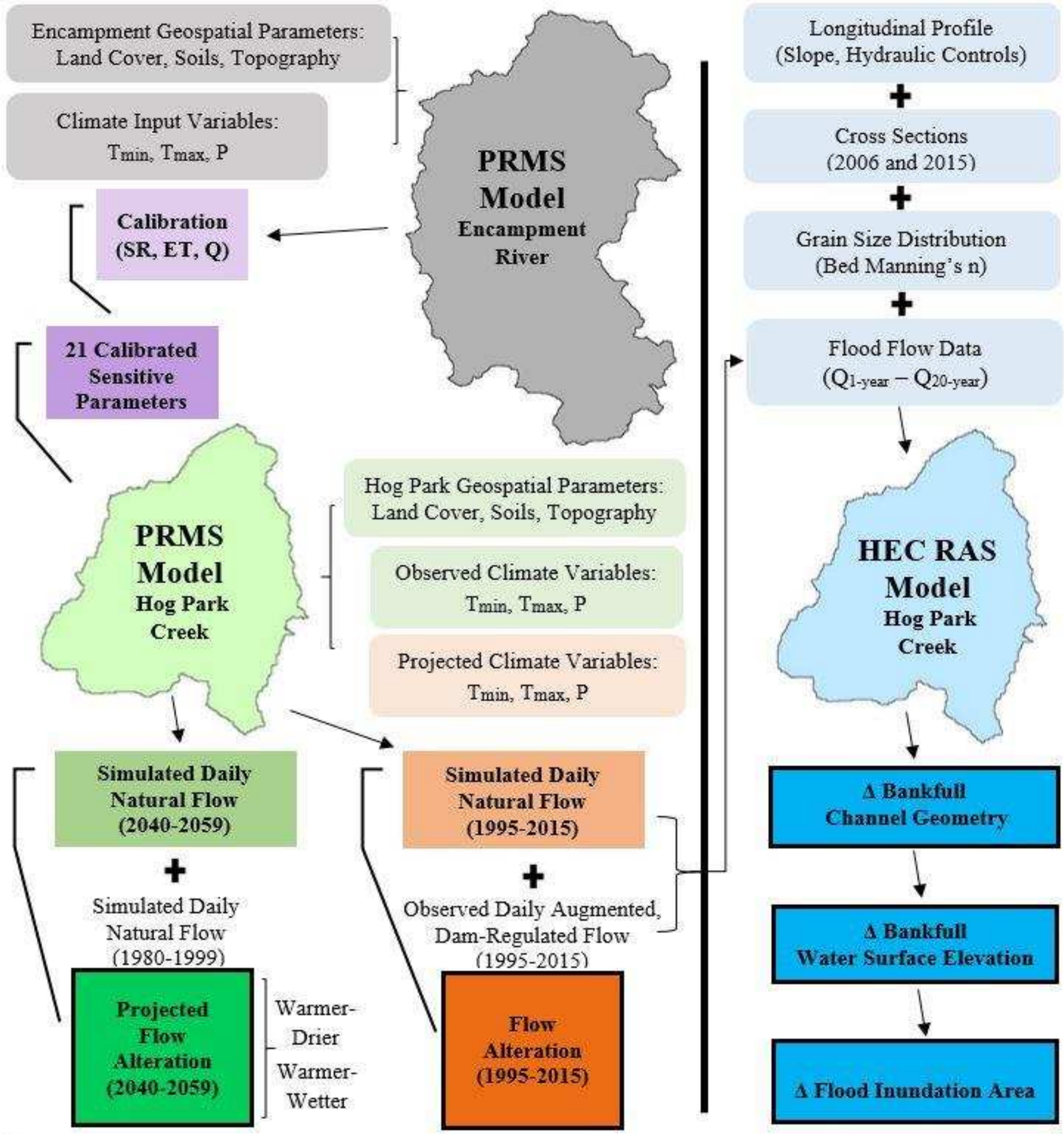

Figure 3: Hog Park modeling schematic. The study begins with parameterizing the surrogate Encampment River PRMS model to transfer its calibrated parameters to the Hog Park Creek model. This allows simulating natural flows at Hog Park Creek to compare with measured flows from 1995-2015. Similarly, simulated natural flows for historic and future time periods were compared to assess flow alterations influenced by climate change (warmer-wetter and warmer-drier scenarios). In addition, Hog Park Creek hydraulic simulations provide a method to understand the progression and implications of channel enlargement. The progression of channel enlargement is tracked by estimating bankfull flow dimensions over time. Implications of channel enlargement are assessed with water surface elevations and flood inundation.

4. RESULTS

4.1 FLOW ALTERATIONS DUE TO DAM MANAGEMENT

Parameterization of the surrogate Encampment River model involved an automated calibration by the LUCA step wise, multiple objective procedure (Hay *et al.*, 2006). The first step in LUCA calibrated the simulated average monthly total solar radiation (SR) to measured SR (Figure 4). The second step in LUCA calibrated simulated average monthly actual evapotranspiration (AET) to measured AET (Figure 4). The final SADL for measured and simulated average monthly SR were 0.07 for the calibration period and 0.17 for the evaluation period. Also showing close agreement, the final SADL for measured and simulated average monthly AET over the growing season were 0.06 for the calibration period and 0.11 for the evaluation period.

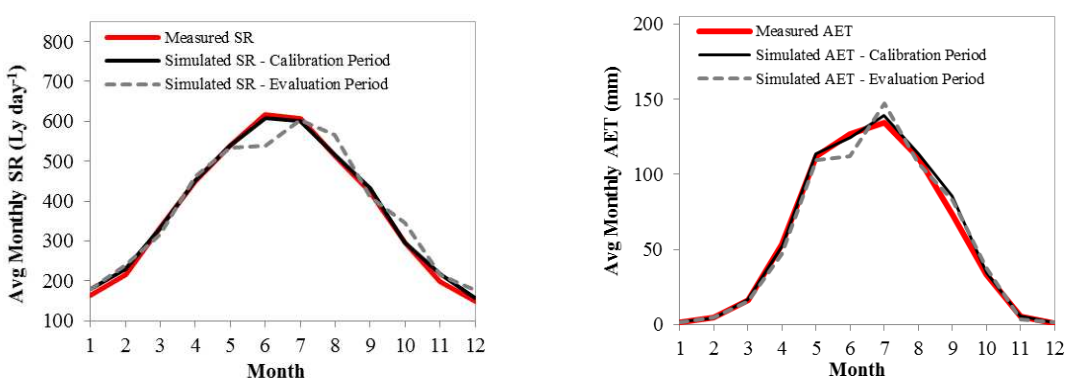

Figure 4: Average monthly total SR and AET for the surrogate Encampment River PRMS model show a good fit between simulated and measured datasets.

The last four steps in LUCA use measured daily average flow from the Encampment River USGS stream gage above Hog Park Creek. Average annual flow volumes for calibration (NRMSE=0.24) and evaluation (NRMSE=0.27) periods show an acceptable 1-to-1 fit (Figure 5a). For monthly flows, the average monthly flow volumes for calibration (NRMSE=0.07) and evaluation (NRMSE=0.10) periods show a good 1-to-1 fit (Figures 5b and 5c). Similarly, monthly average flow volumes for calibration (NRMSE=0.16) and evaluation (NRMSE=0.30) periods show a good 1-to-1 fit (Figures 5d and 5e).

The timing of daily average flows for the calibration (NRMSE = 0.31) and evaluation (NRMSE = 0.41) periods show an acceptable 1-to-1 fit (Figures 6a and 6b). The daily peak flows for calibration (NRMSE = 0.32) and evaluation (NRMSE = 0.26) periods show an acceptable 1-to-1 fit, though peak flows have a tendency to slightly underestimate during wet years (Figures 6c and 6d). The simulated low flows for calibration (NRMSE = 0.57) and evaluation (NRMSE =

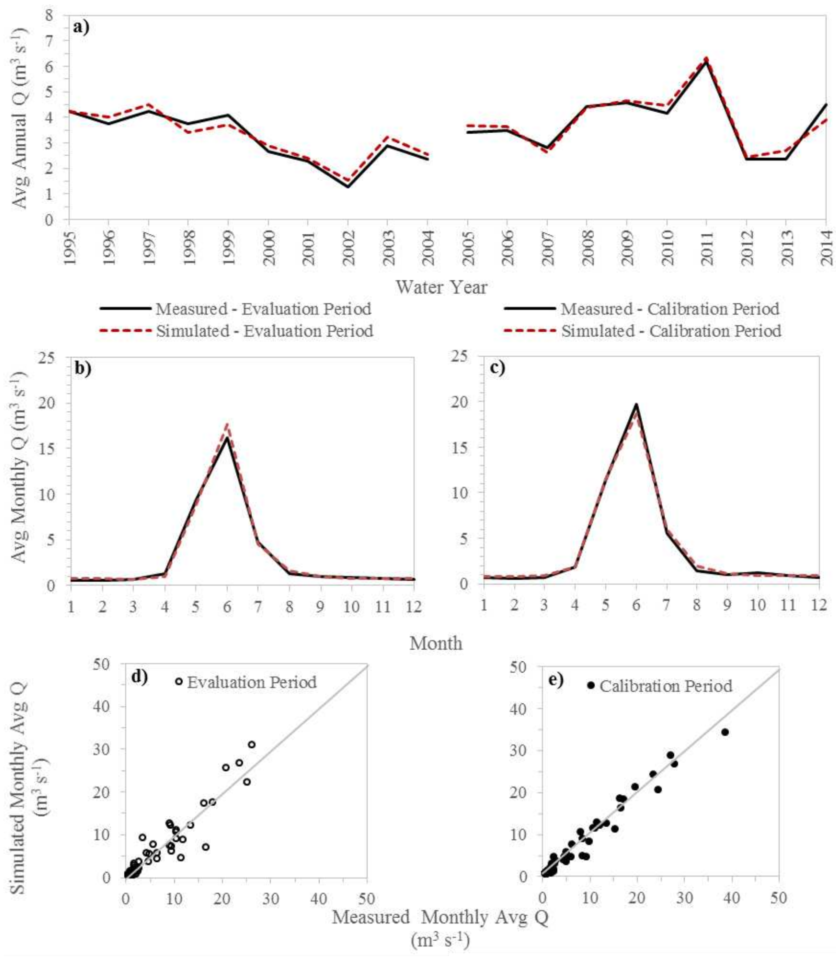

Figure 5: (a) Average annual flow and average monthly flow for (b) evaluation and (c) calibration periods indicate a good 1-to-1 fit. Similarly, the monthly average volumes have a close 1-to-1 fit for (d) evaluation and (e) calibration periods.

0.78) periods show a poorer 1-to-1 fit (Figures 6e and 6f). This is due to a tendency to overestimate low flows, particularly during droughts.

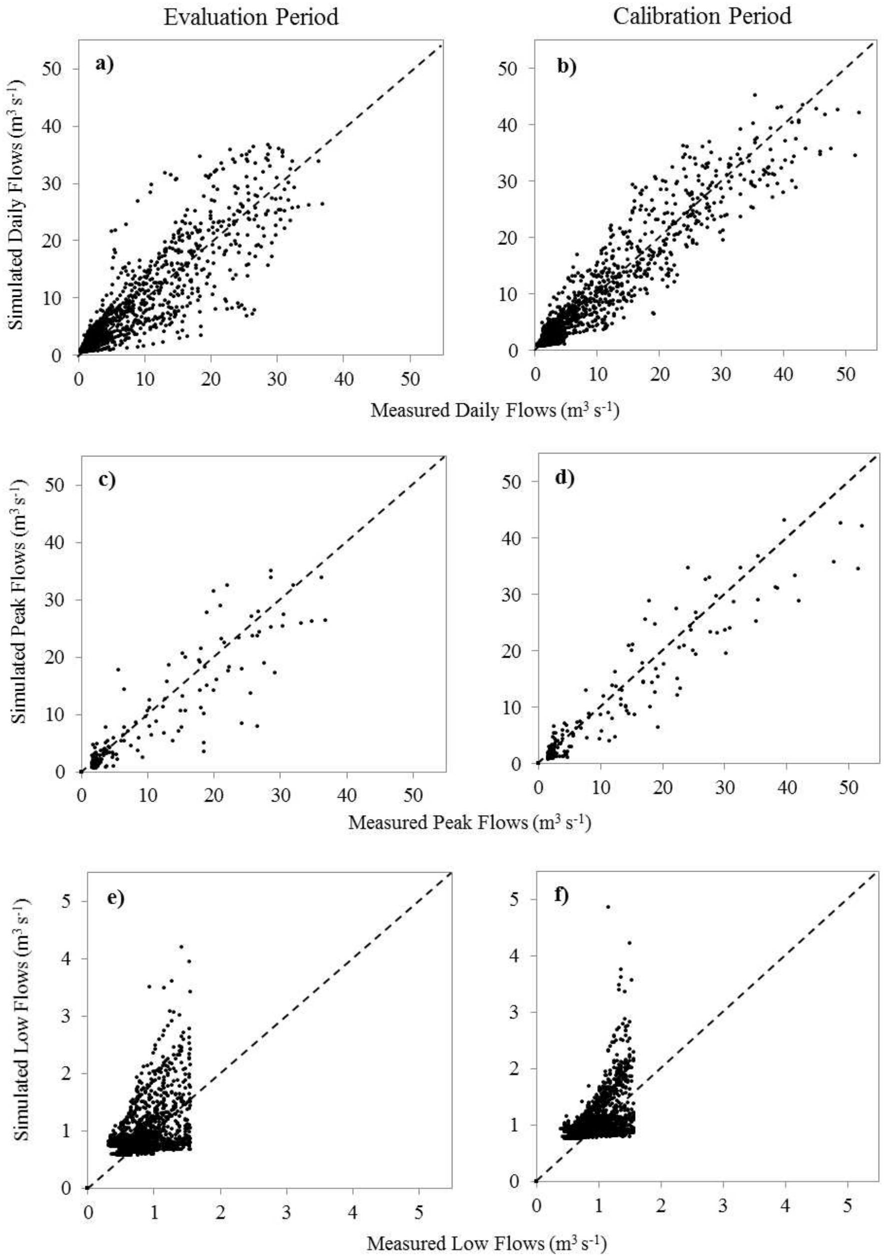

Figure 6: The timing of daily, peak, and low flows are compared during evaluation (**a,c,e**) and calibration (**b,d,f**) periods at the surrogate Encampment River model.

Overall model performance evaluated by NSE and PBIAS statistics indicate satisfactory results: NSE=0.89 and PBIAS= -1.9% for calibration period and NSE=0.82 and PBIAS= -4.5%

for the evaluation period. In addition, NSE is above 60% and PBIAS is within 20% for all years (Figure 7). Low NSE corresponds to either early or late simulated snowmelt runoff, while high bias corresponds to simulations overestimating (negative) or underestimating (positive) total runoff volume. The resulting simulated Encampment River flows closely mimic the measured (Figure 8). Floods including the rising and falling limbs and peaks are simulated closely to the measured flows; whereas, low flows are generalized and typically overestimated.

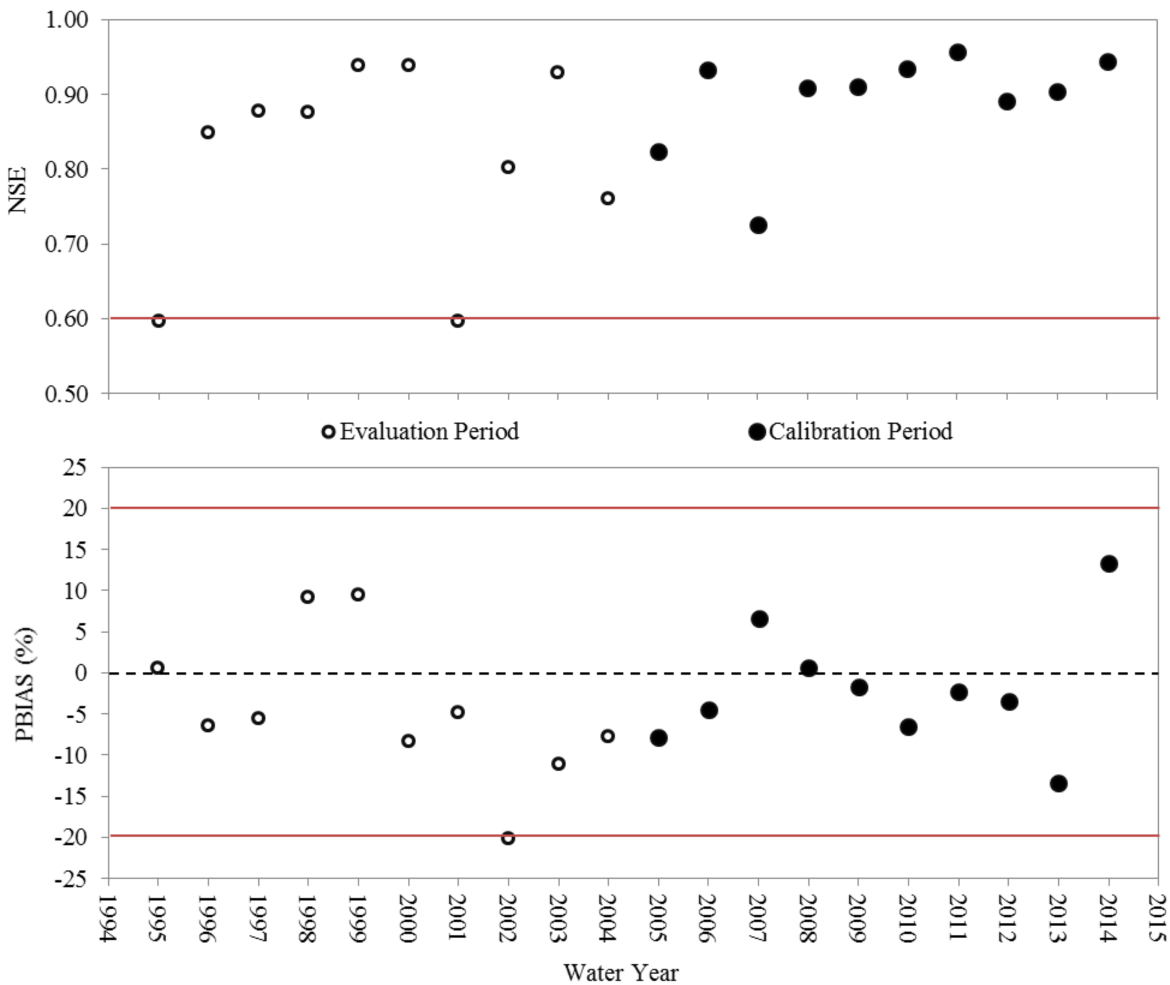

Figure 7: Annual NSE and PBIAS for calibration and evaluation periods for the surrogate Encampment River PRMS hydrologic model. Red lines indicate bounds for acceptable values.

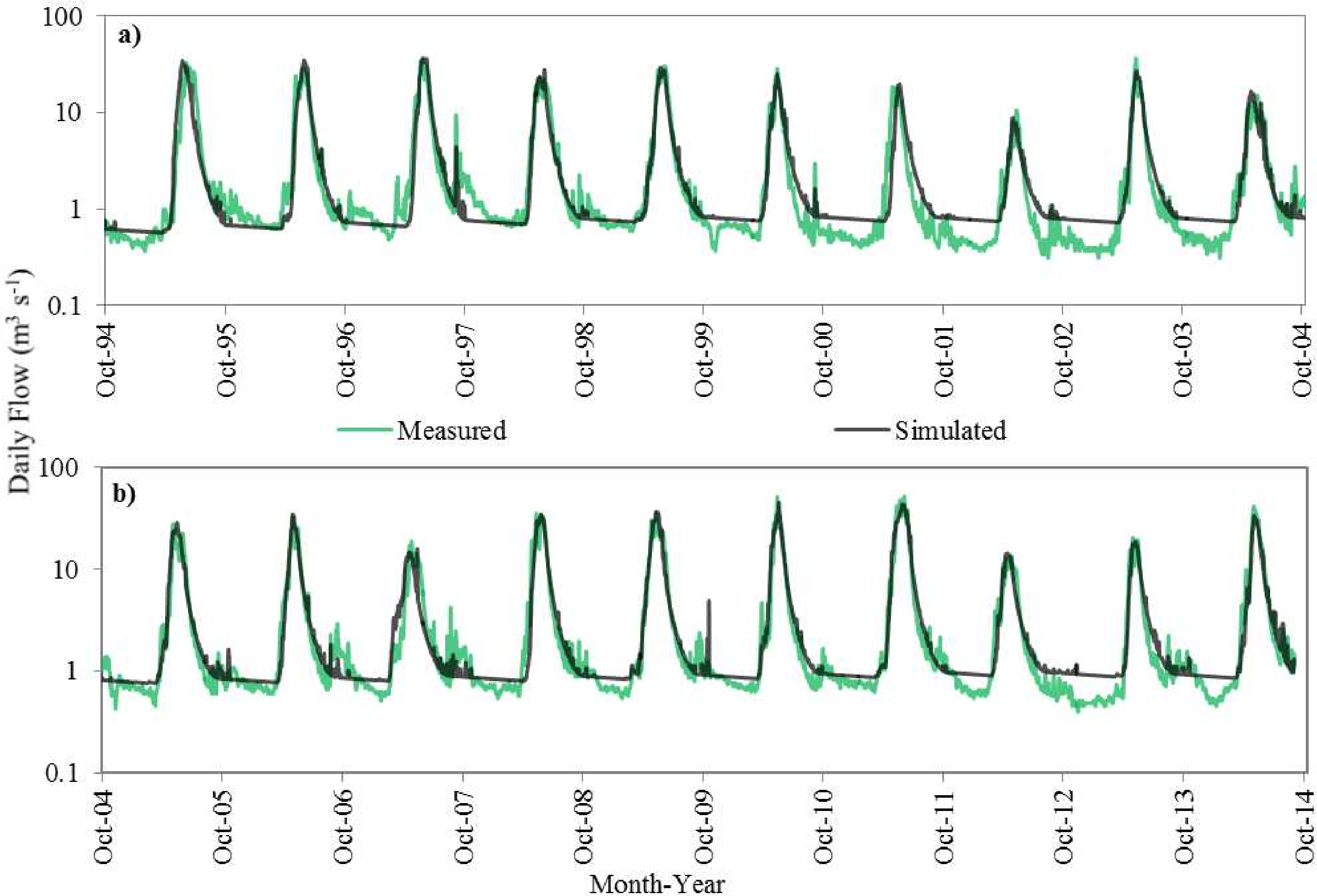

Figure 8: Simulated and measured daily average flow at the Encampment River plotted on a logarithmic scale for a) evaluation and b) calibration periods. Simulations closely mimic the major components of a snow dominated hydrograph, particularly the rising and falling limbs and peak flows. The logarithmic scale emphasizes the low flow overestimation, especially in dry years (*e.g.*, 2012).

The sensitive parameters used to calibrate the Encampment River model were transferred to the Hog Park Creek model (Table 1). The Hog Park Creek PRMS model simulated natural flows from 1995-2015. The resulting simulated natural flows mimic a snow dominated hydrograph with a rapid rising limb, peak, gentler falling limb, and low flow period (Figure 9).

Using the simulated natural flows at Hog Park Creek, flow alterations due to dam regulation were assessed over the 21-years from 1995 to 2015. IHA statistics indicate most flow alterations were significantly different. As indicated by deviation factor, the greatest significant deviations were increased winter and spring monthly flows and increased 7-day lows (Table 2). To a lesser degree of deviation, significant flow alterations include higher, longer duration, more frequent, and earlier peak flows as well as faster fall rates and increased number of flow reversals.

Table 1: Parameters transferred to the Hog Park Creek model. Monthly values in Appendix.

Step	Calibration Data	Sensitive Parameter	Value	Parameter Description
1	Basin Avg Monthly SR	*dday_intcp* *tmax_index*	Appx. Appx.	Intercept in temperature degree-day relationship Index temperature used to determine precipitation adjustments to solar radiation
2	Basin Avg Monthly ET	*jh_coef*	Appx.	Coefficient used in the Jensen- Haise PET computations
3	(Volume) Avg Annual Avg Monthly Monthly Avg Flows	*adjust_rain* *adjust_snow*	Appx. Appx.	Precipitation adjustment factor for rain days Precipitation adjustment factor for snow days
4	(Timing) Daily Flows	*adjmix_rain* *cecn_coef* *emis_noppt* *free_h20cap* *potet_sublim* *slowcoef_lin* *slowcoef_sq* *snowinfil_max* *tmax_allrain* *tmax_allsnow*	Appx. Appx. 1.0 0.11 0.154 0.003 0.004 2.695 Appx. 34.4	Factor to adjust rain in mixed rain/snow events Convection condensation energy coefficient Emissivity of air on days without precipitation Free water holding capacity of snowpack Proportion of PET that is sublimated from the snowpack surface Linear coeff. in the eqn to route gravity-reservoir storage downslope Exponent in the eqn to route gravity-reservoir storage downslope Daily maximum snowmelt infiltration for the HRU If a HRU max temperature exceeds this value, precipitation as rain If a HRU max temperature is below this value, precipitation as snow
5	(Timing) Peak Flows	*smidx_coef* *smidx_exp*	0.005 0.303	Coefficient in non-linear surface runoff contributing area algorithm Exponent in non-linear surface runoff contributing area algorithm
6	(Timing) Low Flows	*gwflow_coef* *soil2gw_max* *ssr2gw_exp* *ssr2gw_rate*	0.001 0.05 0.005 0.026	Groundwater routing coefficient Maximum rate of soil water excess moving to groundwater Exponent to route water from the gravity-reservoir to groundwater Linear coefficient to route water from the gravity-reservoir to gw

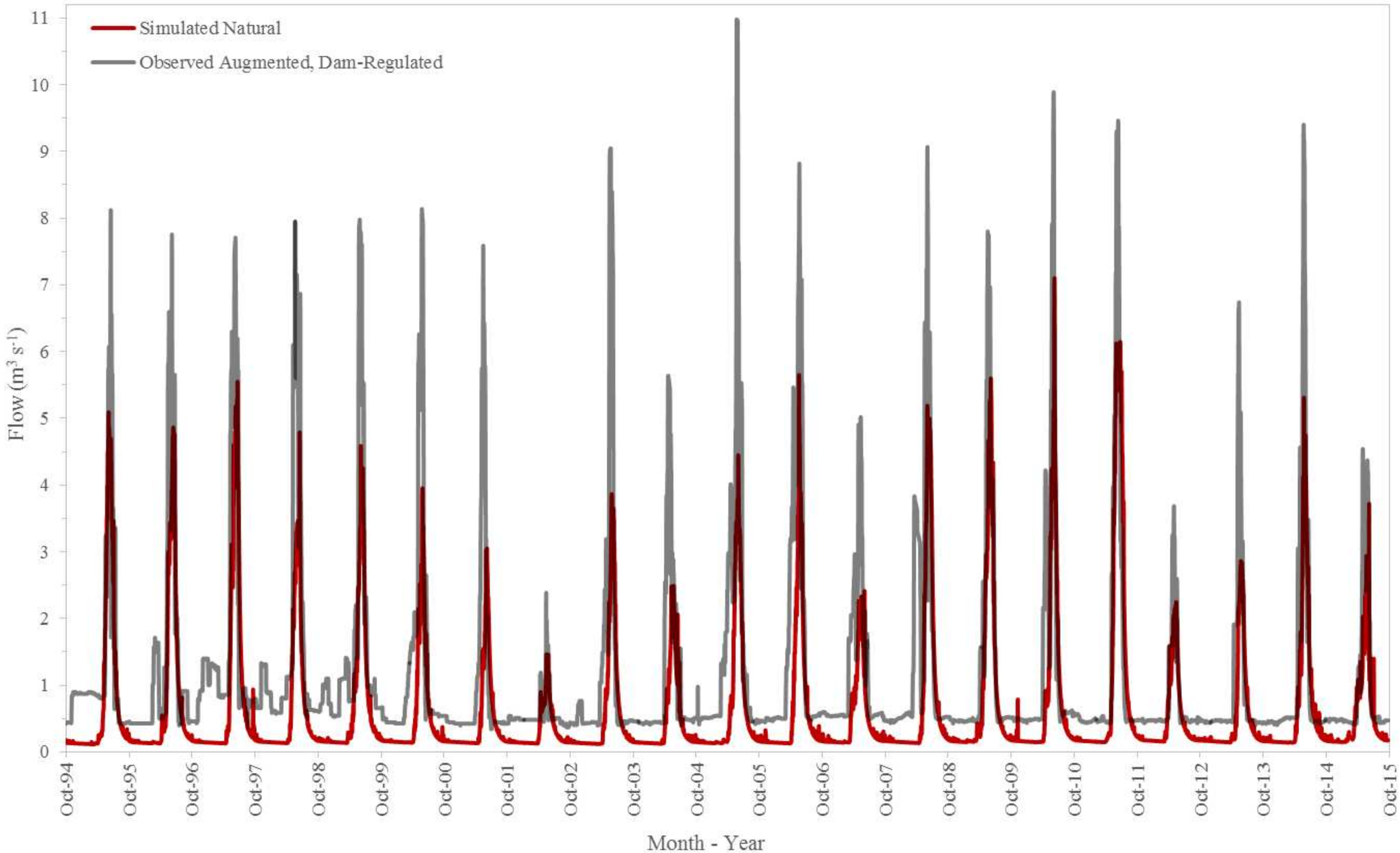

Figure 9: Simulated natural and measured flows at Hog Park Creek for 1995–2015. Simulated natural flows mimic a snow dominated hydrograph. A minimum flow of 15 $ft^3 s^{-1}$ (0.42 $m^3 s^{-1}$) was implemented in the 1980s after dam enlargement. Measured flows have higher peak and low flows, earlier winter releases, and reduced interannual variability of peaks (*e.g.*, 1995-2000).

Table 2: Flow alterations amongst Hog Park Creek simulated (HP-S) and measured (HP-M) flows, Encampment River normalized (E-N) and Hog Park Creek measured (HP-M) flows, and Battle Creek measured (B-M) and Hog Park Creek measured (HP-M) flows. DF is the deviation factor and Sig. is significance, with 0 being highly significant.

	Simulated Hog Park *vs* Hog Park				**Encampment *vs* Hog Park**				**Battle *vs* Hog Park**			
	Median				***Median***				***Median***			
	HP-S	***HP-M***	***DF***	***Sig.***	***E-N***	***HP-M***	***DF***	***Sig.***	***B-M***	***HP-M***	***DF***	***Sig.***
Number of Years (n)	***21***	***21***	-	-	***45***	***21***			***7***	***21***		
Monthly Flows												
Oct ($m^3 s^{-1}$)	0.17	0.48	1.9	0	0.17	0.48	0.6	0.2	0.13	0.48	0.7	0
Nov ($m^3 s^{-1}$)	0.15	0.48	2.1	0	0.16	0.48	0.7	0.3	0.10	0.48	0.8	0
Dec ($m^3 s^{-1}$)	0.15	0.47	2.2	0	0.12	0.47	0.7	0.3	0.10	0.47	0.8	0
Jan ($m^3 s^{-1}$)	0.14	0.47	2.3	0	0.12	0.47	0.8	0.3	0.08	0.47	0.8	0
Feb ($m^3 s^{-1}$)	0.14	0.50	2.5	0	0.11	0.50	0.8	0.3	0.08	0.50	0.8	0
Mar ($m^3 s^{-1}$)	0.14	0.51	2.7	0	0.11	0.51	0.8	0.3	0.10	0.51	0.8	0.1
Apr ($m^3 s^{-1}$)	0.35	1.13	2.2	0	0.21	1.13	0.8	0.1	0.15	1.13	0.9	0.3
May ($m^3 s^{-1}$)	1.95	3.22	0.7	0	1.59	3.22	0.5	0.1	2.07	3.22	0.4	0.1
Jun ($m^3 s^{-1}$)	3.10	3.35	0.1	0.7	2.90	3.35	0.1	0.8	3.51	3.35	0.0	0.9
Jul ($m^3 s^{-1}$)	0.66	0.52	0.2	0.3	0.55	0.52	0.1	0.6	0.45	0.52	0.1	0.2
Aug ($m^3 s^{-1}$)	0.30	0.49	0.6	0	0.20	0.49	0.6	0.1	0.18	0.49	0.6	0
Sep ($m^3 s^{-1}$)	0.20	0.47	1.4	0	0.15	0.47	0.7	0.3	0.15	0.47	0.7	0
Annual Flows												
7-day Low ($m^3 s^{-1}$)	0.13	0.44	2.3	0	0.09	0.44	0.8	0.3	0.08	0.44	0.8	0
Annual Peak ($m^3 s^{-1}$)	4.6	8.0	0.7	0	4.9	8.0	0.4	0	6.6	8.0	0.2	0.2
Baseflow Index	0.20	0.35	0.8	0	0.16	0.35	0.6	0.1	0.10	0.35	0.7	0
Reversals	100	146	0.5	0	100	146	0.3	0	46	146	0.7	0.4
Floods [Period from Start of Rising Limb to End of Falling Limb & Q_{peak} > 3.8 $m^3 s^{-1}$ (135 $ft^3 s^{-1}$)]												
Count (# of years)	14/21	19/21			30/45	19/21			7/7	19/21		
Peak ($m^3 s^{-1}$)	5.1	8.0	0.5	0	5.8	8.0	0.3	0.1	6.6	8.0	0.2	0.1
Duration (d)	93	103	0.1	0.1	73	103	0.3	0	72	103	0.3	0.1
Date of Peak	6/6	5/26	0.1	0	6/4	5/26	0.1	0.1	5/30	5/26	0.0	0.6
Rise Rate ($m^3 s^{-1} d^{-1}$)	0.10	0.14	0.3	0	0.16	0.14	0.2	0.2	0.24	0.14	0.7	0
Fall Rate ($m^3 s^{-1} d^{-1}$)	-0.09	-0.16	0.7	0	-0.12	-0.16	0.2	0.1	-0.13	-0.16	0.2	0.5

In addition to the alterations between simulated natural and measured flows at Hog Park Creek, measured flows at the Encampment River normalized by drainage area and Battle Creek were assessed (Table 2). Similar to the alterations assessed using the Hog Park Creek simulated natural flows, both the Encampment River normalized and Battle Creek flows deviated the greatest for winter and early spring monthly flows and 7-day low flows. Also, significant flow alterations of a lesser degree include higher, longer duration, more frequent, and earlier peak flows as well as faster fall rates and increased number of flow reversals.

Though similar alterations exist, there are difference amongst simulated natural Hog Park Creek, measured normalized Encampment River, and measured Battle Creek flows. Battle Creek is on the west side of the Continental Divide and has a short record. During this limited period, Battle Creek has earlier, higher magnitude, shorter duration, and flashier (*i.e.*, greater rise and fall rates) peak flows than both the Encampment River and Hog Park Creek datasets. Also, the 7-day low flow, baseflow index, and flow reversal count are less. The consistently high peak flows indicate this short sample set was during a wetter period. Compared to the simulated natural Hog Park Creek flows, the measured Encampment River flows have slightly greater and flashier (*i.e.*, rise and fall rates) peaks though slightly lower flood duration, monthly median flows, low flows, and baseflow index.

4.2 FLOW ALTERATIONS DUE TO CLIMATE

In addition to dam management, flow alterations influenced by climate are projected at Hog Park Creek using the two climate change scenarios. Both warmer-wetter and warmer-drier climate change scenarios predict more frequent, flashier peak flows. Differences between both climate change scenarios include timing, duration, and low flows (Table 3).

For the warmer-wetter scenario, simulations predict earlier snowmelt runoff for mid-century. The earlier timing is inferred by increases in April and May monthly flows, decreases in June and July monthly flows, and a shift to earlier peak flows (Table 3). Faster snowmelt is inferred by the increased frequency of floods and the faster flood rise rates. The significant increase in winter low flows results from increased basin storage from additional precipitation. For the warmer-drier scenario, simulations do not indicate earlier snowmelt timing for mid-century. Instead, a shorter snowmelt period is predicted as inferred by increased May and June monthly flow magnitudes, faster flood rise rates, and shorter duration flooding. The shorter, higher magnitude runoff along with reduced annual precipitation likely decreases basin storage. This is indicated by a slight reduction of monthly flows seen in October and April.

Table 3: Flow alterations for the warmer-wetter and -drier climate scenarios at Hog Park Creek.

	Warmer - Wetter Scenario (CanESM2 RCP 8.5) 1980-1999 vs 2040-2059				**Warmer - Drier Scenario** (INM-CM4 RCP 8.5) 1980-1999 vs 2040-2059			
	Median		*Deviation Factor*	*Significance*	***Median***		*Deviation Factor*	*Significance*
	1980s	*2040s*			*1980s*	*2040s*		
Monthly Flows								
Oct (m^3 s^{-1})	0.17	0.18	0.1	0	0.17	0.16	0	0.1
Nov (m^3 s^{-1})	0.15	0.17	0.1	0	0.15	0.15	0	0.4
Dec (m^3 s^{-1})	0.15	0.16	0.1	0	0.15	0.15	0	0.1
Jan (m^3 s^{-1})	0.14	0.16	0.1	0	0.14	0.14	0	0.1
Feb (m^3 s^{-1})	0.14	0.16	0.2	0	0.14	0.14	0	0.1
Mar (m^3 s^{-1})	0.14	0.18	0.3	0	0.14	0.14	0	0.2
Apr (m^3 s^{-1})	0.29	1.16	3.0	0	0.29	0.20	0.3	0.5
May (m^3 s^{-1})	1.59	3.66	1.3	0	1.59	1.94	0.2	0
Jun (m^3 s^{-1})	2.81	1.29	0.5	0	2.81	4.03	0.4	0
Jul (m^3 s^{-1})	0.74	0.46	0.4	0	0.74	0.83	0.1	0.5
Aug (m^3 s^{-1})	0.30	0.28	0.1	0.3	0.30	0.34	0.1	0.2
Sep (m^3 s^{-1})	0.20	0.20	0	0.8	0.20	0.21	0	0.6
Annual Flows								
7-day Low (m^3 s^{-1})	0.13	0.15	0.1	0	0.13	0.13	0	0.4
Annual Peak (m^3 s^{-1})	4.3	5.1	0.2	0.2	4.3	5.2	0.2	0.1
Date of Peak	6/8	5/18	0.1	0	6/8	6/7	0	0.6
Floods [Period that Begins during the rising limb and ends after the falling limb & Q_{peak} > 3.8 m^3 s^{-1} (135 ft^3 s^{-1})]								
Count (# of years)	14	18			14	17		
Peak (m^3 s^{-1})	5.2	5.2	0	1	5.2	5.2	0	0.9
Duration (d)	133	132	0	0.9	133	126	0	0.1
Date of Peak	6/16	5/19	0.2	0	6/16	6/9	0	0
Rise Rate (m^3 s^{-1} d^{-1})	0.09	0.12	0.2	0.1	0.09	0.11	0.2	0.1
Fall Rate (m^3 s^{-1} d^{-1})	-0.06	-0.06	0	0.7	-0.06	-0.07	0.1	0

Compared to the projected flow alterations of the two climate change scenarios, historical trends at the Encampment River provide an indication of actual flow response in a natural, reference system. Significant trends include earlier peak flows, earlier central timing of flow (tQ50), and increased low flows (Table 4). Though not significant, other trends to note include increasing peak flows and cumulative flow volume. These trends resemble the flow alterations of the projected warmer-wetter climate scenario.

The warmer-wetter climate change trend is also observed at the Whiskey Park SNOTEL site, which is most central to the Hog Park area. Though having a limited period of record, the Whiskey Park SNOTEL site had a significant warming temperature trend of 0.7 °C $decade^{-1}$ from 1987-2004 (Table 5). This trend is higher than the AR5 global warming projection of approximately 0.3 °C $decade^{-1}$ (IPCC, 2014). And, it is higher than the AR5 locally-downscaled Hog Park area warming projection of approximately 0.4 °C $decade^{-1}$. This warming trend is associated with a significantly earlier date of peak SWE trend of -6.4 days $decade^{-1}$. Also not significant, but of note, were increasing peak SWE and precipitation trends.

In contrast, the other two nearby SNOTEL sites closer resemble the warmer-drier climate change trend. To the south, the Elk River site above Willow Creek had no significant trends. The trends suggest slight warming of 0.2 °C $decade^{-1}$, a slight decrease in precipitation of -3.5 mm $decade^{-1}$, and an earlier peak SWE of -4 days $decade^{-1}$. To the north, the Webber Springs site above the North Fork of the Encampment River had a significant warming trend of +0.6 °C $decade^{-1}$. Trends that were not significant included earlier peak SWE of -2 days $decade^{-1}$, decreased SWE, and decreased precipitation. Differences amongst SNOTEL site trends indicates the spatial variability of climate distribution surrounding the Hog Park area.

Table 4: Results of the non-parametric Mann-Kendall test to detect trends and Sen's method to estimate slopes for Encampment River flows (Sen, 1968; Yue *et al*., 2002).

Encampment River Above Hog Park Creek (USGS 06623800) Period of Record: 1965 - 2015 (n = 51)					
Flow Metric	**Avg**	**Min**	**Max**	**Trend**	**Significance (α)**
Peak Q (m^3 s^{-1})	26	11	52	+ 1.2 m^3 s^{-1} $decade^{-1}$	None
Day of Peak Q	8-Jun	16-May	5-Jul	- 4.0 days $decade^{-1}$	0.001
tQ20	13-May	21-Mar	6-Jun	- 2.3 days $decade^{-1}$	0.1
tQ50	7-Jun	14-May	25-Jun	- 2.7 days $decade^{-1}$	0.01
tQ80	27-Jun	8-Jun	13-Jul	- 2.5 days $decade^{-1}$	0.01
Annual Coeff. Of Var.	1.7	1.3	2.1	+ 0.01 $decade^{-1}$	None
Cumulative Q (m^3 s^{-1})	1190	470	2260	+ 22.1 m^3 s^{-1} $decade^{-1}$	None
7-day Low Q (m^3 s^{-1})	0.5	0.3	0.70	+ 0.03 m^3 s^{-1} $decade^{-1}$	0.05

Table 5: Results of the non-parametric Mann-Kendall test and Sen's method to estimate slope of trend for nearby NRCS SNOTEL meteorological data (Sen, 1968; Yue *et al*., 2002). A full and reduced period of record for temperatures are analyzed due to sensor upgrade and relocation during 2005 and 2006, which resulted in a discontinuity in temperature data (Oyler *et al*., 2015).

NRCS SNOTEL	**Elk River**	**Whiskey Park**	**Webber Springs**
County, State	Routt, CO	Carbon, WY	Carbon, WY
Elevation (m)	2650	2730	2820
Latitude, Longitude	40.85, -106.97	41.00, -106.91	41.16, -106.93
Median Peak SWE (mm)	530	760	640
POR (n)	1979 – 2015 (37)	1987 – 2015 (29)	1981 – 2015 (35)
Trend Peak SWE (α)	- 30.5 mm $decade^{-1}$ (None)	+ 28.1 mm $decade^{-1}$ (None)	- 50.7 mm $decade^{-1}$ (None)
Trend Day of Peak SWE (α)	- 3.7 days $decade^{-1}$ (None)	- 6.4 days $decade^{-1}$ (0.1)	- 2.1 days $decade^{-1}$ (None)
Average Annual P (mm)	820	1080	1030
POR (n)	1979 – 2015 (37)	1987 – 2015 (29)	1982 – 2015 (34)
Trend P (α)	- 3.5 mm $decade^{-1}$ (None)	+ 64.8 mm $decade^{-1}$ (None)	- 6.7 mm $decade^{-1}$ (None)
Average Annual T (˚C)	3.4	1.2	2.1
Full POR (n)	1987 – 2015 (25)	1987 – 2015 (25)	1989 – 2015 (25)
Trend T (α)	+ 0.6 °C $decade^{-1}$ (0.001)	+ 1.0 °C $decade^{-1}$ (0.001)	+ 0.9 °C $decade^{-1}$ (0.001)
Reduced POR (n)	1987 – 2005 (15)	1987 – 2004 (15)	1989 – 2004 (15)
Trend T (α)	+ 0.2 °C $decade^{-1}$ (None)	+ 0.7 °C $decade^{-1}$ (0.05)	+ 0.6 °C $decade^{-1}$ (0.1)

4.3 CHANNEL ENLARGEMENT

The net channel enlargement for the Hog Park Creek reach was 12.6 m^2 for the last 10-year (2006-2015) period. In comparison, a South Fork Hog Park Creek reach enlarged 4.1 m^2. The unregulated South Fork reach is considered a reference because it has a similar native drainage area (32 km^2), legacy of anthropogenic impacts, and climate. However, several notable disturbances in the last decade including road crossing washouts, logging, and cattle grazing likely affected channel stability. A representative Hog Park Creek pool (Site 1, XS 0.9) widened 3.6 m compared to 0.7 m of widening at the South Fork pool (Site 4, XS 1.1) (Figure 10).

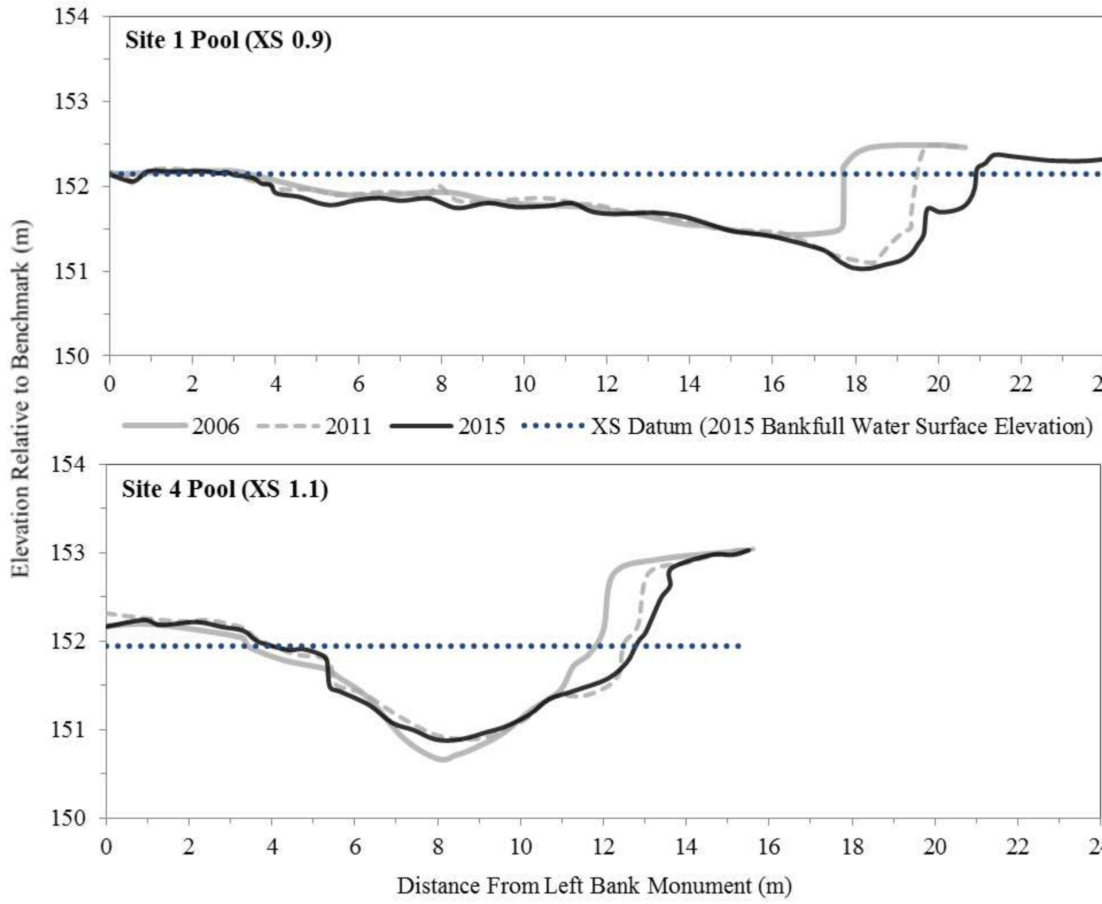

Figure 10: Comparing representative pools at Hog Park (Site 1) and its South Fork (Site 4). Blue dotted line approximates bankfull level.

The spatially variable enlargement of Hog Park Creek made identification of ocular bankfull field indicators difficult. To assist, HEC RAS simulated the wetted perimeter of high flows between 2.8-7.1 $m^3 s^{-1}$ for 2006 and 2015. A breakpoint on the wetted perimeter-flow curve approximates the geomorphic bankfull flow. Major breakpoints indicate bankfull flow increased from 4.6-4.8 $m^3 s^{-1}$ in 2006 to 5.4-5.6 $m^3 s^{-1}$ in 2015 (Figure 11). Additionally, minor breakpoints exist near 3.7-4.0 $m^3 s^{-1}$ in both 2006 and 2015, which may indicate the bankfull flows of an earlier period.

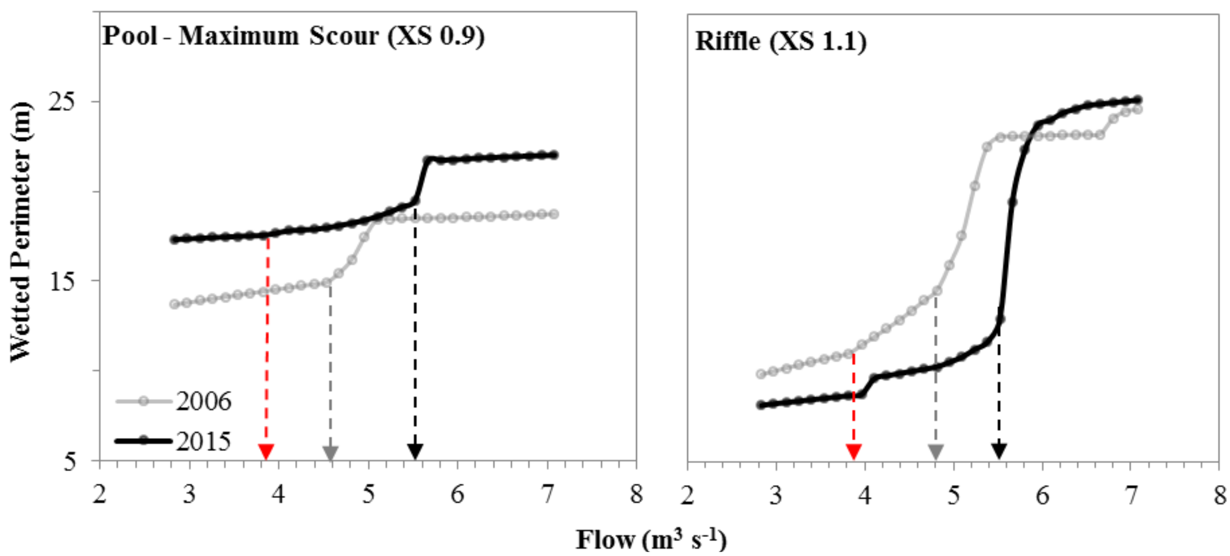

Figure 11: HEC RAS wetted perimeter-flow curves estimate bankfull flow at Hog Park Creek below the dam. Major breakpoints in 2006 (gray dash) and 2015 (black dash) indicate bankfull flows increased from about 4.7 to 5.5 $m^3 s^{-1}$. Additionally, minor breakpoints (red dash) present in both 2006 and 2015 indicate bankfull flows may have been 3.9 $m^3 s^{-1}$ for an earlier period.

The 2015 wetted perimeter-flow curve breakpoints correspond to the average of 2015 ocular field indicator estimates, but differ from recurrence interval and effective discharge estimates of bankfull flow. The recurrence interval estimates depend on the period of record. The measured 1.5-year flood is 5.8 $m^3 s^{-1}$ when using the period since dam enlargement (1987-2015) and is 6.1 $m^3 s^{-1}$ when using the full period (1970-2015). When using the last 21 years, the 1.5-year flood is 7.6 $m^3 s^{-1}$ for the measured flows. Similar to the measured 1.5-year flood for the period since dam enlargement, the effective discharge bankfull flow is 5.8 $m^3 s^{-1}$. In comparison, the 1.5-year flood using the simulated natural flows is 3.8 $m^3 s^{-1}$. This is similar to the wetted perimeter-flow curve minor breakpoint and normalized Encampment River estimates of bankfull flow (Table 6).

Table 6: The wetted perimeter-flow curve bankfull flow estimate, recurrence intervals, regional regression, effective discharge, and ocular estimates. WY Rocky Mountain area Regional Regression value has a standard error of prediction of 56% (Miller, 2003).

Method to Estimate Bankfull Flow	**Year(s)**	**Bankfull Q ($m^3 s^{-1}$)**	**Bankfull Q ($ft^3 s^{-1}$)**
1.5-year Flood: WY Regional Regression	< 2000	2.8	99
1.5-year Flood: Encampment River Normalized Flows	1965-2015	3.6	126
Wetted Perimeter-Flow Curve: Minor Breakpoints	2006 & 2015	3.7-4.0	130-140
1.5-year Flood: PRMS Simulated Natural Flows	1995-2015	3.8	133
Wetted Perimeter-Flow Curve: Major Breakpoints	2006 / 2015	4.6-4.8 / 5.4-5.6	160-170 / 190-200
Ocular Indicators	2015	5.2-5.6	185-200
Effective Discharge: Observed flows (Stage II)	1987-2015	5.8 (5.7-6.1)	206 (200-215)
1.5-year Flood: Observed Flows (Stage II)	1987-2015	5.8	206
1.5-year Flood: Observed Flows (Stage I & II)	1970-2015	6.1	215
1.5-year Flood: Observed Flows (Last 21 years)	1995-2015	7.6	269

Using the 2006 and 2015 wetted perimeter-flow curve bankfull flow estimates, the effect of channel enlargement is further evaluated by simulating water surface elevation (WSE) and flood inundation area. Even as bankfull flow estimates increase from 2006 to 2015, HEC RAS simulates a WSE decrease of 1.8 cm at the representative pool and 4.2 cm at the representative riffle. This results in an average decrease in WSE of 3.0 cm over the reach. Additionally, the simulated flood inundation area decreases 2025 m^2 along the upstream 30 m pool-to-pool segment (XS 0.9 to XS 1.3) of the reach (Figure 12). This is a rate of -70 m^2 per 1 m of stream length per decade. Thus, the enlargement at Hog Park Creek during the last 10 years is shown to correspond to increased bankfull flow magnitude and decreased WSE and flood inundation area.

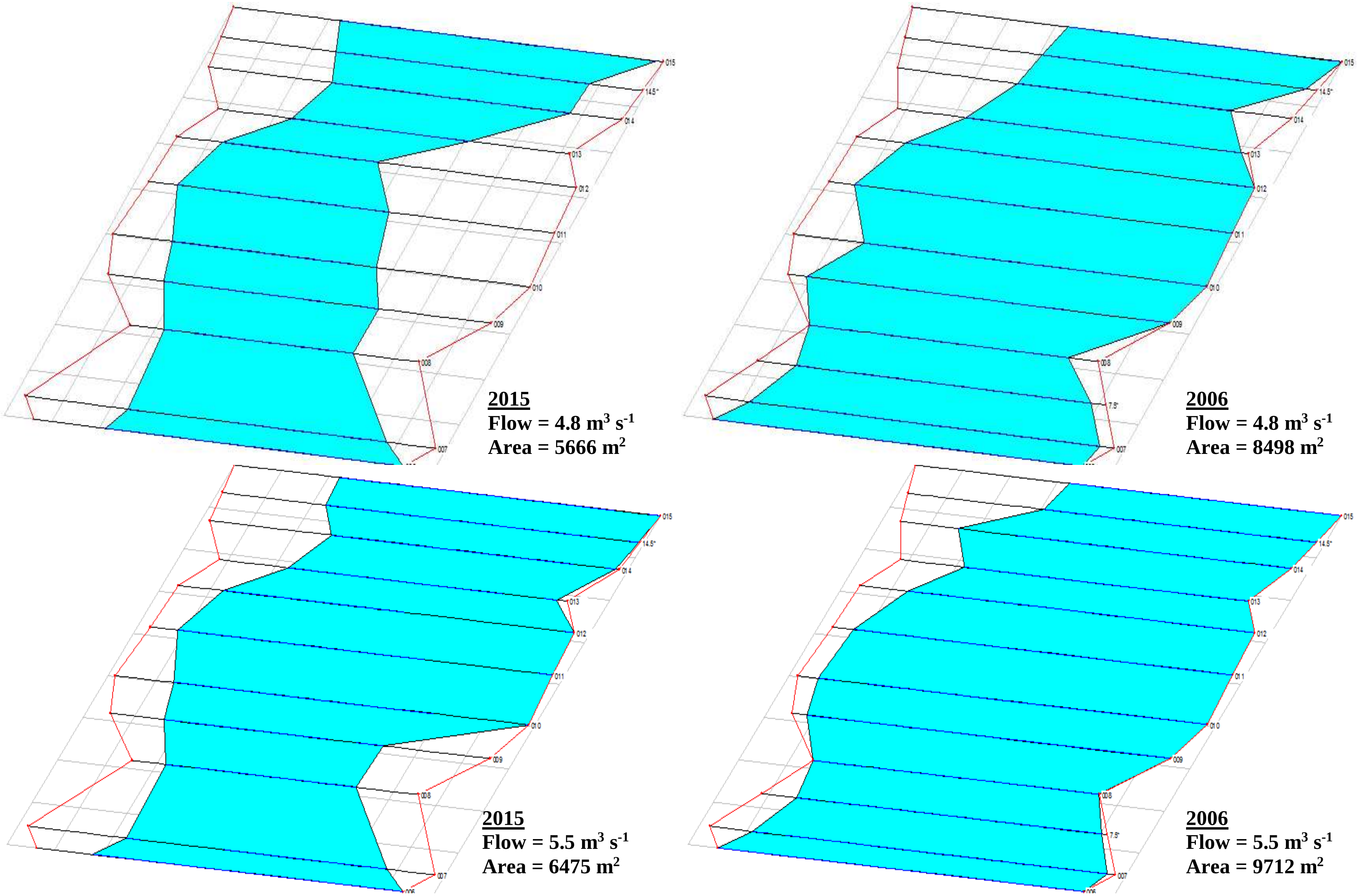

Figure 12: The upstream 30 m pool-to-pool segment of the Hog Park Creek reach below the dam (Site 1, Pool XS 0.9 and Pool XS 1.3). Comparing wetted perimeter-flow curve estimated bankfull flows (4.8 $m^3 s^{-1}$ in 2006 and 5.5 $m^3 s^{-1}$ in 2015), simulated flood inundation area (blue) decreased near a rate of 70 m^2 per 1 m of stream length per decade.

5. DISCUSSION

5.1 FLOW ALTERATIONS

To assess flow alterations due to dam management, the measured flows were compared to simulated natural and reference flows. All three comparisons indicate the greatest deviations were increased 7-day low and January-April monthly flows. To a lesser degree of deviation, all three comparisons indicate earlier floods; faster flood fall rates; and increased flood magnitude, duration, and frequency. The causes of these three main sets of flow alterations are considered from the specific aspects of dam management.

The first flow alteration considered is increased low flow. The 7-day low flow more than tripled from an estimated 0.13 to 0.44 $m^3 s^{-1}$. This increase is due to a 0.42 $m^3 s^{-1}$ (15 $ft^3 s^{-1}$) minimum flow specified in the WWF settlement that is incorporated in the 1982 and 2014 easements. In addition, the WWF settlement stipulates the minimum flow may be reduced from 0.42 $m^3 s^{-1}$ (15 $ft^3 s^{-1}$) to 0.21 $m^3 s^{-1}$ (7 $ft^3 s^{-1}$) if agreed to by the Forest Supervisor. Augmenting low flow year-round has the potential to increase boundary shear stress at the bank toe. In two similar trans-basin diversion case studies with increased low flow and no change to peak flows, continued channel enlargement was observed (Kellerhals *et al.,* 1979; Petts and Pratt, 1983).

Similar to low flows, increased intermediate flows in the early spring potentially increase boundary shear stress against lower stream banks. The April monthly flows in Hog Park Creek more than tripled from an estimated 0.35 to 1.13 $m^3 s^{-1}$. This is due to advancing Little Snake River water stored during April for surplus North Platte River water diverted during June snowmelt. Thus, coordinating the exchange of Little Snake and North Platte River water during snowmelt is important for reducing early releases.

One aspect limiting this one-for-one exchange is channel capacity. Channel capacity is limited during snowmelt when conveying native Hog Park Creek water and extra Little Snake River water. Based on Hog Parks Creek's relatively small channel capacity during the 1970s, the 1982 easement stipulated a maximum flow of 5.7 $m^3 s^{-1}$ (200 $ft^3 s^{-1}$) except during wet years when native flows exceeded the limit. The intent of this term was to 1) minimize channel enlargement by limiting artificial peak flows during average and dry years, but 2) retain naturally large floods during wet years. However, implementing this limit has been problematic without estimating natural flows. This is seen during 1995-2001 when simulated natural flows indicate average and dry water years, but measured flows are consistently high (Figure 9).

Peak flow alterations are the third set considered. In similar trans-basin diversion case studies, increased magnitude of peak flows are a main contributor of channel enlargement (Dominick and O'Neill, 1998; Wohl and Dust, 2012). The peak flow attributes most altered at Hog Park Creek are influenced by inflow regulation of Little Snake River water and reservoir storage. For example, the measured Hog Park Creek peak flows occur at about the same time as the Little Snake River inflow peaks. The measured peak flow timing is commonly earlier than Hog Park Creek simulated natural and Encampment River normalized peak flow timing (Table 7). The influence of Little Snake River inflows on peak flow timing and magnitude is most apparent in average and dry water years (Figures 13a and 13c). Additionally, the Hog Park Creek measured fall rates are increased by rapid inflows from the Little Snake River diversions. For example, the highest measured fall rate of -3.8 $m^3 s^{-1} d^{-1}$ at Hog Park Creek occurred the same year as the Little Snake River inflow maximum fall rate -5.9 $m^3 s^{-1} d^{-1}$ in 2008 (Table 7). However, the consistently lower fall rates at Hog Park Creek indicates the rapid fall rates of the Little Snake River inflows are attenuated by reservoir storage.

Table 7: Peak flow attributes of Little Snake measured inflows (LS-M) compared to Hog Park measured outflows (HP-M), Hog Park simulated natural flows (HP-S), and measured Encampment River normalized flows (E-M). [*inflow peak is bimodal 5/18 and 5/27]

	Peak Flow Magnitude ($m^3 s^{-1}$)				Date of Peak				Max Fall Rate ($m^3 s^{-1} d^{-1}$)			
WY	LS-M	HP-M	HP-S	E-M	LS-M	HP-M	HP-S	E-M	LS-M	HP-M	HP-S	E-M
2006	9.2	8.8	5.6	5.5	5/23	5/25	5/23	5/23	-2.0	-1.5	-0.9	-1.1
2007	6.3	5.0	2.4	3.2	5/15	5/16	5/19	5/21	-1.2	-1.1	-0.9	-0.7
2008	11.0	9.1	5.2	6.0	6/8	6/6	6/6	6/5	-5.9	-3.8	-0.4	-1.2
2009	7.7	7.8	5.6	6.0	5/20	5/22	6/9	6/3	-1.7	-2.0	-1.7	-0.8
2010	10.0	9.9	7.1	8.8	6/7	6/8	6/13	6/8	-2.4	-1.4	-1.7	-1.4
2011	4.9	9.5	6.1	8.9	6/16	6/17	6/29	6/30	-1.6	-2.0	-1.0	-1.8
2012	3.7	3.7	2.2	2.3	5/6	5/6	5/20	5/20	-0.6	-0.9	-0.4	-0.5
2013	7.2	6.7	2.9	3.5	5/18*	5/18	5/29	5/26	-1.2	-1.4	-0.3	-0.5
2014	7.4	9.4	5.3	7.0	5/27	5/28	5/30	5/30	-2.3	-1.1	-0.7	-1.1
2015	3.4	4.5	3.7	3.7	5/7	5/6	6/12	6/3	-1.4	-0.9	-0.8	-0.3
Avg	7.1	7.4	4.6	5.5	5/24	5/24	6/3	6/1	-2.0	-1.6	-0.9	-0.9
Min	3.4	3.7	2.2	2.3	5/6	5/6	5/19	5/20	-5.9	-3.8	-1.7	-1.8
Max	11.0	9.9	7.1	8.9	6/16	6/17	6/29	6/30	-0.6	-0.9	-0.3	-0.3

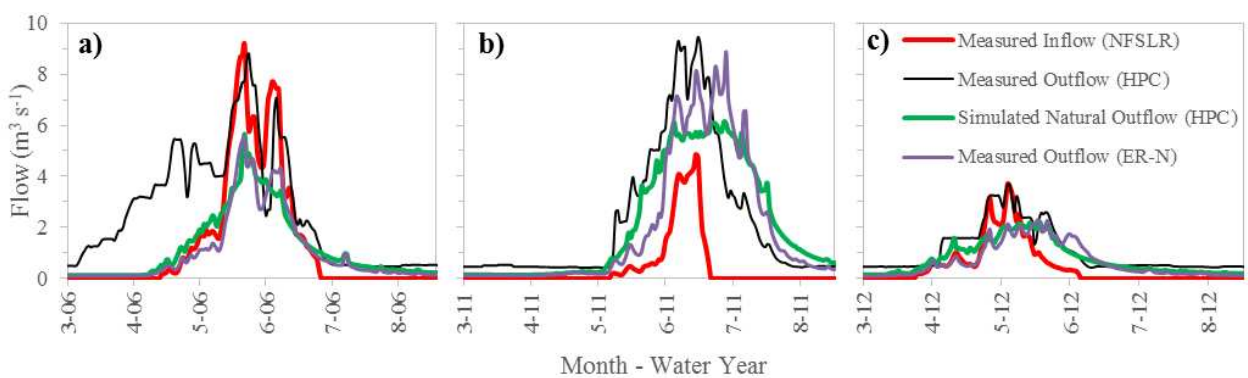

Figure 13: The peak flow period for measured Little Snake River inflows, measured Hog Park Creek outflows, simulated natural Hog Park Creek flows, and measured Encampment River normalized flows. a) Average year (2006); b) wet year (2011); and c) dry year (2012).

In addition to flow alterations influenced by dam management, flow alterations influenced by climate change were assessed using historical flow trends using Encampment River flow and future flow projections using Hog Park Creek simulated natural flows. The historical flow trends reflect increased temperature and precipitation. Increases in temperature and precipitation were measured at the nearby Whiskey Park SNOTEL site. This warmer-wetter historic climate trend places Hog Park Creek on course with the mid-century warmer-wetter climate change scenario. The flow alterations projected by the warmer-wetter climate change scenario by mid-century include increasing low flows and earlier, more frequent and greater magnitude peak flows.

When compared to the flow alterations due to dam management at Hog Park Creek, most of the projected flow alterations due to climate change are minor. The projected increase in peak flow magnitude is +0.13 $m^3 s^{-1}$ per decade, which is an increase from the median magnitude of 4.3 to 5.1 $m^3 s^{-1}$ by mid-century (Table 3). This is a minor increase compared to the current artificial median peak magnitude of 8.0 $m^3 s^{-1}$ (Table 2). Similarly, the projected low flow increase of 0.13 to 0.15 $m^3 s^{-1}$ for mid-century is minor compared to the currently observed 0.44 $m^3 s^{-1}$ (Tables 2 and 3). However, the peak flow timing is projected to shift towards earlier peaks than what is currently observed. Presently, the artificial peak flow timing occurs around late May. The historic trend is -4 days per decade and similarly, the warmer-wetter climate change scenario projection is -3.5 days per decade (Tables 3 and 4). This predicts a shift in peak flow timing from early June in 2015 to mid-May by mid-century. For this particular flow attribute, dam management has the potential to buffer changes to peak flow timing due to climate change.

5.2 CHANNEL ENLARGEMENT

The geomorphic response to flow alteration at Hog Park Creek includes irregular channel widening and bed degradation. This response is consistent with the qualitative response model and findings of similar trans-basin diversion case studies (Brandt, 2000; Wohl and Dust, 2012). Specifically, riffle cross-sections (XS) changed little and pool XSs located near the maximum point of scour enlarged substantially in width and depth. The result of the spatially-variable enlargement is an overall decrease in water surface elevations and flood inundation. Thus, as the channel continues to enlarge the minimum bankfull flow or flow required to overtop banks and disperse into the floodplain increases.

Assuming bankfull flow is the primary influence of alluvial channel form at Hog Park Creek, increases in bankfull flow track the progression of channel enlargement. One consistency between bankfull flow estimate results was found in 2015. Both the 2015 ocular indicators and wetted perimeter-flow curve major breakpoints indicate the channel enlarged to a bankfull capacity near 5.5 $m^3 s^{-1}$ (195 $ft^3 s^{-1}$). A second consistency in bankfull flow estimate results was between the simulated natural 1.5-year flood and the 2006 and 2015 wetted perimeter-flow curve minor breakpoints. These two methods indicated a pre-dam bankfull flow near 4 $m^3 s^{-1}$ (140 $ft^3 s^{-1}$). Additionally, this agreement suggests the 1.5-year flood is an appropriate recurrence interval for approximating bankfull flow. Thus, it is probable Hog Park Creek is enlarging to a bankfull channel capacity near the contemporary 1.5-year flood.

At Hog Park Creek, the value of the contemporary 1.5-year flood depends on the period of record. The 1.5-year flood for the last 30-year period since dam enlargement is 5.8 $m^3 s^{-1}$ (206 $ft^3 s^{-1}$). This magnitude is consistent with the effective discharge for the same period. Because 5.8 $m^3 s^{-1}$ is slightly greater than the estimated 2015 bankfull channel capacity 5.5 $m^3 s^{-1}$ (195 $ft^3 s^{-1}$), channel enlargement may be approaching an end. Alternatively, the channel may be enlarging to a much greater capacity of 7.6 $m^3 s^{-1}$ (269 $ft^3 s^{-1}$). This magnitude reflects the 1.5-year flood for the last 20-year period. The large discrepancy between 1.5-year flood estimates of 30- and 20-year time periods is indicative of the highly variable flow regime. These two scenarios based on the 1.5-year flood highlight the importance of a stable flow regime for supporting channel stabilization and ecologic processes.

6. CONCLUSIONS

This study assessed flow alterations and channel enlargement at Hog Park Creek. Climate change was also evaluated to understand its role in past and future flow alterations. To understand the possible causes of flow alterations, unique aspects of dam management were reviewed. To understand the progression of channel enlargement, a connection between the 1.5-year flood and geomorphic bankfull channel capacity was explored. The ecologic implications of continued channel enlargement were evaluated by modeling changes in water surface elevations and flood inundation area. Based on the findings of this study, recommendations are prescribed for adaptive management.

The flow alterations due to dam management were determined by comparing Hog Park Creek measured flows to simulated natural flows and measured reference flows. All three of the flow comparisons indicated the greatest significant deviations were increased low flows and increased January-April monthly flows. The 7-day low flow and April monthly flows increased by more than three-fold. To a lesser degree, attributes of peak flows were also significantly altered. Peak flow alterations included increased magnitude, duration, and frequency as well as faster fall rates and earlier timing.

Presently, the flow alterations due to climate change are minor relative to the flow alterations due to dam management. The historic flow trends at the Encampment River include significantly greater low flows and earlier peak flow timing. These historic flow trends reflect increased temperature and precipitation. Correspondingly, the nearby Whiskey Park SNOTEL site measured a warmer-wetter climate. Assuming the warmer-wetter climate trend continues into the future, increases to low flows and earlier peak flows are projected to continue. For the warmer-wetter climate change scenario, the mid-century date of peak flow is projected to occur earlier than peak flow timing under current dam management. Based on the measured trends and modeled projections, future dam management could be affected by climate change and thus, the future flow regime and channel stability.

The causes of flow alterations due to dam management stem from unique state water rights and exchange agreements. One consequence is the need to rapidly exchange trans-basin diversion inflows using Hog Park Creek for upstream North Platte River water captured during snowmelt. The rapid inflow of trans-basin diversion water in dry and average water years has contributed to altered peak flow timing, magnitude, and fall rates. Additionally, advanced releases of stored trans-basin diversion water has contributed to the flow alterations in January-April. Thus, a key limiting factor in this unique situation is the channel capacity of Hog Park Creek to convey native and imported water during snowmelt.

Since flows have increased in Hog Park Creek following dam construction and trans-basin diversion, the channel capacity has continued to increase. Channel enlargement includes irregular channel widening and bed degradation. The 1960s pre-dam bankfull channel capacity is estimated to hold a flow of 3.8 $m^3 s^{-1}$ (135 $ft^3 s^{-1}$). Over the last decade from 2006 to 2015, the bankfull channel capacity increased from a flow of 4.8 to 5.5 $m^3 s^{-1}$ (170 to 195 $ft^3 s^{-1}$). Evidence that the 1.5-year flood approximates the geomorphic bankfull flow at Hog Park Creek supports bankfull theory for alluvial channels. Thus, the 1987 to 2015 1.5-year flood places channel enlargement on trajectory to reach 5.8 $m^3 s^{-1}$ (205 $ft^3 s^{-1}$). However, if peak flows remain higher as observed over the last 21 years, the 1995 to 2015 1.5-year flood could place channel enlargement on trajectory to reach 7.6 $m^3 s^{-1}$ (270 $ft^3 s^{-1}$). This suggests channel enlargement will continue under current dam management, but the endpoint will depend on the flow regime.

The implications of continued channel enlargement due to dam management are decreased water surface elevation and decreased flood inundation area. Between 2006 and 2015, HEC RAS modeling indicated a decrease in water surface elevation by 3 cm per decade and a decrease in flood inundation area of about 70 m^2 per 1 m of stream length per decade. The effect of a wider and deeper channel, drop in water table depth, and reduction of flood inundation extent is the contraction of aquatic and riparian habitat. The future channel stability of Hog Park Creek is unlikely without a stable flow regime, such as one that hinges around a consistent 1.5-year flood. Similarly, the greatest flow alterations were identified and their causes were explored through review of dam management guiding documents. The understanding of how channel enlargement is influenced by dam management provides a foundation for improving riparian and aquatic resource conditions. Using this knowledge, recommendations are developed for dam management to better integrate aquatic and riparian resource protection with their critical water supply objectives.

7. RECOMMENDATIONS

In the case of Hog Park Creek, the channel is disturbed by the increased flows. Given the altered flows and enlarging channel, the goal is to develop a modified flow regime which supports a stable channel form. Attributes of this modified flow regime will not equal its natural state, but mimic characteristics of its natural state. Similarly, the magnitude of flows will be modified to support a larger, self-regulating channel form. These recommendations focus on the attributes of the modified flow regime including the magnitude of flows that support a stable channel form near the current capacity.

The attributes of a modified flow regime are based on findings of this study. These attributes focus on low, average monthly, and peak flows. Peak flow attributes include timing, frequency, magnitude, duration, and fall rates. Additionally, a range of peak flow magnitudes are discussed to align the 1.5-year flood over the next 20 years closer to the current channel capacity.

Implementing these flow recommendations without modeling reservoir operations may not be conducive to meeting all water resource objectives. Simulating reservoir operations can assist in understanding where limitations exist when balancing these flow recommendations with essential water resource objectives. The Hydrologic Engineering Center’s Reservoir System Simulation (HEC-ResSim) is one example of a reservoir operations model (USACE, 2007). Using the flow recommendations in this chapter with operating limits to parameterize a reservoir model assists in determining flows required under different snowpack scenarios. A reservoir operations model is one method for understanding how to implement flow releases which meet both environmental and water resource objectives.

Regarding low flows, minimum flow limit of 15 $ft^3 s^{-1}$ is exceeded August through February, when flows are commonly between 18-21 $ft^3 s^{-1}$. These flows should be reduced closer to 15 or 16 $f^{t3} s^{-1}$, if not lower if determined by future aquatic habitat analysis. The WWF settlement specified a minimum flow of 15 $ft^3 s^{-1}$ which at least triples the natural low flows. There was also a stipulation in the WWF settlement to reduce this requirement to 7.5 $ft^3 s^{-1}$, should future analysis confirm this value. If the current minimum flow is based on fish habitat requirements in the 1970s, a new aquatic habitat analysis is likely needed since there are extensive channel changes. The possible benefit of reevaluating the minimum flow is improving aquatic habitat. Additionally, should reevaluated aquatic habitat requirements discover low flow recommendations which are less than 15 $ft^3 s^{-1}$, there is a cost savings of not storing the Little Snake River exchange water downstream in Seminoe Reservoir in years when it is not needed.

More of an influence on channel enlargement than low flows are the increased spring flows in April, which at least tripled. In contrast, flows in July are less than the natural flows (Table 2). Therefore, April releases should be redistributed to July. In the provided table of average monthly flow recommendations, April and May flows are reduced and June and July flows are increased (Table 8). It should be noted that simulating reservoir operations in conjunction with all of the flow recommendations could refine the average monthly flow estimates as well as provide an additional range of flows for dry and wet years.

The result of reducing low and intermediate flows is decreased annual cumulative volume of flow. Relative to flows during 1995-2015, this is approximately a 4,000 AF (acre-feet) annual reduction which is a drop from about 17,000 to 13,000 AF for an average water year (Table 8). This is a substantial drop from a proposed water release schedule from 1981 where the cumulative volume of flow was estimated near 21,000 AF (Table 8).

Table 8: An example of recommended water release scheduling using average monthly flows. For comparison, three sets of natural average monthly flows include the Hog Park Creek simulated natural, Encampment River normalized, and Hog Park Creek natural flows. The Hog Park Creek natural flows (1947-1971) were obtained from a table in the original proposed water release schedule (FEIS, 1981). The Cheyenne Board of Public Utilities (CBPU) flow is the total flow released below the dam (native and trans-basin diversion water) minus the 'Hog Park Natural' flow. The cumulative (Σ) flow in acre-feet (AF) estimates the volume of water.

Average Monthly Flows																	
	Natural Flows						***Original Proposal*** *(FEIS, 1981)*			***Measured Flows***			***Recommended Flows***		
	Hog Park Simulated Natural (1995-2015)		**Encampment River Normalized** (1995-2015)		**Hog Park Natural** (1947-1971)		**Hog Park Water Release Schedule**			**Hog Park Creek Measured** (1995-2015)			**Hog Park Creek Water Release Schedule** (2015-2035)		
Month	*($ft^3\ s^{-1}$)*	*(AF)*	*($ft^3\ s^{-1}$)*	*(AF)*	*($ft^3\ s^{-1}$)*	*(AF)*	*Total ($ft^3\ s^{-1}$)*	*CBPU ($ft^3\ s^{-1}$)*	*CBPU (AF)*	*Total ($ft^3\ s^{-1}$)*	*CBPU ($ft^3\ s^{-1}$)*	*CBPU (AF)*	*Total ($ft^3\ s^{-1}$)*	*CBPU ($ft^3\ s^{-1}$)*	*CBPU (AF)*
Oct	**6**	369	**6**	369	**4**	246	**20**	16	984	**18**	14	861	**15**	11	676
Nov	**6**	357	**5**	298	**3.4**	202	**20**	17	988	**20**	17	988	**15**	12	690
Dec	**5**	307	**4**	246	**2.9**	178	**20**	17	1051	**20**	17	1051	**15**	12	744
Jan	**5**	307	**4**	246	**2.6**	160	**20**	17	1070	**19**	16	1008	**15**	12	762
Feb	**5**	278	**4**	222	**2.7**	150	**20**	17	961	**21**	18	1016	**15**	12	683
Mar	**6**	369	**4**	246	**3.3**	203	**20**	17	1027	**30**	27	1642	**15**	12	719
Apr	**17**	1012	**10**	595	**10**	595	**24**	14	833	**60**	50	2975	**25**	15	893
May	**72**	4427	**62**	3812	**72**	4427	**170**	98	6026	**135**	63	3874	**105**	33	2029
Jun	**99**	5891	**107**	6367	**102**	6069	**200**	98	5831	**125**	23	1369	**140**	38	2261
Jul	**32**	1968	**31**	1906	**21**	1291	**38**	17	1045	**28**	7	430	**50**	29	1783
Aug	**12**	738	**8**	492	**6**	369	**25**	19	1168	**19**	13	799	**25**	19	1168
Sep	**8**	476	**6**	357	**3.9**	232	**15**	11	660	**18**	14	839	**15**	11	660
Annual Σ Volume (AF)		16,499		15,156		14,123			21,645			16,853			13,070

The recommended increase in July flows should coincide with a gradual fall rate during the recession of peak flows. The rise and fall rates are calculated as the difference in daily average flows between two consecutive days. The recommended rise or fall rate depends on the initial day's daily average flow. For example, if the initial day has a daily average flow above 100 $ft^3 s^{-1}$ and flows are receding, then the recommended fall rate is approximately -20 $ft^3 s^{-1} d^{-1}$ (Table 9). A range of rise and fall rates are included, but the rates should increase and decrease in proportion to the magnitude of the annual peak flow. For example, if the annual peak flow was 250 $ft^3 s^{-1}$ and flows began to recede, an initial fall rate should be near -30 $ft^3 s^{-1} d^{-1}$ for the first day, then -25 $ft^3 s^{-1} d^{-1}$ for the second day, and then level off near -20 $ft^3 s^{-1} d^{-1}$ for the next several days until 100 $ft^3 s^{-1}$. At 100 $ft^3 s^{-1}$, the fall rates should slowly decrease from -15 $ft^3 s^{-1} d^{-1}$. The intent of these recommendations is to provide simple, reasonable bounds to expect for rise and fall rates while also incorporating flexibility for larger or small peak flows.

Table 9: Comparison of annual maximum rise and fall rates at Hog Park Creek and the Encampment River from 1995 to 2015. Units are in cubic feet per second per day ($ft^3 s^{-1} d^{-1}$).

	Flow Criteria ($ft^3 s^{-1}$)	**Hog Park Creek Simulated Natural**		**Encampment River Normalized**		**Hog Park Creek Measured**		**Recommended Rise and Fall Rates**
		Median ($ft^3 s^{-1} d^{-1}$)	**Range** ($ft^3 s^{-1} d^{-1}$)	**Median** ($ft^3 s^{-1} d^{-1}$)	**Range** ($ft^3 s^{-1} d^{-1}$)	**Median** ($ft^3 s^{-1} d^{-1}$)	**Range** ($ft^3 s^{-1} d^{-1}$)	**Median (Range)** ($ft^3 s^{-1} d^{-1}$)
Annual Max Rise Rate	*All Q*	33	11 to 65	29	11 to 65	57	26 to 90	
	Q>100	30		31		52		30 (10 to 65)
	Q<100	18		22		43		< 25
Annual Max Fall Rate	*All Q*	-28	-9 to -60	-27	-10 to -65	-57	-26 to -135	
	Q>100	-25		-30		-63		-20 (-10 to -60)
	Q<100	-12		-14		-20		< -15
	Q>250	*-59*	*-59*	*-56*	*-48 to -65*	*-46*	*-23 to -71*	
	150<Q<250	*-25*	*-13 to -60*	*-31*	*-18 to -56*	*-54*	*-11 to -135*	
	60<Q<150	*-17*	*-9 to -42*	*-21*	*-4 to -37*	*-35*	*-18 to -74*	
	Q<60	*-10*	*-4 to -28*	*-10*	*-4 to -20*	*-13*	*-6 to -29*	

Along with reducing the annual cumulative volume of flow, a reduction in peak flows relative to the peaks measured in 1995-2015 is recommended. A jump in peak flows is observed from the 206 $ft^3\ s^{-1}$ 1.5-year flood of the last 30 years compared to the 269 $ft^3\ s^{-1}$ 1.5-year flood of the last 21 years (Table 6 and 10). As of 2015, Hog Park Creek has enlarged to a bankfull flow near 195 $ft^3\ s^{-1}$. To support channel stabilization efforts, flood magnitude recommendations for the next 21 years are based on a 1.5-year flood of 200 $ft^3\ s^{-1}$. Additionally, a maximum daily average flow of 315 $ft^3\ s^{-1}$ is recommended based on the highest Encampment River normalized peak flow from 1965-2015. This can be simplified into drier years with peaks between 130-200 $ft^3\ s^{-1}$, average years with peaks between 200-275 $ft^3\ s^{-1}$, and wetter years with peaks between 275-315 $ft^3\ s^{-1}$. To maintain a 1.5-year flood of 200 $ft^3\ s^{-1}$ for the next 21 years, the count should be approximately 7 peaks varied in each 130-200 $ft^3\ s^{-1}$, 200-275 $ft^3\ s^{-1}$, and 275-315 $ft^3\ s^{-1}$ range.

Since peak flows are partly controlled by climate, the artificial peak flows should attempt to mimic the interannual variability of dry, average, and wet years. Based on the simulated and reference natural flows, less-frequent large floods with high peak flows should not occur in consecutive years. Instead, consecutive years of small peak flows with small floods or no flooding should follow a wet year where there is a large flood with a high peak flow (Figure 14).

The timing of the artificial peak flows measured at Hog Park Creek are typically too early. In addition to the shifting of flows from April and May to June and July, it is recommended to shift peak flow timing to occur closer to June 8th. Based on the earliest and latest peak flows on record at the Encampment River, a recommended window for peak flows is May 16th to July 5th (Figure 14). In addition, a recommendation for the earliest date to start the slow rise of flows in the spring is April 15th. Similarly, a recommendation for the latest date to end the slow fall of flows in the summer is August 15th (Figure 14).

Table 10: Peak flow recommendations for recurrence intervals based on the 2015 channel capacity near a 1.5-year flood of 200 $ft^3\ s^{-1}$.

Recurrence Intervals (RI)						
RI (years)	**% Chance of Occurrence in Any Given Year**	**Hog Park Simulated Natural ($ft^3\ s^{-1}$)** 1995-2015	**Encampment River Normalized ($ft^3\ s^{-1}$)** 1995-2015	**Hog Park Measured ($ft^3\ s^{-1}$)** 1995-2015	**Hog Park Measured ($ft^3\ s^{-1}$)** 1987-2015	**Recommended Peak flow ($ft^3\ s^{-1}$)** 2015-2035
1.1	91%	80	81	130	160	130
1.5	66.6%	133	135	269	206	200
2	50%	162	172	281	268	230
5	20%	197	220	327	319	275
20	5%	244	313	379	361	315

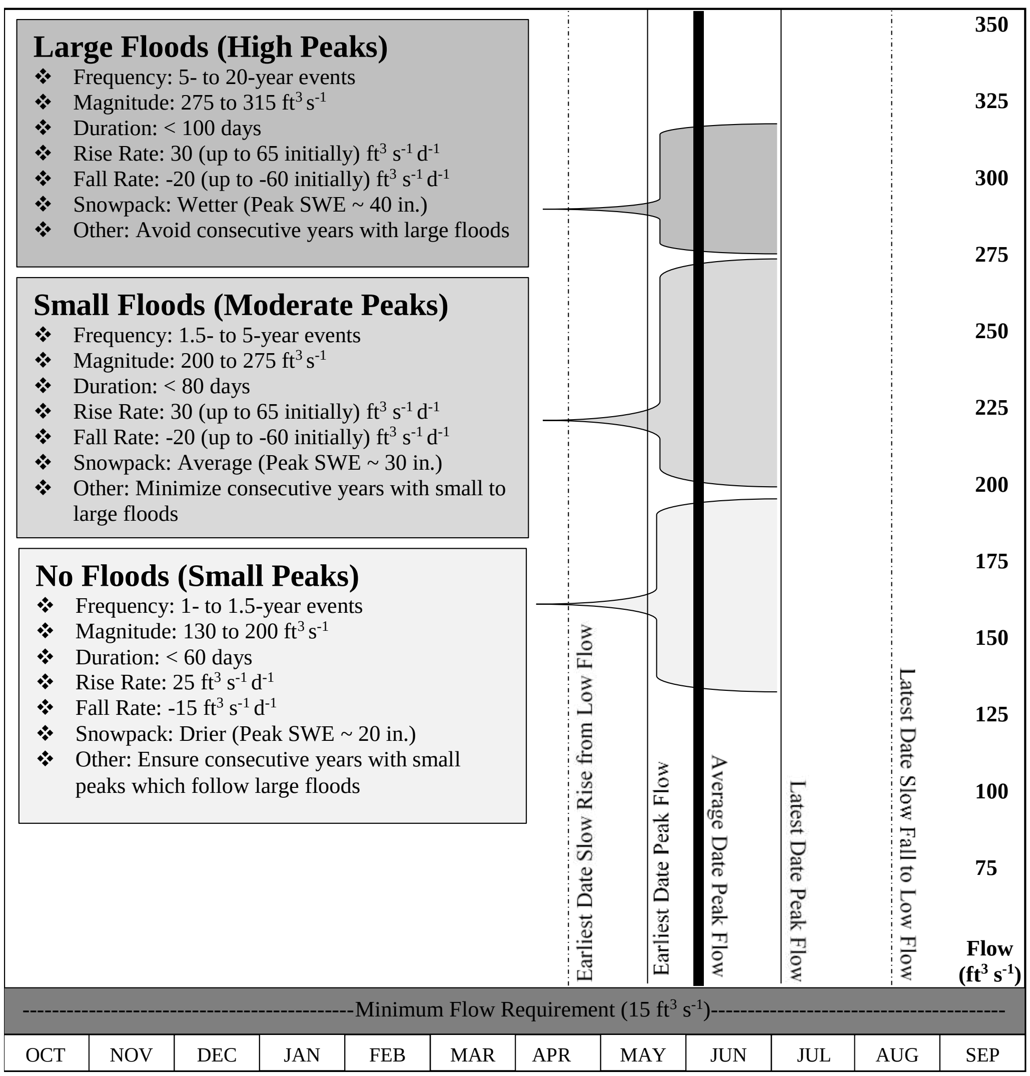

Figure 14: Summary of recommended flow attributes at Hog Park Creek for the years 2015-2035.

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APPENDIX

Table 11: Hog Park Creek PRMS model parameter file placed into four parts from one column.

Parameter File (Part 1)	Parameter File (Part 2)	Parameter File (Part 3)	Parameter File (Part 4)
XYZ - MOPEX basin monoc	####	####	####
Version: 1.7	snow_intcp 0	radadj_intcp 0	tsta_month_min 0
** Dimensions **	1	1	2
####	nhru	one	ntemp
nradpl	34	1	nmonths
20	2	2	60
####	0.044799998	1	2
ndays	0.071999997	####	8
366	0.089400001	radpl_slope 0	10
####	0.033	1	8
one	0.072700001	nradpl	10
1	0.058800001	20	10
####	0.0605	2	8
ntemp	0.092200004	0	11
5	0.097599998	0.1873	8
####	0.091399997	0.1708	10
nrain	0.095600002	0.0381	12
5	0.092799999	0.2017	14
####	0.098399997	0.1951	17
ngw	0.0973	0.1992	15
34	0.092799999	0.2148	16
####	0.0099	0.261	17
nhru	0.088	0.1978	21
34	0.092	0.2071	23
####	0.098800004	0.2467	20
ndepl	0.093400002	0.2519	21
2	0.098099999	0.2248	24
####	0.094300002	0.306	29
ndeplval	0.088399999	0.2764	31
22	0.094400004	0.2708	29
####	0.0911	0.2992	29
nobs	0.100000001	0.3296	32
1	0.064599998	0.2772	36
####	0.0977	####	40
nssr	0.0999	z_div 0	39
34	0.097199999	1	37
####	0.075800002	one	40
nlapse	0.100000001	1	43
3	0.099399999	2	47
####	0.096900001	132.3037872	47
nmonths	####	####	45
12	dday_intcp 0	snarea_curve 0	47
** Parameters **	1	1	42
####	nmonths	ndeplval	45
soil_type 0	12	22	44
1	2	2	44
nhru	9.964	0.050000001	45
34	9.998	0.239999995	34
1	9.968	0.400000006	38
2	-1.949	0.529999971	39
2	2.165	0.649999976	37
2	-13.367	0.75	38
2	-32.135	0.819999993	25
2	-14.134	0.879999995	29
2	4.305	0.930000007	26
2	9.998	0.99000001	27
2	9.07	1	29

2	10	0.050000001	15
2	####	0.25	19
2	jh_coef 0	0.400000006	17
2	1	0.479999989	17
1	nmonths	0.540000021	18
2	12	0.579999983	8
2	2	0.610000014	11
2	0.006	0.639999986	8
2	0.019	0.660000026	10
2	0.035	0.680000007	11
2	0.012	0.699999988	####
2	0.012	####	psta_freq_nuse 0
2	0.01	ppt_add 0	1
1	0.02	1	nrain
2	0.054	one	5
1	0.056	1	1
2	0.021	2	1
2	0.005	-0.107035786	1
1	0.005	####	1
2	####	slowcoef_lin 0	1
2	pmo 0	1	1
2	1	nhru	####
2	one	34	ppt_rad_adj 0
2	1	2	1
2	1	0.003	nmonths
2	0	0.003	12
####	####	0.003	2
tmax_allrain 0	potet_sublim 0	0.003	0.02
1	1	0.003	0.02
nmonths	one	0.003	0.02
12	1	0.003	0.02
2	2	0.003	0.02
89.431	0.154	0.003	0.02
65.778	####	0.003	0.02
65.409	ssstor_init 0	0.003	0.02
52.916	1	0.003	0.02
68.81	nssr	0.003	0.02
81.706	34	0.003	0.02
60.467	2	0.003	0.02
68.192	0	0.003	####
75.843	0	0.003	cecn_coef 0
82.594	0	0.003	1
63.749	0	0.003	nmonths
85.035	0	0.003	12
####	0	0.003	2
radj_wppt 0	0	0.003	4.735
1	0	0.003	9.653
one	0	0.003	2.388
1	0	0.003	0.076
2	0	0.003	5.752
0.5	0	0.003	9.531
####	0	0.003	7.18
adjmix_rain 0	0	0.003	8.745
1	0	0.003	0.969
nmonths	0	0.003	0.884
12	0	0.003	0.087
2	0	0.003	8.196
2.922	0	0.003	####
0.569	0	####	soil_moist_max 0
0.63	0	albset_snm 0	1
0.453	0	1	nhru
1.663	0	one	34
2.737	0	1	2
2.033	0	2	8.039200068
1.243	0	0.200000003	8.400099993
0.807	0	####	8.684400082

0.131	0	x_div 0	8.10800004
0.993	0	1	8.809499979
2.943	0	one	8.528000116
####	0	1	8.723200083
carea_max 0	0	2	9.333300114
1	0	8890.792969	9.546000004
nhru	0	####	9.556499958
34	####	albset_rna 0	9.381099939
2	ssr2gw_exp 0	1	9.723199844
0.308	1	one	10.01739979
0.308	nssr	1	8.673199892
0.308	34	2	9.231400013
0.308	2	0.800000012	7.512700081
0.308	0.005	####	9.156899929
0.308	0.005	cov_type 0	8.790199995
0.308	0.005	1	10.03259993
0.308	0.005	nhru	9.024300098
0.308	0.005	34	9.182699919
0.308	0.005	1	10.04250002
0.308	0.005	3	9.409600019
0.308	0.005	3	10.12080002
0.308	0.005	3	9.52120018
0.308	0.005	3	9.586699963
0.308	0.005	3	7.324300051
0.308	0.005	3	9.56580019
0.308	0.005	3	9.235899925
0.308	0.005	3	9.414700031
0.308	0.005	3	8.754899979
0.308	0.005	3	9.288500071
0.308	0.005	3	9.348599911
0.308	0.005	3	9.150300026
0.308	0.005	3	####
0.308	0.005	3	transp_tmax 0
0.308	0.005	3	1
0.308	0.005	2	nhru
0.308	0.005	3	34
0.308	0.005	3	2
0.308	0.005	3	500
0.308	0.005	3	500
0.308	0.005	3	500
0.308	0.005	3	500
0.308	0.005	3	500
0.308	0.005	3	500
####	0.005	3	500
transp_beg 0	0.005	3	500
1	0.005	3	500
nhru	0.005	3	500
34	####	3	500
1	adjust_snow 0	3	500
4	1	3	500
4	nmonths	3	500
4	12	3	500
4	2	3	500
4	0.377	####	500
4	0.997	radadj_slope 0	500
4	0.14	1	500
4	0.006	one	500
4	0.008	1	500
4	0.009	2	500
4	0.04	1	500
4	0.452	####	500
4	0.996	dday_slope 0	500
4	0.004	1	500
4	0.004	nmonths	500
4	0.002	12	500
4	####	2	500

4	y_add 0	0.522810638	500
4	1	0.502654374	500
4	one	0.532888293	500
4	1	0.542965949	500
4	2	0.694133818	500
4	-2053800.125	0.553043664	####
4	####	0.815067708	snarea_thresh 0
4	tmin_div 0	0.865456998	1
4	1	0.643744528	nhru
4	one	0.593355238	34
4	1	0.623589218	2
4	2	0.522810638	8.279999733
4	15.2042942	####	8.06499958
4	####	psta_elev 0	7.710000038
4	soil2gw_max 0	1	6.565000057
4	1	nrain	4.900000095
4	nhru	5	4.75
####	34	2	4.489999771
hru_area 0	2	2727.959961	2.045000076
1	0.05	2717.290039	2.045000076
nhru	0.05	2993.129883	1.715000033
34	0.05	2819	2.75
2	0.05	2652	1.945000052
259.6549988	0.05	####	1.544999957
102.5429993	0.05	radpl_aspect 0	3.25
63.35699844	0.05	1	1.105000019
139.7149963	0.05	nradpl	0
203.621994	0.05	20	0.660000026
106.0230026	0.05	2	0.714999974
413.2869873	0.05	359	1.159999967
858.2520142	0.05	154.5198	0.280000001
292.4320068	0.05	108.1321	3.50999999
133.1230011	0.05	15.6097	0.74000001
252.8800049	0.05	277.1977	2.315000057
91.55699921	0.05	37.3206	1.5
188.6069946	0.05	112.5456	0.38499999
303.4190063	0.05	3.7149	2.515000105
156.9279938	0.05	198.7824	5.380000114
598.7810059	0.05	204.9764	0.699999988
173.2250061	0.05	359.9182	0.88499999
102.177002	0.05	56.1592	3.569999933
191.3529968	0.05	245.2613	3.86500001
78.92199707	0.05	168.21	2.779999971
115.7279968	0.05	140.5692	2.055000067
139.5319977	0.05	95.3686	3.910000086
230.3569946	0.05	91.7836	####
242.4420013	0.05	40.2941	radmax 0
122.685997	0.05	136.6972	1
136.9689941	0.05	169.7382	one
309.2780151	0.05	####	1
159.3090057	0.05	basin_area 0	2
149.0540009	0.05	1	0.800000012
115.1780014	0.05	one	####
844.8850098	####	1	tmax_adj 0
105.1070023	ppt_div 0	2	1
229.4409943	1	7761.075195	nhru
223.947998	one	####	34
####	1	albset_sna 0	2
rad_trncf 0	2	1	1.200000048
1	0.203848124	one	0
nhru	####	1	1.200000048
34	soil_rechr_init 0	2	1
2	1	0.050000001	1.700000048
0.668900013	nhru	####	1.200000048
0.3741	34	solrad_elev 0	1
0.2456	2	1	1.700000048

0.742699981	0.5	one	1.200000048
0.276800007	0.5	1	0
0.341899991	0.5	2	0
0.390199989	0.5	1980	1
0.198200002	0.5	####	-1
0.139599994	0.5	albset_rnm 0	0
0.185299993	0.5	1	0
0.148499995	0.5	one	-1.700000048
0.156000003	0.5	1	1.200000048
0.151199996	0.5	2	1.200000048
0.154899999	0.5	0.600000024	-1
0.177399993	0.5	####	1.700000048
0.909300029	0.5	hru_deplcrv 0	-1
0.276499987	0.5	1	0
0.227799997	0.5	nhru	0
0.133300006	0.5	34	-1.700000048
0.204099998	0.5	1	-1
0.127000004	0.5	1	-1
0.164499998	0.5	1	1
0.181099996	0.5	1	-1
0.138600007	0.5	1	-1
0.174400002	0.5	1	-1
0.114399999	0.5	1	-1
0.382999986	0.5	1	-1
0.136800006	0.5	1	-1
0.126699999	0.5	1	-1
0.1303	0.5	1	####
0.240500003	0.5	1	psta_month_ppt 0
0.112899996	0.5	1	2
0.132400006	0.5	1	nrain
0.128000006	0.5	1	nmonths
####	0.5	1	60
smidx_exp 0	0.5	1	2
1	0.5	1	0.340000004
nhru	####	1	0.349999994
34	max_lapse 0	1	0.289999992
2	2	1	0.280000001
0.303	nlapse	1	0.230000004
0.303	nmonths	1	0.289999992
0.303	36	1	0.349999994
0.303	2	1	0.319999993
0.303	0	1	0.270000011
0.303	0	1	0.230000004
0.303	0.02	1	0.289999992
0.303	0	1	0.270000011
0.303	0	1	0.270000011
0.303	0.039999999	1	0.25999999
0.303	0	1	0.209999993
0.303	0	1	0.310000002
0.303	0.050000001	1	0.330000013
0.303	0	1	0.370000005
0.303	0	####	0.289999992
0.303	0.050000001	hru_elev 0	0.239999995
0.303	0	1	0.280000001
0.303	0	nhru	0.300000012
0.303	0.039999999	34	0.330000013
0.303	0	2	0.270000011
0.303	0	3084	0.25
0.303	0.050000001	3071	0.270000011
0.303	0	3050	0.310000002
0.303	0	2980	0.25999999
0.303	0.059999999	2878	0.25
0.303	0	2869	0.25
0.303	0	2853	0.239999995
0.303	0.059999999	2704	0.270000011
0.303	0	2704	0.239999995

0.303	0	2684	0.25
0.303	0.059999999	2747	0.209999993
0.303	0	2698	0.189999998
0.303	0	2674	0.239999995
0.303	0.029999999	2778	0.230000004
####	0	2647	0.209999993
tsta_nuse 0	0	2580	0.189999998
1	0.01	2620	0.25
ntemp	0	2623	0.349999994
5	0	2650	0.239999995
1	0.01	2597	0.25999999
1	####	2794	0.219999999
1	tsta_elev 0	2625	0.280000001
1	1	2721	0.379999995
1	ntemp	2671	0.340000004
1	5	2603	0.289999992
####	2	2733	0.230000004
rain_code 0	2727.959961	2908	0.300000012
1	2717.290039	2622	0.310000002
nmonths	2993.129883	2634	0.300000012
12	2819	2797	0.300000012
1	2652	2815	0.219999999
5	####	2749	0.310000002
5	hru_radpl 0	2705	0.349999994
5	1	2818	0.349999994
5	nhru	####	0.300000012
5	34	emis_noppt 0	0.219999999
5	1	1	####
5	20	one	tmax_add 0
5	13	1	1
5	9	2	one
5	15	1	1
5	9	####	2
5	19	psta_nuse 0	-48.96524811
####	15	1	####
covden_win 0	9	nrain	tmax_index 0
1	10	5	1
nhru	17	1	nmonths
34	9	1	12
2	7	1	2
0.0594	12	1	66.473
0.251599997	16	1	40.08
0.466800004	5	1	101.567
0.028999999	4	####	45.131
0.395599991	2	moyrsum 0	62.531
0.285400003	14	1	97.441
0.232500002	12	one	92.825
0.554400027	5	1	68.718
0.705799997	6	1	107.316
0.556599975	3	0	101.907
0.667599976	3	####	100.899
0.654100001	11	gwstor_init 0	74.125
0.672399998	4	1	####
0.65990001	12	ngw	hru_type 0
0.591199994	7	34	1
0.0058	6	2	nhru
0.421099991	12	2	34
0.520600021	8	2	1
0.7245	6	2	1
0.557399988	18	2	1
0.734499991	5	2	1
0.622399986	6	2	1
0.54430002	####	2	1
0.691100001	covden_sum 0	2	1
0.598100007	1	2	1
0.783900023	nhru	2	1

0.212500006	34	2	1
0.712899983	2	2	1
0.745599985	0.188600004	2	1
0.716199994	0.387100011	2	1
0.386900008	0.537800014	2	1
0.788500011	0.152199998	2	1
0.728900015	0.541100025	2	1
0.721800029	0.491100013	2	1
####	0.405200005	2	1
srain_intcp 0	0.60650003	2	1
1	0.719099998	2	1
nhru	0.621699989	2	1
34	0.699199975	2	1
2	0.694999993	2	1
0.0297	0.685299993	2	1
0.039500002	0.681299984	2	1
0.046	0.644299984	2	1
0.027000001	0.067199998	2	1
0.045200001	0.494599998	2	1
0.0418	0.572399974	2	1
0.040399998	0.733399987	2	1
0.048300002	0.601499975	2	1
0.049899999	0.752399981	2	1
0.047400001	0.663900018	2	1
0.0491	0.630699992	####	1
0.049600001	0.726999998	soil_rechr_max 0	1
0.049899999	0.652199984	1	####
0.049199998	0.783900023	nhru	conv_flag 0
0.048099998	0.381599993	34	1
0.0068	0.727500021	2	one
0.047699999	0.746699989	3.348700047	1
0.049899999	0.742500007	3.485800028	1
0.050000001	0.545599997	3.290100098	0
0.048500001	0.788500011	3.537800074	####
0.0493	0.732900023	3.376100063	outlet_sta 0
0.049400002	0.746999979	3.367399931	1
0.046500001	####	3.393199921	one
0.048900001	tmax_allsnow 0	3.474999905	1
0.0493	1	3.502500057	1
0.050000001	one	3.574199915	1
0.036699999	1	3.402800083	####
0.050000001	2	3.583300114	runoff_units 0
0.050000001	34.403	3.682300091	1
0.048900001	####	3.159100056	one
0.041999999	gwsink_coef 0	3.439199924	1
0.050000001	1	3.133700013	1
0.050000001	ngw	3.478100061	0
0.049199998	34	3.313199997	####
####	2	3.576900005	elev_units 0
snowinfil_max 0	0	3.387599945	1
1	0	3.231400013	one
nhru	0	3.612799883	1
34	0	3.411499977	1
2	0	3.608799934	1
2.695	0	3.484999895	####
2.695	0	3.293299913	precip_units 0
2.695	0	2.688199997	1
2.695	0	3.46420002	one
2.695	0	3.394999981	1
2.695	0	3.311700106	1
2.695	0	3.191900015	0
2.695	0	3.305799961	####
2.695	0	3.396100044	pref_flow_den 0
2.695	0	3.328299999	1
2.695	0	####	nhru
2.695	0	x_add 0	34

2.695	0	1	2
2.695	0	one	0
2.695	0	1	0
2.695	0	2	0
2.695	0	906737.125	0
2.695	0	####	0
2.695	0	den_init 0	0
2.695	0	1	0
2.695	0	one	0
2.695	0	1	0
2.695	0	2	0
2.695	0	0.100000001	0
2.695	0	####	0
2.695	0	tmin_adj 0	0
2.695	0	1	0
2.695	0	nhru	0
2.695	0	34	0
2.695	####	2	0
2.695	tsta_x 0	1.200000048	0
2.695	1	0	0
2.695	ntemp	1.200000048	0
2.695	5	1	0
####	2	1.700000048	0
melt_force 0	-908186	1.200000048	0
1	-910857.625	1	0
one	-891741	1.700000048	0
1	-907722.875	1.200000048	0
1	-915178.1875	0	0
140	####	0	0
####	adjust_rain 0	1	0
epan_coef 0	1	-1	0
1	nmonths	0	0
nmonths	12	0	0
12	2	-1.700000048	0
2	0.831	1.200000048	0
1	0.761	1.200000048	####
1	0.199	-1	fastcoef_lin 0
1	0.043	1.700000048	1
1	0.998	-1	nhru
1	0.378	0	34
1	0.005	0	2
1	0.929	-1.700000048	0
1	0.155	-1	0
1	0.021	-1	0
1	0.893	1	0
1	0.126	-1	0
1	####	-1	0
####	tsta_y 0	-1	0
gwflow_coef 0	1	-1	0
1	ntemp	-1	0
ngw	5	-1	0
34	2	-1	0
2	2051432	####	0
0.001	2058925	melt_look 0	0
0.001	2054858	1	0
0.001	2069026.375	one	0
0.001	2034759	1	0
0.001	####	1	0
0.001	slowcoef_sq 0	90	0
0.001	1	####	0
0.001	nhru	radj_sppt 0	0
0.001	34	1	0
0.001	2	one	0
0.001	0.004	1	0
0.001	0.004	2	0
0.001	0.004	0.600000024	0

0.001	0.004	####	0
0.001	0.004	print_type 0	0
0.001	0.004	1	0
0.001	0.004	one	0
0.001	0.004	1	0
0.001	0.004	1	0
0.001	0.004	1	0
0.001	0.004	####	0
0.001	0.004	soil_moist_init 0	0
0.001	0.004	1	####
0.001	0.004	nhru	fastcoef_sq 0
0.001	0.004	34	1
0.001	0.004	2	nhru
0.001	0.004	1	34
0.001	0.004	1	2
0.001	0.004	1	0
0.001	0.004	1	0
0.001	0.004	1	0
0.001	0.004	1	0
0.001	0.004	1	0
0.001	0.004	1	0
####	0.004	1	0
ppt_lapse 0	0.004	1	0
2	0.004	1	0
nlapse	0.004	1	0
nmonths	0.004	1	0
36	0.004	1	0
2	0.004	1	0
0	0.004	1	0
0	0.004	1	0
0	0.004	1	0
0	####	1	0
0	wrain_intcp 0	1	0
0	1	1	0
0	nhru	1	0
0	34	1	0
0	2	1	0
0	0.029300001	1	0
0	0.039500002	1	0
0	0.046	1	0
0	0.024900001	1	0
0	0.039799999	1	0
0	0.034600001	1	0
0	0.0352	1	0
0	0.0473	1	0
0	0.0491	1	0
0	0.0473	1	0
0	0.0484	####	0
0	0.0473	imperv_stor_max 0	0
0	0.049899999	1	####
0	0.048999999	nhru	sat_threshold 0
0	0.047699999	34	1
0	0.0068	2	nhru
0	0.047699999	0	34
0	0.0495	0	2
0	0.049600001	0	999
0	0.048500001	0	999
0	0.0493	0	999
0	0.048300002	0	999
0	0.046	0	999
0	0.047699999	0	999
0	0.046999998	0	999
0	0.050000001	0	999
0	0.036699999	0	999
####	0.049400002	0	999
den_max 0	0.050000001	0	999

1	0.048900001	0	999
one	0.041099999	0	999
1	0.050000001	0	999
2	0.049899999	0	999
0.5	0.048799999	0	999
####	####	0	999
temp_units 0	tstorm_mo 0	0	999
1	1	0	999
one	nmonths	0	999
1	12	0	999
1	1	0	999
0	0	0	999
####	0	0	999
tmax_div 0	0	0	999
1	0	0	999
one	1	0	999
1	1	0	999
2	1	0	999
18.57032013	1	0	999
####	1	0	999
z_add 0	0	0	999
1	0	####	999
one	0	tmin_add 0	999
1	####	1	####
2	tsta_month_max 0	one	gwstor_min 0
-2781.82959	2	1	1
####	ntemp	2	ngw
hru_percent_imperv 0	nmonths	-25.50355721	34
1	60	####	2
nhru	2	freeh2o_cap 0	0
34	26	1	0
2	30	one	0
0	27	1	0
0	28	2	0
0	31	0.11	0
0	29	####	0
0	31	settle_const 0	0
0	27	1	0
0	31	one	0
2.00E-04	34	1	0
0	38	2	0
0	40	0.100000001	0
0	37	####	0
0	41	radpl_lat 0	0
0	41	1	0
0	45	nradpl	0
0.0035	46	20	0
0.086	42	2	0
0.0063	48	41.03831	0
0	48	41.03988	0
0	54	41.03031	0
0.030200001	55	41.03271	0
0	51	41.02766	0
0	56	41.01975	0
0.0016	57	41.0323	0
0.0174	63	41.02023	0
0.0075	66	41.05313	0
0	64	41.05181	0
0	66	41.02649	0
0	68	41.03404	0
0	71	41.06774	0
0	74	41.03733	0
0	71	41.05606	0
0	74	41.03736	####
0	77	41.04928	basin_lat 0
0	69	41.02057	1

####	70	41.06163	one
jh_coef_hru 0	68	41.06934	1
1	72	####	2
nhru	74	min_lapse 0	41.038311
34	59	2	####
2	62	nlapse	hru_aspect 0
11.99909973	60	nmonths	1
12.0223999	62	36	nhru
12.06659985	65	2	34
12.28199959	47	0	2
12.62180042	48	0	169.738205
12.67420006	43	0.029999999	245.2613068
12.72140026	48	0	200.4441071
13.15799999	52	0	138.2675018
13.18220043	34	0.02	209.4181976
13.24660015	39	0	136.6972046
13.0618	34	0	141.5128021
13.20359993	35	0.029999999	184.363205
13.33539963	38	0	204.9763947
12.98139954	25	0	91.78359985
13.3757	29	0.02	235.4757996
13.62059975	24	0	138.6808014
13.48410034	26	0	73.40190125
13.47239971	30	0.01	95.36859894
13.38379955	####	0	233.2373047
13.54039955	print_freq 0	0	14.81299973
12.90939999	1	0.02	154.4859009
13.4769001	one	0	168.2100067
13.20189953	1	0	23.46549988
13.34140015	1	0.029999999	231.6183014
13.52120018	3	0	7.646299839
13.09980011	####	0	61.02069855
12.55790043	y_div 0	0.029999999	132.4938965
13.48309994	1	0	359.9182129
13.40750027	one	0	18.53039932
12.94019985	1	0.039999999	63.38339996
12.78359985	2	0	104.9153976
13.07320023	12523.93066	0	33.40219879
13.19559956	####	0.02	76.41439819
12.84230042	smidx_coef 0	0	3.714900017
####	1	0	32.5265007
hru_x 0	nhru	0.01	40.29410172
1	34	0	318.2009888
nhru	2	0	60.72219849
34	0.005	0.02	####
2	0.005	####	hru_slope 0
-905580.5625	0.005	psta_y 0	1
-905006.875	0.005	1	nhru
-904321.875	0.005	nrain	34
-904639.375	0.005	5	2
-905325.5625	0.005	2	0.277200013
-906197.5625	0.005	2051432	0.251899987
-908027.0625	0.005	2058925	0.25060001
-906635.25	0.005	2054858	0.292800009
-905173.0625	0.005	2069026.375	0.291900009
-905575.0625	0.005	2034759	0.329600006
-904288.3125	0.005	####	0.310499996
-904680.125	0.005	ssr2gw_rate 0	0.262400001
-907615.875	0.005	1	0.197799996
-908946.0625	0.005	nssr	0.270799994
-904530.1875	0.005	34	0.234099999
-905125.375	0.005	2	0.215299994
-907363.5625	0.005	0.026	0.250400007
-904143.4375	0.005	0.026	0.2764
-907690	0.005	0.026	0.186299995
-904793.875	0.005	0.026	0.018200001

-908650.1875	0.005	0.026	0.187099993
-907053.625	0.005	0.026	0.224800006
-907755.125	0.005	0.026	0.25029999
-907020.1875	0.005	0.026	0.132400006
-906124	0.005	0.026	0.198899999
-907939.5625	0.005	0.026	0.138699993
-909752.4375	0.005	0.026	0.190400004
-905659.1875	0.005	0.026	0.207100004
-905336.5	0.005	0.026	0.135399997
-906548.9375	0.005	0.026	0.212500006
-908495	0.005	0.026	0.194399998
-906035.5625	0.005	0.026	0.182500005
-905070.125	####	0.026	0.26910001
-905888.1875	transp_end 0	0.026	0.2148
####	1	0.026	0.187600002
hru_y 0	nhru	0.026	0.299199998
1	34	0.026	0.236100003
nhru	1	0.026	0.230800003
34	10	0.026	####
2	10	0.026	hru_lat 0
2058617.375	10	0.026	1
2058371.125	10	0.026	nhru
2058445.375	10	0.026	34
2057951	10	0.026	2
2057573.75	10	0.026	41.06933975
2057820	10	0.026	41.06774139
2057107.75	10	0.026	41.0690918
2056620.25	10	0.026	41.06438828
2056594.75	10	0.026	41.06034088
2056356.375	10	0.026	41.06163025
2056485	10	####	41.05344009
2056356	10	psta_x 0	41.05054092
2055994.5	10	1	41.05181122
2055401.25	10	nrain	41.04927826
2055349.625	10	5	41.05173874
2054495.25	10	2	41.05018997
2055502.5	10	-908186	41.04399109
2054845.125	10	-910857.625	41.03736115
2055202	10	-891741	41.04141998
2054850.375	10	-907722.875	41.03322983
2054794.875	10	-915178.1875	41.03987885
2054757	10		41.03733063
2054215.625	10		41.03688049
2053954.5	10		41.03672028
2054257.125	10		41.03227997
2054563.5	10		41.03358078
2054318.25	10		41.02806091
2053717.875	10		41.02648926
2053109	10		41.03010178
2053194	10		41.03096008
2053264.375	10		41.02693176
2053173.875	10		41.02579117
2052477.75			41.02070999
2052140.125			41.02022934
			41.01885986
			41.02056885
			41.01538086
			41.0115509