AN INVESTIGATION INTO THE WATER BUDGET AND THE MANAGEMENT OF THE SNAKE RIVER SYSTEM

by

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The following individuals read and discussed the thesis submitted by student John Whitney Hildreth, and they evaluated his presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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ABSTRACT

Future climate change poses a major conceptual challenge to the availability of water resources due to the uncertainty involved with changes to the hydrologic cycle. Over the past decades, observed warming temperatures across the Western United Sates have shown significant impacts on river basin scale hydrology. This research uses physically based modeling tools to assess the hydrologic impacts of climate change in the Snake River Basin. Physically based hydrologic modeling studies of future climate do not typically take into account interactions between groundwater and surface water. To account for these interactions, the Variable Infiltration Capacity model is coupled with the United States Geologic Survey MODFLOW model over the Eastern Snake Plain Aquifer to generate natural streamflow. The results showed that under climate change projections peak streamflow will decrease by 12.5%; the peak streamflow will shift 7-11 days earlier; in the late summer months, baseflow is expected to decrease by 5%; and in the winter months, flows are expected to increase by 25%. This will cause water users to shift their water management strategies from relying on natural flow rights to using storage rights in the late summer months of the irrigation season. The impact of these findings suggests that water users with junior rights might be curtailed because of the hydrologic changes in future climate.

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LIST OF ABBREVIATIONS

af	Acre-feet
BCF	Block Centered Flow
BIOP	Biological Opinion
BSU	Boise State University
cfs	Cubic Feet per Second
CIG	Climate Impacts Group (University of Washington)
CMIP5	Coupled Model Intercomparison Project Phase 5
ESPA	Eastern Snake Plain Aquifer
ESPAM	Eastern Snake Plain Aquifer Model
ET	Evapotranspiration
GCM	Global Climate Model
HRU	Hydrologic Response Unit
IDWR	Idaho Department of Water Resources
INL	Idaho National Lab
IPCC	International Panel on Climate Change
kaf	Thousand Acre-Feet

LAI	Leaf Area Index
LPF	Layer Property Flow
MACA	Multivariate Adaptive Constructed Analogs
MAF	Million Acre-Feet
MKMOD	Make MODFLOW program
MODFLOW	Modular Groundwater Flow Model
MODSIM	Modular River Simulation Model
PRMS	Precipitation Runoff Modeling System
RCP	Representative Concentration Pathway
RMJOC	River Management Joint Operating Committee
SCE	Shuffled Complex Evolution
SPM	Snake Planning Model
USBR	United States Bureau of Reclamation
USGS	United States Geologic Survey
VIC	Variable Infiltration Capacity

CHAPTER ONE: INTRODUCTION

Water plays an important part in the existence of life on our planet; it makes up 60% of the human body and is also used to stimulate economic growth (US EPA 2013). Water has been the central cause of most conflicts over the course of human history. In the past century, water resources have become heavily managed in areas of scarce water supply to maximize the marginal benefit of the resource. Many engineering projects across the globe are aimed at increasing the water supply to fulfill demands. Managers of the water supply try to operate the water to its optimal potential for each system. Agricultural use is the largest consumer of fresh water on our planet, and it is important for water managers to plan for the sustainability of water resources for irrigation. In the last century, water has been managed by the assumption that what happened in the past will continue in the future with the same variability. Recent studies from the International Panel on Climate Change (IPCC) have determined that this assumption of stationary climate is inappropriate with the development of climate change (Bates et al. 2008).

Climate change scenarios provide equal probable projections of possible future climate for global, regional, and local landscapes. Global Climate Models (GCM) are commonly used to simulate the general circulation of the atmosphere and ocean physics. The role of land atmosphere interactions has become an increasingly important aspect of capturing accurate representations of climate. With the predicted changes to climate, there is the potential to alter the river-basin-scale hydrology and water resources. Water managers need to plan adaptation strategies for the consumption of water resources, and to do this, it is fundamental to understand the potential changes to the surface water availability, groundwater availability, and the hydrologic characteristics of the basin. This research seeks to understand the changes in hydrology from projected future climate in the Snake River Basin and the impacts it will have on supply and demand of water resources.

The Snake River is the largest tributary to the Columbia River, contributing nearly 26% of total flow in the Columbia River system or 134 million acre-feet (MAF) at the Dalles, Oregon. The drainage area of the Snake River is approximately 248,500 sq. miles mostly contained in Idaho (Slaughter 2004). In Figure 1.1, the Snake River Basin can be seen for this study as defined as the Snake River from its headwaters to Hells Canyon Dam, ID.

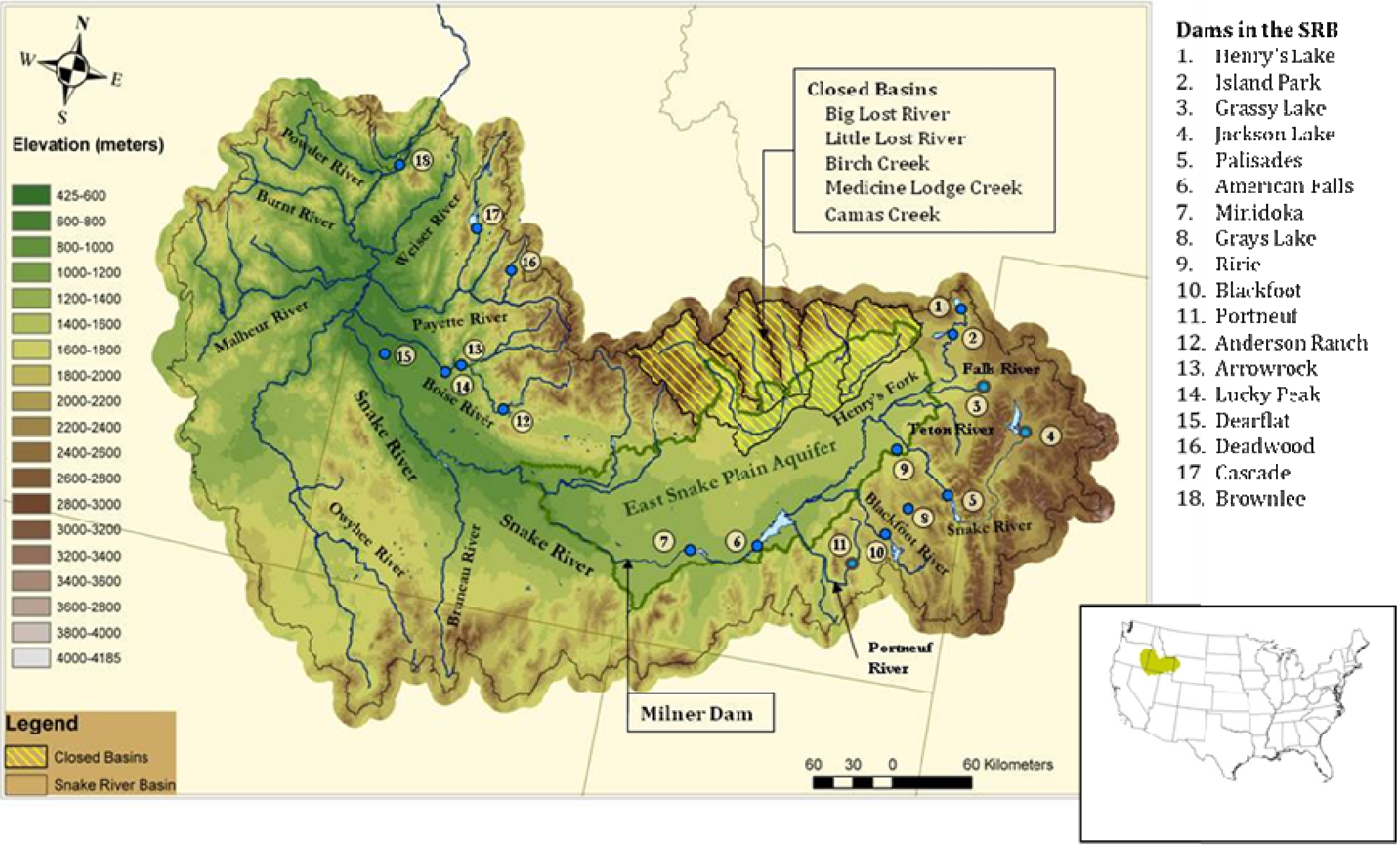


Figure 1.1 Study Area Map of the Snake River Basin Upstream of Hells Canyon Dam (Hoekema and Sridhar 2011)

The Snake River generates nearly 25 million megawatt-hours of electricity serving over two million people. Long-term planning of water resources for agricultural use is important in the semi-arid region of the Snake River where water is a scarce commodity. This is especially important above Milner Dam where the river is completely diverted through nearly 1,000 miles of canals that cover nearly 600,000 acres of farmland. In total, the Snake River is used to irrigate nearly 3.8 million acres of cropland of which over 3 million of the acres are in Idaho (Slaughter 2004). The Eastern Snake River Plain contains a substantial underlying aquifer, called the Eastern Snake Plain Aquifer (ESPA), which stimulates agricultural irrigation with groundwater. The aquifer spans 10,000 square miles and is used to irrigate about 1 million acres of farmland (Wulfhorst and Glenn 2002). Major regions of the aquifer return to the river in the form of spring discharge, which is important in the calculation of natural flow rights for irrigator's water rights. The aquifer acts as an unconfined aquifer system throughout the fractured basalt medium in the ESPA (Cosgrove et al. 2006).

Hoekema and Sridhar (2011) showed that declining streamflows, increasing temperatures, and fluctuations of precipitation impacted the allocation of water resources in the Snake River Basin (1971-2005), and they concluded that a decrease in annual surface-water diversions exist over the Snake River Basin. The research presented in this thesis looks to expand on their research to study how future projected climate will continue to change the allocation of water resources in the Snake River Basin. The research looks to investigate the interactions that exist between surface-water and groundwater to evaluate how water table elevation in the underlying aquifer can be included into a physically based modeling system. These changes in hydrology will be investigated to characterize the system response to climate change and the impacts it will have on water managers operation of the system and the demand from irrigators in the system.

1.1 Background

1.1.1 History of Irrigated Agriculture

Irrigation is the most important factor contributing to crop production in the Western United States. To encourage settlement in the Western United States, the federal government adopted the Homestead Act of 1862 (Slaughter 2004), and as a result, many settlers attempted to develop dry farms in Southern Idaho. These farms were abandoned due to the arid climate and a lack of irrigation structures. To counter this problem, the United States Congress passed the Desert Land Act of 1877, which provided settlers with 640 acres of land, if they could successfully irrigate the land (Chaney 1977). This act was also unsuccessful due to the financial limitations of investors to finance irrigation facilities. Some irrigation structures were constructed in Idaho with mostly non-permanent coffer dams and waterworks, but these proved inadequate, and there still existed a need for large-scale investment in irrigation systems. The Cary Act of 1894 was passed to solve the financial problems, the act acquisitioned large land grants to western states who could then administer the grant to canal companies to finance irrigation projects. The Twin Falls Project is a successful example of this act in Idaho. The project found a reliable source of unallocated natural flow in the Snake River at Milner, ID and constructed Milner Dam to facilitate delivery of water to 260,000 acres of land (Lovin 1987; Slaughter 2004; Williams 1970). Milner Dam was one successful example of the

Cary Act, but still many private developments of water failed to secure sufficient unallocated water to endure. Thus, in 1902, the Newlands Reclamation Act (NRA) of 1902 was passed; this act essentially created the United States Bureau of Reclamation (USBR) and gave them authorization to solve the issue of storage and create a reliable supply of water for irrigation (Slaughter 2004). Beginning in 1902, the USBR started about thirty projects in the Western United States to supplement irrigation delivery. In Idaho, the Minidoka Project (1904), the Boise Project (1905), and the Palisades Project (1950) were completed with authorization from the NRA (Gilbert et al. 1983; Piety et al. 1986; Simonds 1997). These projects provided storage water to supplement natural flow rights and hydropower facilities to generate electricity. Surface water irrigation had undergone dramatic changes in Idaho. In 1889, about 217,000 acres of land was irrigated, and in 1997, about 3,400,000 acres of land was irrigated (Greer and Pair 1966; NRCS 2001).

Like many western states, the Idaho Constitution adopted Prior Appropriation as the legal basis for water allocation. In a region that experiences about 8-14 inches of precipitation a year, the availability of water for irrigation is stressed in the system. The Minidoka and Palisades projects lead to the allocation of all natural flow rights in the Snake River above Milner dam (Wulfhorst and Glenn 2002). Due to the total allocation of all natural flow and the development of economically efficient pumps, the use of groundwater resources grew. In 1951, the State of Idaho enacted legislation to acquire groundwater rights, because groundwater was not covered in the Constitutional Prior Appropriations (Slaughter 2004). Around the same time period, the Desert Land Act, which originally had failed due to financial limitations, was used very successfully to irrigate lands, with groundwater that had previously been unavailable for irrigation, and increased land area for agriculture in Idaho (Greer and Pair 1966). Groundwater irrigation in Idaho rose substantially, in 1950, about 100,000 acres of land was irrigated with groundwater resources, and in 1980, about 1,100,000 acres of land was irrigated with groundwater (Slaughter 2004). Decreases in ESPA elevations were caused by the increase in pumping of groundwater and sprinkler efficiency. This decrease in aquifer levels caused Idaho to adopt a Conjunctive Management of groundwater and surface water because of the complex interactions of surface water and groundwater in the region. The State of Idaho gave authority to the Idaho Department of Water Resources (IDWR) in 1989 to shut down unauthorized wells, and in 1994, IWDR required metering on commercial wells (Slaughter 2004).

In 1995, a biological opinion (BIOP) by the USBR was released, finding several species in the Snake River to be endangered. This resulted in the suggestion of flow augmentation of 427 KAF to aide migrating steelhead and salmon bellow the Hells Canyon dam complex. The BIOP also defined minimum target flows in river reaches to support habitat for endangered and threatened species (Payne et al. 2004).

Since the 1960’s, national policy preferences have been changing, and today the Snake River is over appropriated. Expansion of irrigation has largely been halted, and some lands have been withdrawn to accommodate industrial, municipal, and environmental uses (Slaughter 2004). Currently in the Snake River, major conflicts exist due to the scarcity of the water and the over allocation of the natural resource. In 1987, the Snake River Basin adjudication was decreed, and the State of Idaho began the massive administrative and legal process of sorting out around 150,000 water right claims in the Snake River Basin Adjudication Court. The Idaho courts have been a major battle-ground for surface-water users and groundwater users fighting over water rights (Slaughter 2004). The research presented in this thesis investigates the impacts that climate change will have on the water users, and how these impacts will affect junior and senior water right holders in the Snake River Basin.

1.1.2 Previous Studies

Climate change has been ongoing since the beginning of the industrial revolution and has the potential to alter the river-basin-scale hydrology and hydrogeology, which has been shown in many modeling studies (Pierce et al. 2008, 2012; Stoll et al. 2011; Sulis et al. 2011, 2012). For water managers to plan adaptation strategies for the consumption of water resources, it is fundamental to understand the potential changes to the surface water availability, groundwater availability, and the hydrologic characteristics of the basin. Across the Pacific Northwest, Global Climate Models (GCMs) have shown that we can expect to see an increase in temperature of at least 0.1^{o} C per decade, and a majority of the GCMs show wetter winters and drier summers than the past 30 year average (Mote and Salathé 2010). The Snake River Basin is the largest tributary to the Columbia River and is an important spawning ground for migrating steelhead and salmon fisheries (Mote et al. 2003). The Snake River provides irrigation water to nearly 3.8 million acres of land and is used extensively for hydropower and municipal purposes (Slaughter 2004). The watershed is climate driven, and understanding changes to the water budget is important, for water managers, to continue to deliver irrigation water.

Irrigation is linked to the availability of water resources, and is the major concern in climate change studies (Puma and Cook 2010). Recent studies show that the annual mean and minimum daily streamflow have decreased from 1967 through 2007 in Idaho, Western Wyoming, and Northern Nevada (Clark 2010). Another study shows that the timing of historic snow melt has been shifted by about 10-12 days earlier (Jin and Sridhar 2012). The IPCC suggests that future climate poses a major challenge to the water managers, water resource users, and policy makers, because it is no longer appropriate to assume past climate and hydrology will continue into the future (Bates et al. 2008). This poses a problem for water managers and users, especially in the Snake River Basin, since studies have shown that management of this system has been dictated by the assumption of stationary climate and hydrology (Payne et al. 2004; Snover et al. 2003). Understanding this potential change in climate and water resources allows water managers and stakeholders the ability to plan for future scenarios so that groundwater and surface water can still be used for agricultural needs.

There have been many studies about the Snake-River hydrology and water resources, and these studies reported on the overall water budget of the Snake River system (Barnett et al. 2004; Mote 2003). The accepted aquifer recharge budget from these studies is that recharge from irrigation seepage is about 60% of the overall recharge to the aquifer (Miller et al. 2003). Another understanding of the water budget from these studies is that both the increase of groundwater pumping and sprinkler irrigation is decreasing the storage of the aquifer since the 1950's.

One of the major studies that have recently been published on water management in the system is the United States Bureau of Reclamation's (USBR) River Management Joint Operating Committee (RMJOC) study (Brekke et al. 2008). In this study, Idaho and Oregon watersheds of multiple rivers were evaluated to determine projected natural streamflow. The streamflow was then routed through a systems planning model of each river system. The results presented the future river and reservoir content under current operating procedures and the effects on water users. The results showed, for the Snake River Basin, that the irrigation districts would shift their water management strategies from relying on natural-flow rights to using storage-water rights in the late summer months of the irrigation seasons.

To understand the water budget under future climate, studies have been completed to determine the change in volumetric streamflow and timing of peak streamflow (Christensen and Lettenmaier 2007; Hoekema and Sridhar 2011; Mote and Salathé 2010). One area of uncertainty in these studies is in the interactions between surface water and groundwater, and how that might impact the streamflow and recharge. To account for this, presently, surface water and groundwater are calibrated into planning models in the form of response functions (Miller et al. 2003). A response function is a stress that would occur and return flow back to the river, if a defined unit of recharge was applied to an area. These curves have some inherent flaws because no physical calibration can be done. It essentially uses the mass balance and forces it to reflect past observed values. This works well for the past but poses an issue in studies of the future. Including the response curves of the past would be an assumption of stationary hydrology, which is not a reasonable assumption. To solve this issue, understanding of the water-table physical elevations into the future will need to be understood by modeling climate-change impacts on groundwater elevations. Understanding of the future is not performed in this research, but MODFLOW-VIC is investigated for the past to determine if it could be used for future projections. This would provide information for water managers to plan adaptation strategies into the future.

Another uncertainty with previous studies was with the amount of calibration points used in the hydrologic model. With large areas of study, only a few points can be calibrated due to the lengthy amount of time consumed by streamflow calibration. For these previous studies, additional streamflow locations in the study area were needed, and to obtain well correlated results for these uncalibrated locations, bias correction was performed (Johnson and Sharma 2012; Li et al. 2010). Bias correction is the process of removing the bias of a model from the model results. This is typically done by shifting the cumulative probability distribution of the model results to the historic observed cumulative probability distribution (Wood et al. 2004). To account for this issue, multiple locations throughout a smaller study area could be used to route to more locations in a smaller area giving better calibration of locations. Then, bias correction can be performed to correct the streamflow.

To account for major interactions between groundwater and surface water in the basin, the Variable Infiltration Capacity (VIC), a macroscale hydrologic model, is coupled with the United States Geologic Society's MODFLOW model. This process is described in Jin and Sridhar (2010). This coupled model is used to generate naturalized streamflow to a few selected locations throughout the basin in order to integrate flows into MODSIM, a system planning model.

1.2 Importance, Motivation, and New Knowledge

This research models the impacts of future climate projections on the hydrology of the Snake River and the effects this impact will have on water users and managers in the system. The modeling takes into account surface water and groundwater, which has not been performed before in the Snake River Basin. Another contribution to new knowledge is the implementation of the newly developed model, which is the first of its kind to combine both MODFLOW and VIC together to account for these surface-water and groundwater interactions. Understanding of the surface water and groundwater in the basin gives a more realistic understanding of the system as a whole and provides better insights we might see for future water use in the Snake River Basin. Another contribution to new knowledge of this work is the inclusion of the latest GCM's from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) climate change project. The inclusion of the CMIP5 data and surface-water and groundwater interactions makes this work the state of the art.

This work has important significance to junior water users in the system that under climate change scenarios could face shortage or curtailment under current water laws in the region. For water managers to accurately plan for water sustainability, it is important that this work is taken into account.

1.3 Objectives

The hypothesis of this work is that climate change will cause a change in the hydrologic characteristics of the Snake River, which will cause the need for new management practices to deliver irrigation water. This study looks to answer the following questions.

- What are the changes to the hydrograph expected due to climate change?
- How will the system be affected under current management practices due to these changes in hydrology?
- How well did MODFLOW-VIC capture aquifer water-table elevations?
- How well did MODFLOW-VIC capture spring discharge?
- How successful was the newly implemented MODFLOW-VIC model in modeling the historic conditions?
- Can MODFLOW-VIC be used for a future climate change study to account for surface-water and groundwater interactions in the Eastern Snake Plain Aquifer?

In summary, the objectives of this research are:

1. Investigate the streamflow in the Snake River by modeling historical and future streamflow using VIC with driving inputs from the CMIP5 GCMs.
2. Investigate and document the differences between MODFLOW-VIC and VIC alone.
3. Investigate the overall water budget of the Snake River Basin.
4. Investigate adaptation options of water managers in the Snake River Basin by modeling current operations in the system using projected future streamflow.
5. Determine the impacts from projected future streamflow on water users and managers in the Snake River Basin.

1.4 Constraints

The major constraints faced by this work are the limitations of computational resources, data availability, and spatial resolution. These limitations are overcome for the completion of the thesis but did impact the quality of the results.

The models were run on super computers at the Idaho National Lab (INL), which are the state of the art computers used for high-performance computing. The major challenge in computing was that the models are run in series on a grid-cell by grid-cell basis. This caused the model run time to be up to 1-2 weeks, which caused difficulty for calibration. Another issue caused by the computational resources was disk space for storage. On the INL computers, 500 GB of storage space was available but approximately 1-2 terabytes was needed to store all the models and results. This was overcome but caused delays during the progress of this work, because transferring of the data to BSU was needed between model runs.

The data availability for this study is another limitation. In an ideal study, we would have all the GCM's and all the future Representative Concentration Pathways (RCP) available to run with the VIC model. In our study, since the data was retrieved from the University of Idaho, we were constrained to only the CMIP5 models and RCPs, which they choose to downscale. This caused results to only show a select ensemble of data from 12 models and 2 RCPs. For our purposes, this worked well, but ideally, we would have the other data to also include in the model-runs for a larger ensemble of models.

The spatial resolution of the data was another limitation of this study. The spatial resolution of the data acquired was 1/24th, but the VIC model is at 1/16th degree spatial resolution; this caused a spatial mismatch between the input forcing data and the VIC model. To solve this problem, bilinear interpolation was performed on the data to upscale the data from the University of Idaho to 1/16th degree. This caused another source of uncertainty in our data, because the data from the GCM's were downscaled initially and then had to be upscaled to acquire the data in the correct spatial resolution for input to VIC.

CHAPTER TWO: EXPERIMENTAL DESIGN

2.1 Study Area

For the purpose of this research, the Snake River Basin will be defined as the head waters of the Snake River in Yellow Stone National Park to the outlet point at Hells Canyon Dam on the Idaho-Oregon border (Figure 1.1). The purpose of defining the Snake River Basin over this region is to encompass the Snake River Plain and the Snake River Basin with the same spatial outlet point for the system; this provides an optimal point to close the water budget. The Snake River Basin is a semi-arid snow-melt dominated basin with a drainage area of approximately 73,300 square miles and has an average annual discharge of 14.2 MAF (1966-2012) (USGS 2013). The basin ranges in elevation from 1,400 feet up to 13,000 feet (USGS 2013). Diversions above Hells Canyon supplement 3.8 million acres of irrigated land of which 742 thousand acres of land are irrigated with groundwater withdrawals (Slaughter 2004).

The Snake River Plain is a semi-arid plain, which encompasses the majority of Idaho's agriculture. The Eastern Snake Plain Aquifer (ESPA) is a substantial aquifer system in the eastern section of the Snake River Plain, which covers approximately 10,800 square miles. The aquifer extends from Ashton, Idaho, to King Hill, Idaho, in the central part of the Snake River Plain (Cosgrove et al. 2006). The aquifer medium is fractured basalt with new and old deposits from lava flows out of the yellow stone cauldron. A second aquifer exists in the Snake River Plain in the western section of the plain. For the purpose of this research, no interactions from the Western Snake Plain Aquifer have been evaluated, and the main focus of groundwater interactions is centered on the exit location of the ESPA near King Hill, Idaho.

Precipitation in the Snake River Plain is highly variable depending on the location. The plain receives about 8 to 14 inches of annual precipitation (Cosgrove et al. 2006). The wettest periods of the year are in the late autumn, winter, and spring with the driest times of the year in the summer and early autumn. Precipitation in the region mostly varies as a function of elevation; mountains surrounding the plain having precipitation of over 120 inches annually falling mostly in the form of snow (PRISM Climate Group).

Surface water in the Snake River originates in the South Fork of the Snake River as the water returns to the river from melting snow out of the Teton Mountains. In the South Fork of the Snake River, the water passes through two USBR dams then enters the Snake River plain at the Snake River near Heise, Idaho. This is an important point in the upper reaches of the system, because this is one of the major flood control points of the river. The river discharges an average annual volume of 5 MAF past the Heise gage. As the river continues west, it meets with the Henrys Fork, the Snake River’s largest tributary, and the rivers confluence near Mennan, Idaho to form the main Snake River. As the river continues to flow west through the Snake River Plain, it eventually comes to Milner dam, which is where the Snake River is fully allocated and the minimum flow past Milner is zero cfs (IDWR 2012). The minimum flow is maintained throughout the irrigation season except when releasing water for flood control, Idaho Power storage water for power generation, or USBR water for salmon flow augmentation. The return flows from the ESPA supply flow from Milner dam to King Hill where almost 5,200 cfs of spring discharge return to the river. The total reservoir storage above the Hells Canyon dam complex used for irrigation storage is 6.9 MAF of storage.

2.2 Model Description

2.2.1 Variable Infiltration Capacity Model 4.1.1

VIC Hydrology and Energy Balance

The Variable Infiltration Capacity (VIC) model (Gao et al. 2010; Liang et al. 1994) is a semi-distributed physically based hydrologic model used for macroscale modeling. VIC balances water-budget components and energy budget on a cell-by-cell basis; VIC also deals with subgrid variability, which is computed statistically. VIC has been well calibrated and applied to a number of large river basin studies for use as both a hydrologic model and land surface scheme coupled with a GCM. VIC is used in both the academia research community and industry related modeling studies. A schematic of this model can be seen in Figure 2.1.

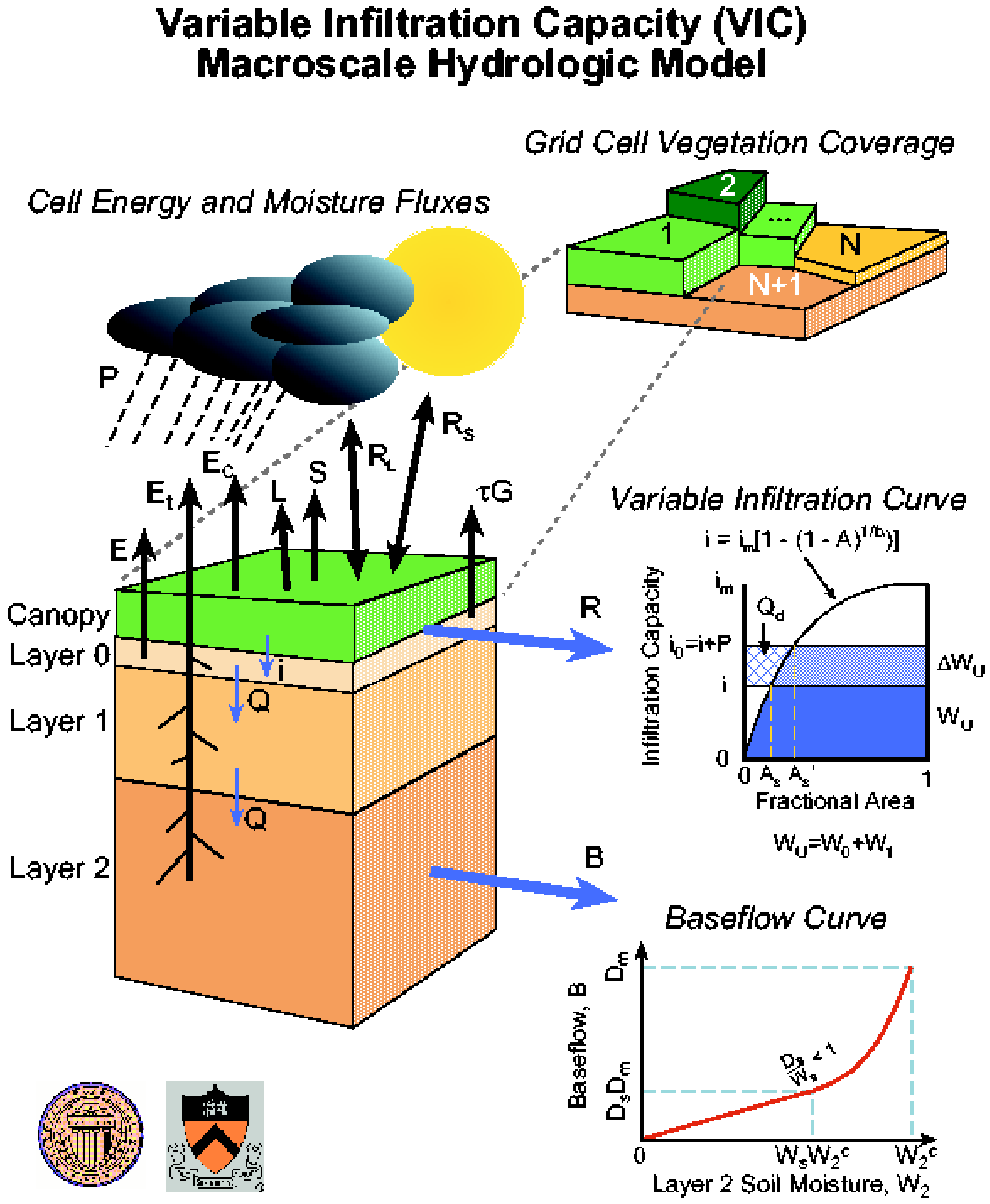


Figure 2.1 Schematic Diagram of the VIC model (Gao et al. 2010)

VIC allows for a mosaic representation of the vegetation and 3 soil layers over each grid cell. A schematic of this can be seen in the Figure 2.1. There is no limit on the number of vegetation tiles per cell and the calculations are performed statistically based on the percentage of vegetation coverage over the cell. For each tile, vegetation characteristics are allowed. These characteristics include leaf-area index (LAI), albedo, minimum stomatal resistance, architectural resistance, roughness length, relative fraction of roots in each soil zone, and displacement length. Using the described characteristics assigned, evapotranspiration (ET) is calculated using the Penman-Monteith equation.

The canopy layer interception is modeled in accordance with the Biosphere-atmosphere transfer scheme parameterization as a function of LAI. The top two soil layers are designed to represent response of soil to infiltration. The bottom layer of soil receives moisture from the middle soil layer by gravity drainage following the Brooks-Corey relationship for unsaturated hydraulic conductivity (Gao et al. 2010). The runoff from the bottom layer is then modeled by the Arno model and water can also be transported out of this layer in the roots through ET (Gao et al. 2010). Unlike vegetation subgrid variability, soil characteristics are held constant over the grid cell. For each vegetation tile of each grid cell over each time step, the model calculates soil moisture distribution, infiltration, drainage between soil layers, surface runoff, and subsurface runoff. Then, for each grid cell, these calculations are used to determine the total heat fluxes, effective surface temperature, and total surface and subsurface runoff by summing the individual tiles as a weighted fraction of coverage.

VIC Routing

The VIC model creates fluxes for each grid cell over the time period of the desired run. To obtain streamflow from the VIC output, the VIC routing model (Lohmann et al. 1998) is used to simulate the flow of the fluxes through a river system. The routing model assumes water can leave a grid cell through only one of the eight neighboring cells. The routing model uses a simple linear-transfer-function model to describe the concentration time for runoff to reach a desired outlet location. The transfer function uses lumped properties; it uses the First Differenced Transfer Function-Excess Rainfall and Unit Hydrograph Iterative technique. A schematic of this model can be seen in Figure 2.2.

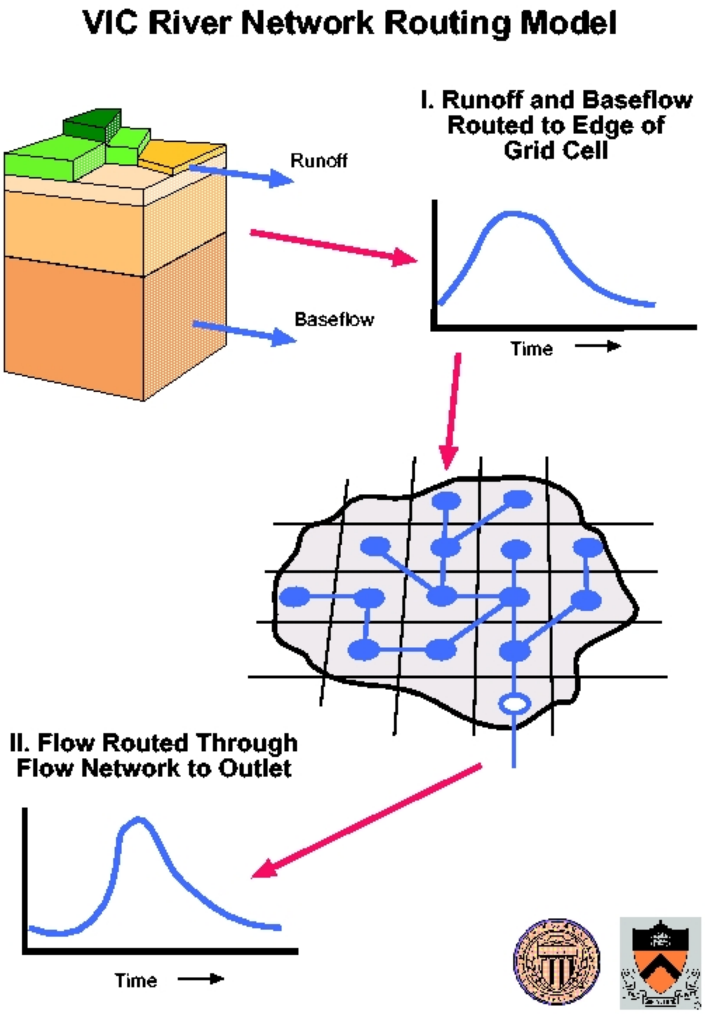


Figure 2.2 Schematic Diagram of the VIC Routing model (Lohmann et al. 1998)

2.2.2 MODFLOW 2005

MODFLOW is a United States Geologic Survey (USGS) modular finite-difference three-dimensional groundwater flow computer model (Harbaugh 2005). The model structure allows for simulation of steady and unsteady flow in irregular flow systems of confined, unconfined, or a combination of both types of aquifers. MODFLOW allows outside stresses to be simulated like flow to wells, recharge, flow from river beds, evapotranspiration, and flow to drains. The model also accounts for hydraulic conductivity or transmissivity for different spatial layers, anisotropy, and storage coefficients and allows these parameters to be heterogeneous.

The model simulated the three-dimensional flow by solving the groundwater flow equation using a finite-difference approximation algorithm. The equation of the groundwater flow equation is setup as a differential equation and solved on a cell-by-cell basis in which the medium properties are assumed to be uniform. The layer thickness can vary, and a flow equation is written for each cell. The model solves for the flow-rate and the cell-by-cell water balances for each type of inflow and outflow computed for each stress period. A schematic of MODFLOW can be seen in Figure 2.3.

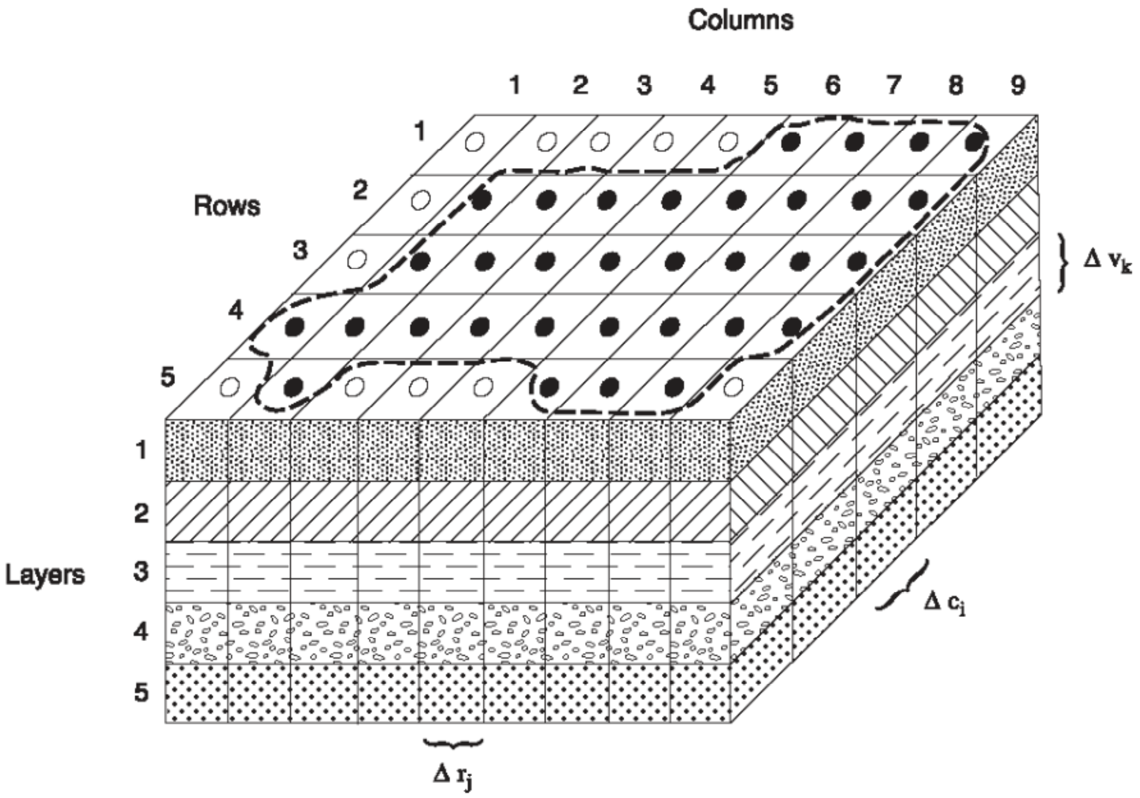


Figure 2.3 Schematic Diagram of the MODFLOW 2005 model (Harbaugh 2005)

2.2.3 MODFLOW-VIC

MODFLOW-VIC is currently under development by the Civil Engineering Department at Boise State University (Jin and Sridhar 2010). MODFLOW has been previously combined with other hydrologic models to successfully simulate the hydrologic response. A good example of the combination of MODFLOW and a hydrologic model is GSFLOW model, which combines MODFLOW and the Precipitation Runoff Modeling System (PRMS) (Leavesley et al. 1983). Although this is considered a successful coupling of MODFLOW with a precipitation runoff model, it still has some limitations. PRMS is a deterministic, distributed-parameter, physically based modeling system developed to simulate streamflow and watershed hydrology. PRMS was designed to look at small basins with typical hydraulic response units of less than 12 km^2 (Leavesley et al. 1995). When looking at the Snake River Basin, a large basin over 640,000 km^2, macroscale hydrologic modeling is needed. VIC is the optimal hydrologic model for dealing with basins of this scale because VIC studies have been performed for scales as large as the entire globe (Gao et al. 2010). Another advantage to VIC over PRMS is the ability of VIC to have sub-grid variability. In PRMS, the hydrologic response unit (HRU) is homogeneous over the spatial domain of the HRU. This is less desirable since large-scale basins have increased variability on the grid-scale basis as grid cells increase in size, differences throughout the grid cell need to be accounted for. This is the reason an additional option of a large macroscale model that encompasses surface water and groundwater interactions on a time step basis is needed for current research. Hence to develop this model, VIC was coupled with MODFLOW to allow large (+100,000 km^2) basins to be modeled and account for groundwater interactions.

The process of coupling the two models to communicate surface water and ground water interactions was coded by Jin and Sridhar (2010). They implemented an algorithm as seen in Figure 2.4 to account for iterations of fluxes between MODFLOW and VIC.

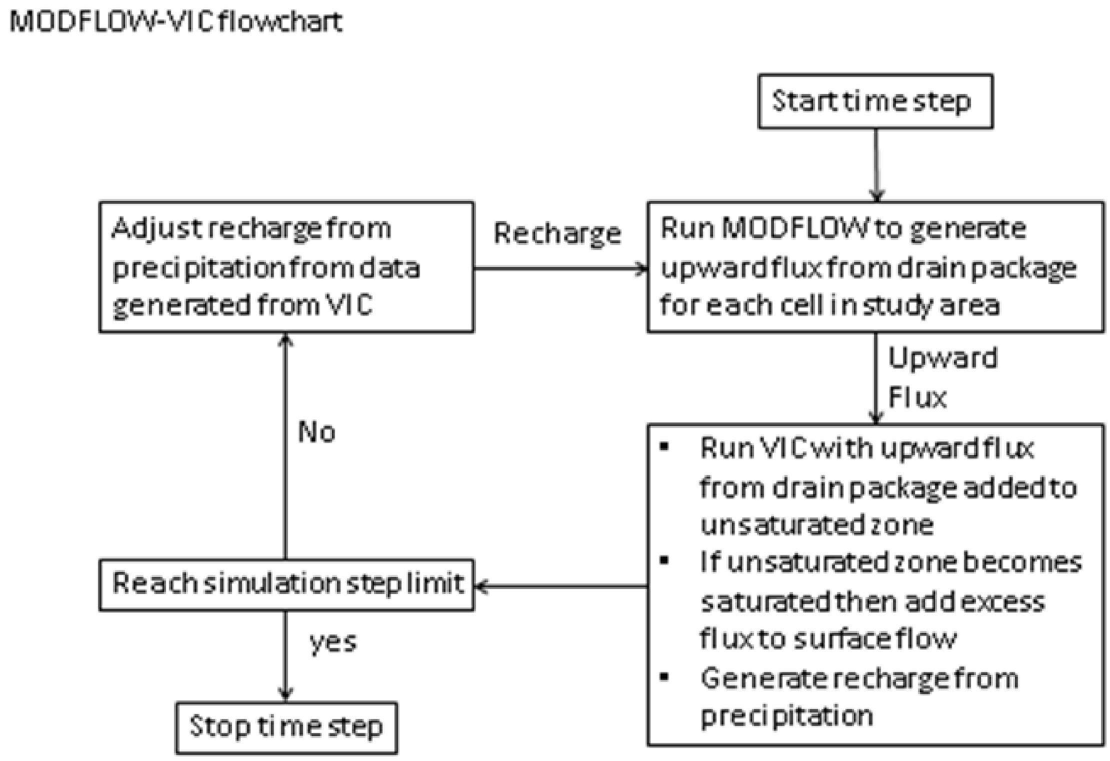


Figure 2.4 Schematic of flowchart showing the logic of the MODFLOW-VIC model (Jin and Sridhar 2010)

MODFLOW-VIC works by first calling MODFLOW and running a stress period to generate a flux out of the aquifer for each cell from the Drain Package. This flux is added to the soil in the VIC model, which determines how to handle this additional water. If soil is unsaturated, VIC adds the water to the unsaturated zone. Once the unsaturated zone becomes saturated, excess water is added to the baseflow. After this step, VIC is run and calculates a recharge flux. The flux is added to MODFLOW, which is run again to determine the new head, and the process is repeated. Limits can be set for how many times to iterate through this process, then the model moves on to the next stress period.

2.2.4 MODSIM-DSS 8.1

MODSIM is a generic river-support system from Colorado State University (Labadie 2006). The model is designed as a decision support system for long-term river and reservoir systems planning. The model incorporates water rights accounting for the solution of water conflict. MODSIM has been used in many basins; a list of these basins can be seen in the MODSIM user's manual.

The inputs to MODSIM include natural streamflow as a time series on a monthly time step. These can be included as a direct inflow to a reservoir node or as a reach gain in the form of a nonstorage node. This inflow is used by MODSIM to route flow into the river and reservoir network, which are connected by links to other nodes in the model interface. These links route the flow into diversion and reservoir nodes and are simple transfer mechanisms.

The reservoir's nodes take inputs of incremental costs, percent of target storage, target reservoir content, reservoir evaporation, runoff forecasts, storage capacity, and hydraulic capacity tables. All this data needs to be setup for each reservoir and is used to create cost functions, which are solved for the system.

The demand nodes use a hydrologic state to determine historic demand during the irrigation season based on water supply. Demands also have an infiltration rate associated with the canal to determine delivery losses. Demands have associated with them a priority date for water-right accounting, which is used to determine what demands are filled and what demands are shorted during the irrigation season.

MODSIM sets up cost functions of all inputs in the model and solves to optimize the solution based on the costs. MODSIM also has a water-right accounting program, which regulates by priority date what demands are filled. In Figure 2.5, a diagram of the MODSIM network structure can be viewed. Included are the behind the scenes artificial nodes the model uses for optimizing in the dashed lines.

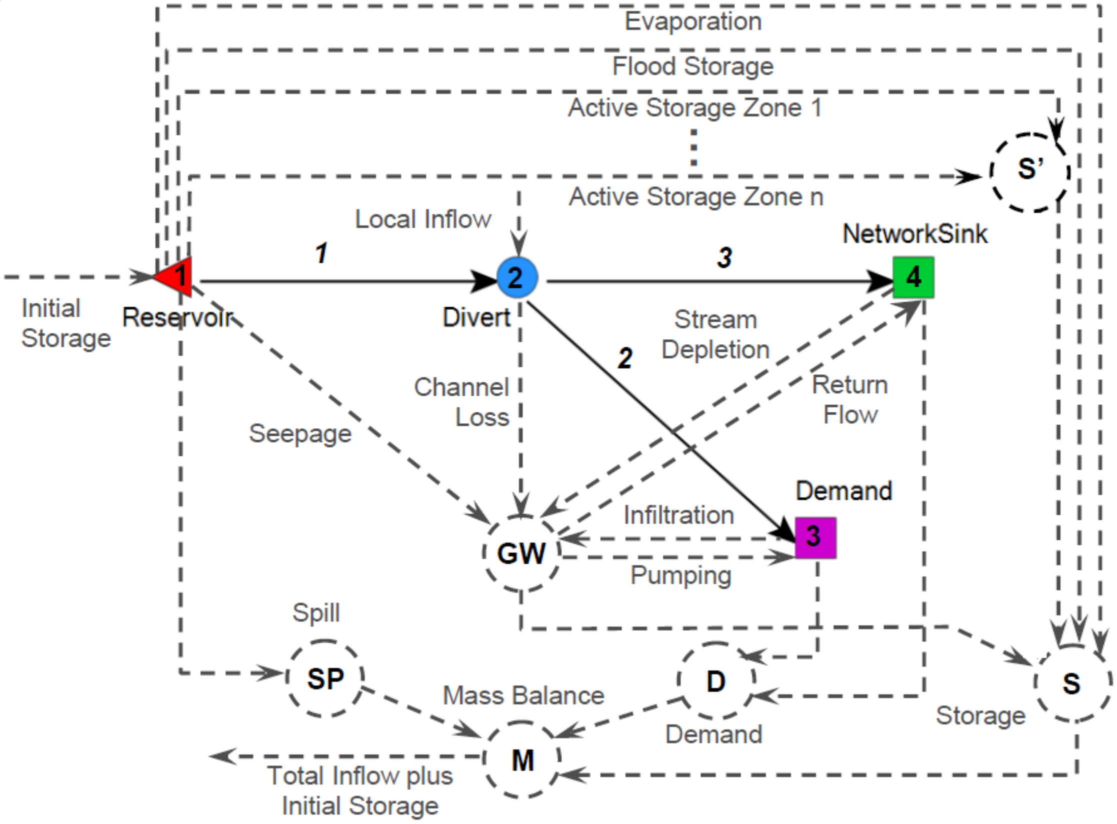


Figure 2.5 MODSIM network structure with model nodes colored and artificial nodes used by the solver in the dashed lines (Labadie and Larson 2007)

2.3 Observed Datasets

2.3.1 Gridded Weather Data

For observed gridded weather data, we choose to use the dataset generated for VIC by the University of Washington Climate Impacts Group. The derivation of this dataset is described in Maurer et al. (2002). This dataset was revised in 2012 to include 1/16th degree spatial resolution and a longer period of record (Livneh et al. 2012). The dataset was initially created to be used by the VIC model and is well accepted as a quality-observed dataset of gridded weather data. This makes the dataset ideal for use in our modeling studies. The parameters to be used from this dataset include maximum daily temperature, minimum daily temperature, total daily precipitation, and average daily wind speed. The resolution of this data is at 1/16th of a degree spatial resolution. The format for the data is already in files labeled for their longitude and latitude of grid-cell center and also already in the VIC-usable ASCII delineated file. The period of record for this data is available from January, 1915 through December, 2008. However, for our modeling purposes, only January, 1950 through December, 2005 will be used due to the period of record of our other datasets.

2.3.2 Natural Streamflow

Natural streamflow was needed for calibration, validation, and testing the results of the VIC model over the historic times. Natural streamflow is the flow that would occur through the basin, if no human influences were experienced in the system. Data for the various locations came from the USBR and from IDWR. After discussing this with Dr. Goyal, the two different agencies share the data and for the most part have the same process and formulas for obtaining natural flow. The table below shows the locations and the data source from where the natural flow was obtained. Equation 2.1 shows a sample calculation for the reach gain in a reach with a reservoir, where R_{gain} is the reach gain (L^3/T), Q_{in} is the inflow (L^3/T), Q_{out} is the outflow (L^3/T), D is the diversion (L^3/T), E is the reservoir evaporation (L^3/T), and Δs is the change in reservoir storage (L^3/T).

$$R_{gain} = Q_{in} - Q_{out} + D + E + \Delta s \qquad (2.1)$$

Typically, the formula for natural flow is the sum of reach gain above the desired location. An equation for reach gain can be seen in Equation 2.2, Q_{nat} is the natural flow (L^3/T) at the desired location, and $i = 0,1,\ldots,n-1,n$ for reach gain upstream of the desired point.

$$Q_{nat} = \sum_{i=0}^{n} R_{gain}(i) \qquad (2.2)$$

Table 2.1 Location of streamflow gages, for which natural flow data was obtained for period of record

Site No.	USGS Gage Name	Longitude	Latitude	USGS	Source
1	Snake River near Moran, WY	-110.58583	43.85833	13011000	USBR
2	Snake River near Irwin, ID	-111.21889	43.35083	13032500	USBR
3	Snake River near Heise, ID	-111.66000	43.61250	13037500	IDWR
4	Henrys Fork near Lake, ID	-111.34972	44.59444	13039500	USBR
5	Henrys Fork near Island Park, ID	-111.39472	44.41667	13042500	USBR
6	Falls River near Ashton, ID	-111.56667	44.01833	13049500	USBR
7	Teton River near St. Anthony, ID	-111.61389	43.92722	13055000	USBR
8	Henrys Fork near Rexburg, ID	-111.90500	43.82583	13056500	IDWR
9	Willow Creek bellow Floodway Channel near Ucon, ID	-111.74611	43.58333	13058000	USBR
10	Snake River at Neeley, ID	-112.87944	42.76750	13077000	USBR
11	Snake River Gaging Station at Milner, ID	-114.01833	42.52806	13087995	IDWR
12	Snake River at King Hill, ID	-115.20250	43.00222	13154500	IDWR
13	Snake River at Hells Canyon Dam ID-OR State Line	-116.69722	45.25138	13290450	IDWR

For our study, we needed important locations of streamflow throughout the Upper Snake river system. Table 2.1 shows the locations at which observed natural streamflow was obtained. The locations correspond with the same 13 points to which VIC was calibrated. These locations represent inflows to major reservoirs, confluences of major tributaries, and flood control points in the Snake River.

2.4 Model Setup

2.4.1 VIC Setup

To prepare for large-scale model runs, VIC was the first model to be setup and calibrated. The locations of streamflow for calibration can be seen in Table 2.1. These locations represent a good portion of the Upper Snake river and one exit location where the river flows into Hells Canyon. The exit location was selected for an opportunity to close the water budget at the exit of the upper and middle Snake River. These locations include inflow locations into reservoirs, flood-control points, areas of known return flow from the ESPA where springs discharge into the reach. A spatial map of the locations and the encompassing VIC grid cells can be seen in Figure 2.6.

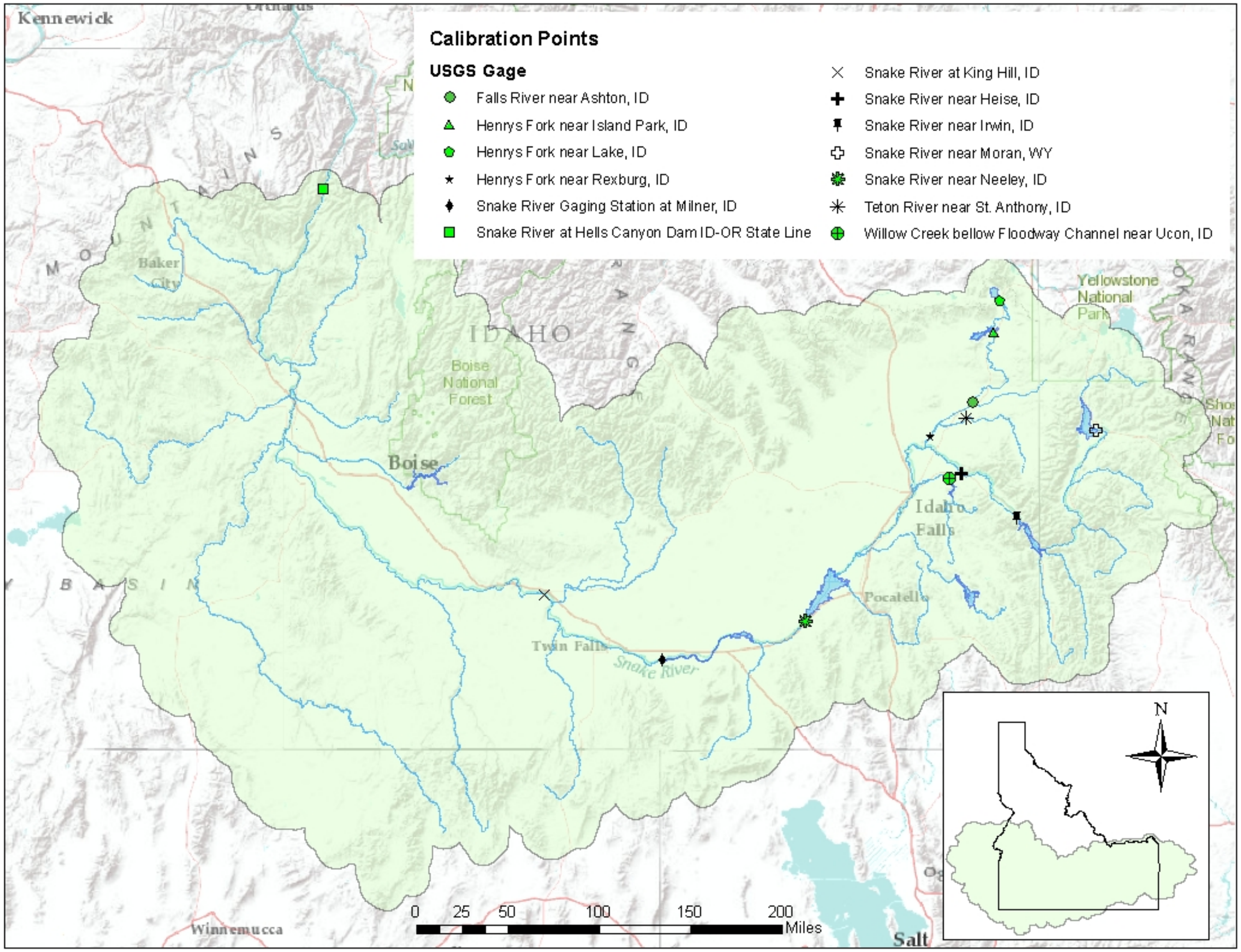


Figure 2.6 Spatial plot of the calibration points in the Snake River Basin

The calibration of VIC was performed for each location mentioned above using the observed meteorological forcing data described in the gridded weather forcing section of this thesis. To calibrate VIC, five parameters were adjusted using the Shuffled Complex Evolution (SCE) (Duan et al. 1993; Thyer et al. 1999; Vrugt et al. 2003) method of calibration for the different locations. The calibration period was water years 1990-1999. The reason this time period was selected is because, in the early 1990's, the Snake River saw some of the driest periods of record, and in the late 1990's the Snake River saw a few very wet years, including the flood of 1997, which is the largest flood on record. Table 2.2 shows the different calibration parameters the SCE method used to calibrate the model. After calibration of the VIC model, the calibrated parameters were held constant for the remainder of this study.

Table 2.2 Description of the VIC calibration parameters to be used by the Shuffled Complex Evolution (SCE) algorithm

Parameter Name	Description
DS	Fraction of Dsmax where non-linear baseflow begins
DSMAX	Maximum velocity of baseflow
BINF	Variable infiltration curve parameter
DEPTH (Layer 1,Layer 2, Layer 3)	Thickness of each soil moisture layer
KSAT	Saturated hydrologic conductivity

2.4.2 MODFLOW Setup

Modeling of the ESPA has been done very successfully by IDWR using the ESPA Model (ESPAM) in the MODFLOW framework. This model is the industry-accepted model of the ESPA and has been used by many modeling studies to model the historic elevations of the ESPA and conjunctive management practices over the ESPA. Although the ESPAM is currently the best complete model of the aquifer, it will not work for our purposes of coupling with the VIC model. This is due to different reasons. One reason the ESPAM model will not work is because the orientation of the model grid cells is perpendicular to the groundwater flow paths and not oriented geographically north to south. This caused a spatial mismatch between the VIC grid cells and the MODSIM cells. Another issue with ESPAM is that the model uses the Block-Centered Flow package (BCF), which uses transmissivity. Transmissivity is dependent on cell dimensions, and hence cell dimensions must be known prior to giving input to the BCF package. For the coupling of VIC and MODFLOW, we need cell dimensions to be dynamic in the feedbacks between both models. VIC already has the dimension-independent hydraulic conductivity specified in the soil file. For MODFLOW, we need to use the Layer Property Flow package (LPF), so that we can give MODFLOW hydraulic conductivity as input, independent of the cell dimensions matching the VIC input. To acquire the appropriate values for hydraulic conductivity for MODFLOW, Equation 2.3 was used to generate K, hydraulic conductivity (L/T) from T, transmissivity (L^2/T) and d, aquifer depth (L).

$$K = T/d \tag{2.1}$$

Other major issues with using the ESPAM model are in the Well Package, Recharge Package, River Package, and Drain Package. Currently, each of these packages is comprised of an observed time series of data, which is configured for input on a stress-period basis into MODFLOW. For our purposes of needing to eventually use MODFLOW for future climate projections, we could not just use the observed time series since in the future we would not know parameters like conductance, river stage, drain elevations, recharge rate from irrigation seepage, and groundwater pumping rates. Hence, to lessen the complexity, it was decided to create static packages that represent the average monthly values. This allows the effects of the aquifer to only be influenced by temperature and precipitation and keep all other parameters the same. Therefore, to create these packages, we took the average monthly values from 1995-2005.

The Drain Package had an extra complexity since VIC communicates to MODFLOW through the Drain Package, at every cell in the model; the Drain Package had to be added. In areas the Drain Package exists, the same value from the ESPAM model was used. In areas the model did not exist, Equation 2.4 and 2.5 were used to calculate the elevation of the drain and conductance.

$$C = \frac{KA}{X_1 - X_0} \tag{2.4}$$

where C is conductance (L^2/T), K is hydraulic conductivity (L/T), A is the area (L^2), and X is the position (L) at which head is measured.

$$D_e = S_e - L \tag{2.5}$$

where D_e is the elevation of the drain (L), S_e is the surface elevation (L) from the ESPAM model, and L is the depth of all the layers (L) from the VIC model.

The Well Package also had to receive extra modifications. The Well Package had the precipitation recharge component added into the model due to the way IDWR adds recharge to the ESPAM model. For our purposes, we need precipitation to first enter the VIC model, and if infiltration occurs, then pass the values back to MODFLOW. Hence, to account for this, we used the IDWR Make MODFLOW (MKMOD) code to generate a Well Package with only the precipitation component and removed these well values from the ESPAM current Well Package. MKMOD is a program that creates input files for MODFLOW using IDWR data.

Now that the model inputs are appropriate for our use, MODFLOW needs to be properly oriented in the north-to-south direction. To do this, each grid cell needed to be rotated by an angle of 31.4°. The original shift of the cells for the ESPAM model is described in Cosgrove et al. (2006). The reason ESPAM had originally been rotated is due to the flow direction of the groundwater; however, with the recent advances in the MODFLOW model programming, it is acceptable now to orient the cells north to south without a loss of model accuracy. After the cells are oriented correctly, they also need to be correctly sized. Hence, grid cells for MODFLOW were changed to 1/80th of a degree, which resulted in 25 MODFLOW cells fitting evenly into a VIC grid cell. All parameters of the ESPAM model were converted to the metric system and fit to these grid cells.

With all these new changes, it is no longer fair to call the model the ESPAM, but the foundation of our new MODFLOW model came from the calibrated values of the ESPAM. The new MODFLOW model is being used as is, since all calibration from the ESPAM model parameters have been preserved in the new model. This new model will be used as is for the remainder of this thesis and, from here on, referred to as the MODFLOW model.

2.4.3 MODFLOW-VIC Setup

See Appendix A for changes made to the source code of VIC and MODFLOW outlined in Jin and Sridhar (2010). The parameters from both VIC and MODFLOW as described above are used for the inputs to MODFLOW-VIC. To setup the run, the paths in the source code needed to be changed to prepare for the different run platforms of either INL computers or BSU computers. The start date, longitude of lower-left-hand corner, latitude of lower-left-hand corner, and the VIC cell size needed to be changed in the model source code. MODFLOW-VIC is then compiled using the Intel compiler on the INL machine. MODFLOW-VIC is then given the calibrated parameters from VIC, observed forcing data, and the MODFLOW model as inputs. Since both MODFLOW and VIC are considered calibrated, no further calibration of the MODFLOW-VIC model is being completed.

2.4.4 MODSIM Setup

In the MODSIM modeling frame work, the USBR have an existing model of the Snake River Basin. The existing model is called the Snake Basin Planning Model (SPM), which was developed by USBR staff to replicate historic data and system operations. The model is structured with a monthly time step and is the same model used for operation simulations from the RMJOC study by the USBR. Input for the model is given to a spreadsheet, which is used to derive the values to give to each node of the model. A custom code, also written by the USBR, loads excel data into each SPM node. Inputs to SPM are the flood-control forecasts and natural flow at different locations.

Flood-control forecasts attempt to simulate real operations by giving the model a forecast of what operators think the volume runoff will be on the 1st of July. For the purposes of our model, forecasts are generated for January through June, forecasting the remaining volume of streamflow expected to runoff from the forecasts date to the 1st of July. Time was a big factor for our study; hence, we used the true volume of the streamflow, from the modeled time series, for our forecast into the SPM. This was a quick and easy way to get a forecast for the model.

CHAPTER THREE: HISTORIC SIMULATIONS INVESTIGATING THE USE OF VIC AND MODFLOW-VIC TO MODEL NATURAL STREAMFLOW

3.1 Introduction

The VIC model is used to simulate naturalized streamflow for periods of historic record to determine if the results can be sufficiently used to model streamflow data in the Snake River basin. The model is simulated using VIC grid cells with a spatial resolution of 1/16th degree on a daily time step. The algorithm for solving VIC uses the energy balance solution to solve for the needed variables and iterate to the solution on each time step of each grid cell. The driving datasets used for VIC are the observed meteorological forcings and historic simulated forcings from 12 GCMs. The model will run for a time period of 1/1950-12/2005 on a daily time step with the observed data and 12 different GCM modeled data inputs. Using the results from the VIC model, natural streamflow for seven locations in the Upper Snake River were used as inputs to the SPM model. The results of the SPM model present the operations of the system for the historic time period.

MODFLOW-VIC is also used to simulate streamflow in the Snake River to investigate how the addition of MODFLOW can potentially model the physical system more precisely by capturing return flow from the aquifer in the late summer and winter months. The dataset used to drive MODFLOW-VIC is the observed meteorological forcing. The MODFLOW-VIC model is a complex algorithm that runs MODFLOW and VIC in multiple iterations per time step. This causes an exponential increase in model run time due to the complexity. Due to the long run times required for MODFLOW-VIC, the model can only be run in 25 year lengths. To validate the MODFLOW-VIC model, the model was run from 1/1980-12/2005.

3.2 Methods

3.2.1 Meterological Forcing Datasets

Observed Dataset

The observed data used in this study is described in Section 2.3 of the previous chapter. This dataset was selected since it already exists in the VIC input format and was created with the purpose of being used with VIC to simulate past hydrology. The data represents the gridded observed daily maximum temperature, minimum temperature, total precipitation, and average wind speed. The period of record used from this dataset was 1/1950-12/2005.

GCM Datasets

The CMIP5 data recently completed for the IPCC Fifth Assessment report is the latest GCM outputs, which have been produced. The CMIP5 models use Representative Concentration Pathways (RCP) to model different scenarios into the future. Many studies have shown the usefulness and quality of these new CMIP5 models and the RCPs, which drive them for work in climate change science (Knutti and Sedláček 2012; Pierce et al. 2012; Taylor et al. 2009, 2012; Van Vuuren et al. 2011). For this research, only the past simulation by 12 different CMIP5 GCMs is used as inputs for the VIC model.

Raw data from the GCM simulations are not usable by the VIC model since the data are presented in scientific binary format, which needs to be converted to the ASCII format. The spatial resolution of the GCM models is typically 1 degree or more. This also cannot be used because VIC needs inputs at 1/16th degree. To acquire data in the proper VIC format, we chose to obtain already downscaled GCM data.

The CMIP5 data was downloaded from the Multivariate Adaptive Constructed Analogs (MACA) statistical downscaling website on the University of Idaho's ftp server (Abatzoglou 2013). This method is a downscaling method, which has shown slightly preferable results in downscaling data for complex terrain over the traditional interpolation an bias correction method of downscaling. A detailed description of this method can be seen on the download website at http://nimbus.cos.uidaho.edu/MACA/. The data from MACA is at 1/24th of a degree grid-cell size on a daily time step. The data covers the time period of 1950-2100. The data used from this dataset are daily maximum temperature, minimum temperature, total precipitation, average north wind vector, and average east wind vector. From the data, 12 GCMs were selected to be used, which can be seen in Table 3.1.

Table 3.1 List of the GCMs used

Global Climate Model	Institution Hosting Model
bcc-csm1-1	Beijing Climate Center, China Meteorological Administration
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University
CanESM2	Canadian Centre for Climate Modelling and Analysis
CNRM-CM5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique (France)
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory
inmcm4	Institute for Numerical Mathematics
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MRI-CGCM3	Meteorological Research Institute

To acquire the data in a usable resolution, and format preprocessing of the data was required after downloading the data from MACA. The data needed to be upscaled from 1/24th degree to 1/16th degree to match VIC resolution. Following the suggestion of the author of the dataset, bilinear interpolation was used to upscale the data in order to preserve the climatology in the complex terrain of the basin. After the upscaling process, data was written to ASCII text files for input to the VIC model.

3.2.2 Experimental Design

The VIC model was forced with the observed data and 12 different MACA downscaled GCM datasets for the historic time period of 1950-2005. This was used with the previously calibrated VIC model to generate streamflow to 13 locations in the Snake River basin. Once the 13 locations had been generated, bias correction was performed on each location to correct monthly bias in the results to the observed data. The results were evaluated to check how well bias-corrected VIC-generated natural streamflow correlates with the observed natural streamflow.

Of the thirteen locations of VIC-generated flow, seven were used for inputs to a spreadsheet, which partitioned the flow and placed the data in the SPM. SPM takes monthly streamflow and routes the flow through the river and reservoir system under operation constraints, which determine management of the system. The temporal scale of the SPM model covers the same time period of 1950-2005 on a monthly time step. Due to the complexities with reservoir fill reaching equilibrium in the system, the first 6 years have been thrown out due to spin up.

The MODFLOW-VIC model was forced with observed data for the historic time period of 1980-2005. MODFLOW-VIC generates streamflow to the same 13 locations from the VIC alone. Comparison between VIC alone and MODFLOW-VIC can be evaluated to see the capturing of base flow with the addition of MODFLOW in the basin.

3.3 Results

This section is divided into 3 subsections. The first is the VIC alone model. The second is results from the SPM. The third section is the MODFLOW-VIC results and how they compare to the VIC alone run. For the remainder of this thesis, baseline will refer to bias-corrected, VIC-generated streamflow using the observed meteorological forcings, and CMIP5 will refer to the averaged time series of the 12 GCMs.

3.3.1 VIC

Streamflow generated using the VIC model forced with the observed meteorological dataset was compared to the observed natural streamflow in the system. In Figure 3.1, a time series can be seen, showing the raw data and bias-corrected data compared to the observed data. It can be seen in the time series that the baseline raw data do not predict the baseflow well. A summary hydrograph can be seen in Figure 3.2, which illustrates the change in the streamflow from the bias-correction method at the Snake River at Hells Canyon dam. From Figure 3.1, it can be seen that the bias-correction method successfully corrects the streamflow to observed conditions. In Table 3.2, the root-mean-square-error (RMSE) and the correlation coefficient of each location is reported for the observed data and the bias-corrected streamflow.

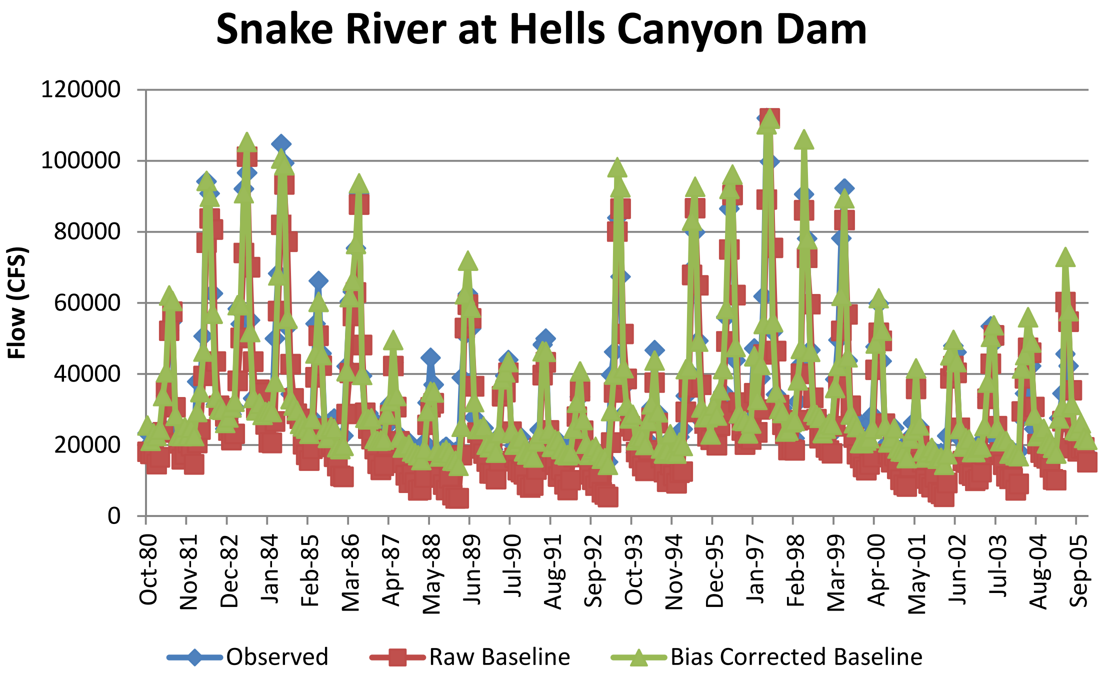


Figure 3.1 Sample time series from the Snake River at Hells Canyon (1980-2005)

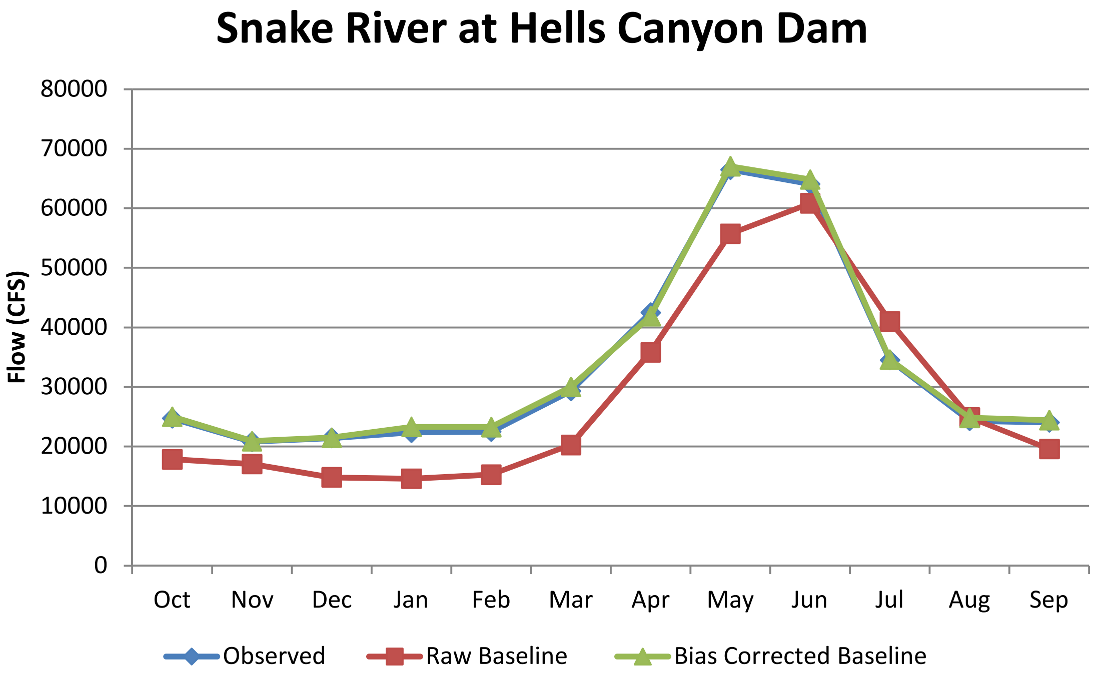


Figure 3.2 Example of the bias-correction method on summary hydrographs at Hells Canyon (1980-2005)

Table 3.2 Correlation coefficient and RMSE of the modeled VIC with observed meteorological forcing data and the observed streamflow in the system comparing 1950-2005 results

Location	R^2	RMSE
Henrys Lake	0.53	37.57
Island Park	0.77	152.97
Falls River	0.93	204.21
Teton River	0.90	224.46
Rexburg	0.92	601.46
Jackson Lake	0.91	533.81
Palisades	0.95	1477.62
Heise	0.94	1718.75
Ririe	0.76	103.69
American Falls	0.94	2367.21
Milner	0.94	2261.39
King Hill	0.93	2603.85
Oxbow	0.91	5835.37

Table 3.3 Correlation coefficient and RMSE of the modeled average CMIP5 streamflow and the observed streamflow in the system comparing 1950-2005 results

Location	R^2	RMSE
Henrys Lake	0.57	36.12
Island Park	0.59	204.12
Falls River	0.78	371.65
Teton River	0.81	315.62
Rexburg	0.68	1202.70
Jackson Lake	0.79	833.04
Palisades	0.75	3251.63
Heise	0.74	3533.56
Ririe	0.44	159.39
American Falls	0.73	4871.33
Milner	0.71	5043.48
King Hill	0.64	5795.32
Oxbow	0.63	11662.48

The results of the VIC model forced with the 12 GCM forcing inputs can be seen in Table 3.3. The GCM's cannot produce the exact weather on any given day but overall capture the climatology. These results are quite favorable for historic simulations resulting in correlation between 0.67 and 0.90 throughout the basin with GCM modeled data. These results have many sources of uncertainty, thus seeing the correlation of the results, shows that streamflow can be produced with reasonable confidence from GCMs.

In Figure 3.3, a time series of the data is presented for the observed, baseline, and CMIP5 data from 1970-2005. The time series represents the annual volume of water exiting the basin at Hells Canyon Dam. From the time series, it can be observed that the CMIP5 average data does not capture the same high-water years and low-water years that the baseline and observed data capture. Figure 3.4 shows the average annual volume for the time series and shows how the different GCMs show different hydrology in the system. The average CMIP5 data show that they capure the overall volume on an annual basis well, but year to year variability is not captured with the averaging of the 12 models.

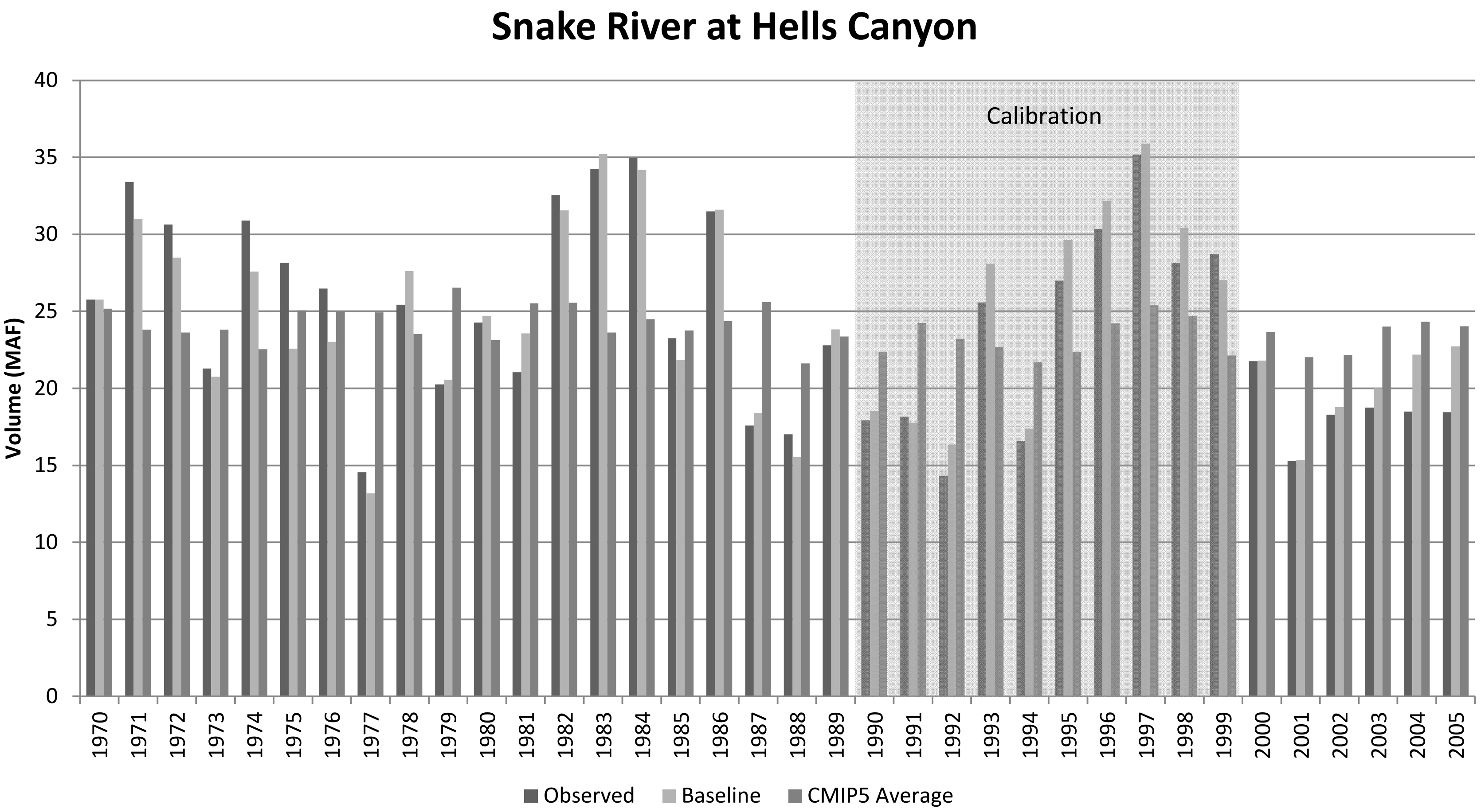


Figure 3.3 Annual volume of water past the Snake River at Hells Canyon for observed, baseline, and average CMIP5 (1970-2005)

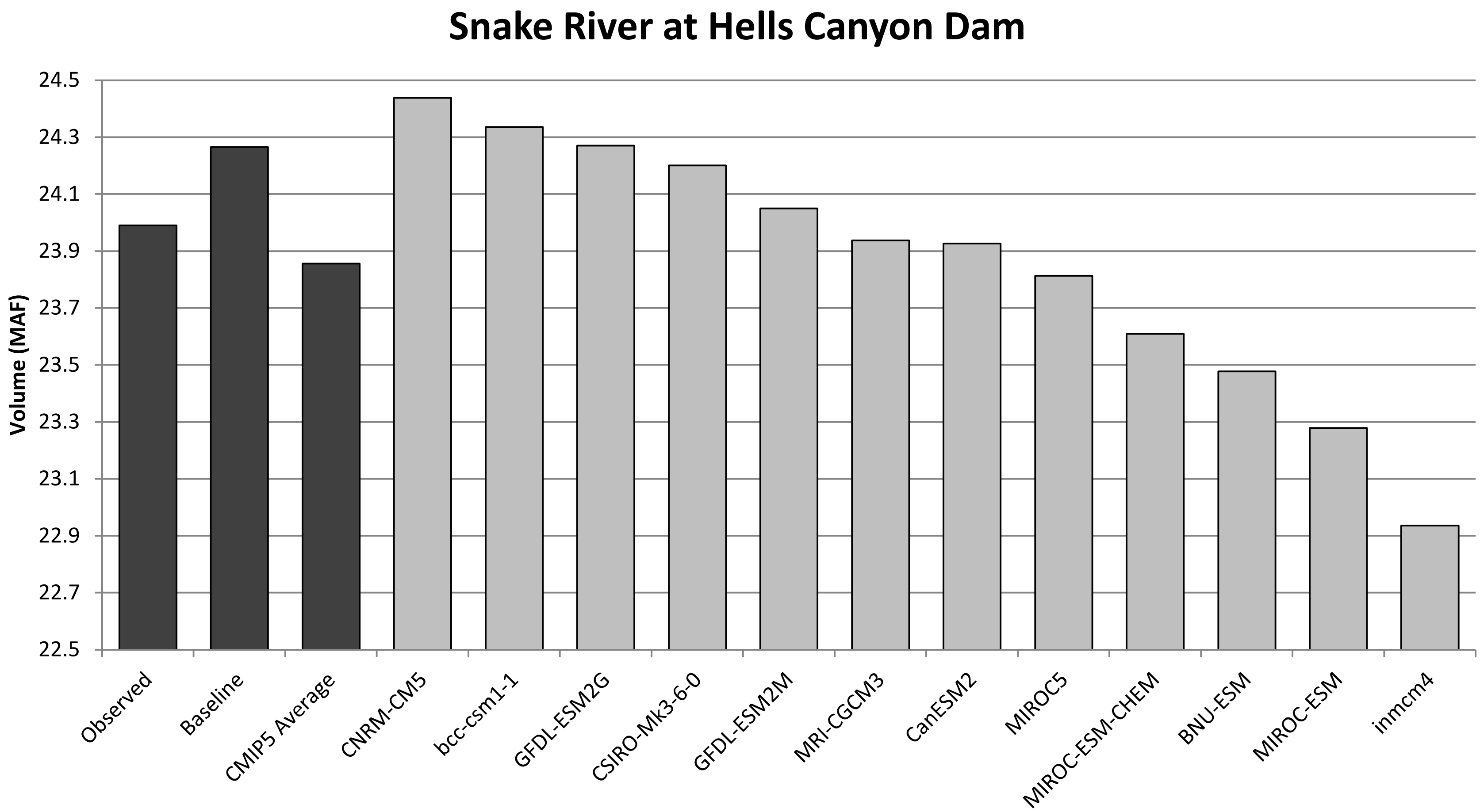


Figure 3.4 Average annual volume in MAF of the Snake River at Hells Canyon in black is the observed, baseline, and CMIP5 average, and in grey is each GCM

3.3.2 SPM

The results from the SPM were simulated for operations of water years 1956-2005. In Table 3.4, the correlation of the end-of-month (EOM) storage and the regulated monthly streamflow (QM) can be seen for the baseline streamflow and the average historic CMIP5 streamflow.

Table 3.4 Correlation of the baseline and the CMIP5 data run through SPM compared with the observed data

	Baseline	Baseline	CMIP5	CMIP5
Location	EOM R^2	QM R^2	EOM R^2	QM R^2
Jackson Lake	0.2026	0.4077	0.0782	0.417
Palisades	0.2059	0.5475	0.1334	0.639
Heise		0.5861		0.6551
American Falls	0.6615	0.4749	0.5215	0.4379
Rexburg		0.7804		0.154

The correlation of the results was not superior and can be contributed to issues with flood-control forecasting and the lack of nodes available to force the SPM. A time series of this data for Jackson Lake can be seen in Figure 3.5, which represents the worst correlated reservoir. The circle in the graph represents construction on the dam, which required the content to be held artificially low and was excluded from the correlation. Although the Jackson lake dam did not correlate well, the overall operations for the yearly volume is captured. In Figure 3.6, the October end-of-month storage content is plotted as a time series for the period of record. The results are essentially the yearly carry over at the end of the year. The decadal cycles in the graph seen in the observed content are also seen in the modeled data. In Figure 3.7, the end-of-month storage content is plotted for June. In the reservoirs, this seemed to be the point in reservoir operations that contained the most error. The model does not respond well to dry years and creates full reservoir content even in years of draught. This is due to the averaging of the CMIP5 models. If the models had been used without averaging the time series, the results would have been better.

Finally, Figure 3.8 shows the total monthly volume of surface water diversion over the period of record for the observed data. The results from the diversion data show that diversion can be accurately captured even though the reservoirs might not be acting exactly the same as the observed data. The diversions represent the reach from American Falls down to Milner. These water rights all have very high priority dates and large volumes of natural flow rights and storage rights. Comparison of the data for the past shows that trends in diversion can be well modeled by the SPM.

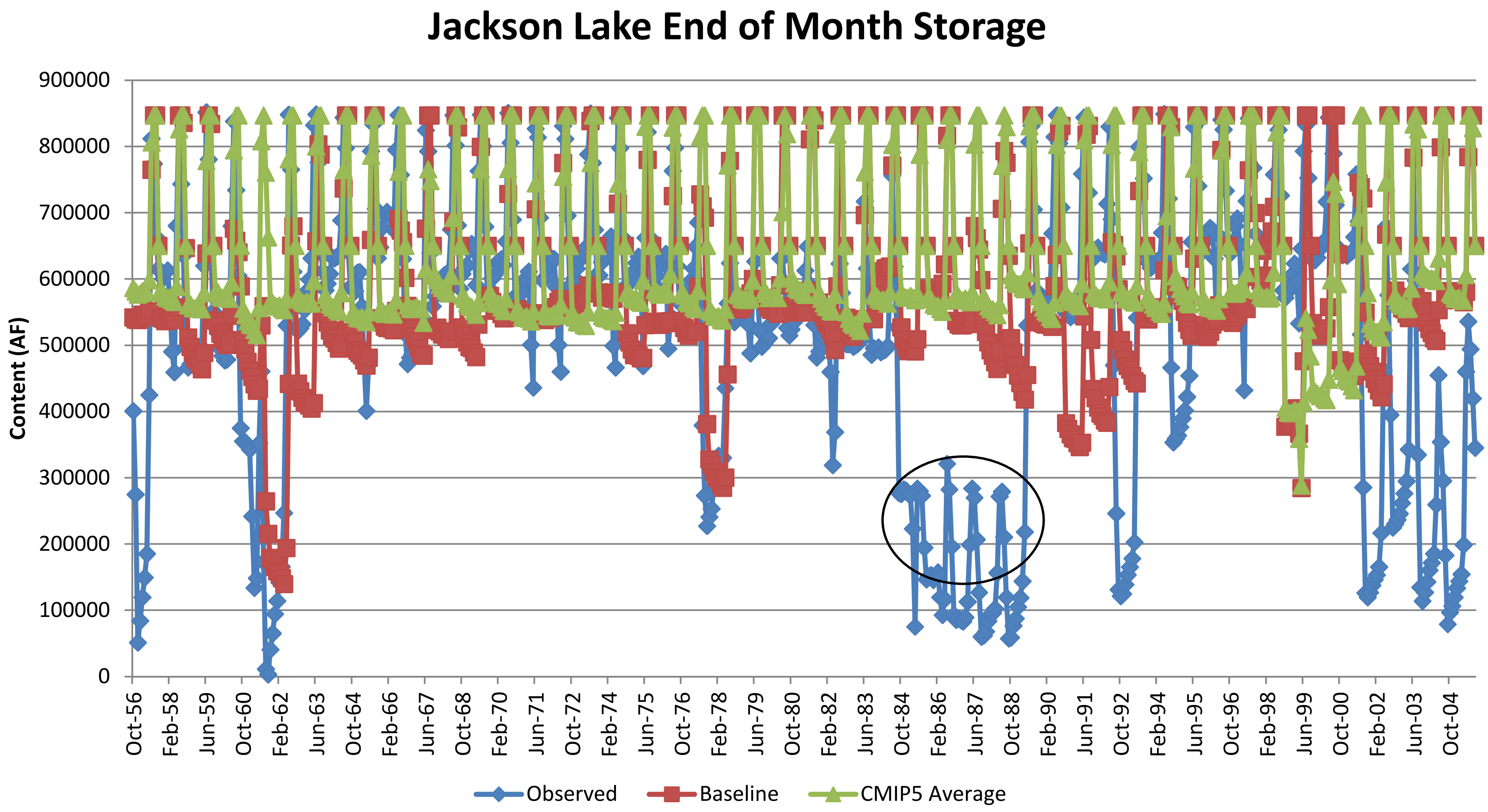


Figure 3.5 **Jackson Lake end-of-month storage content for water years (1956-2005)**

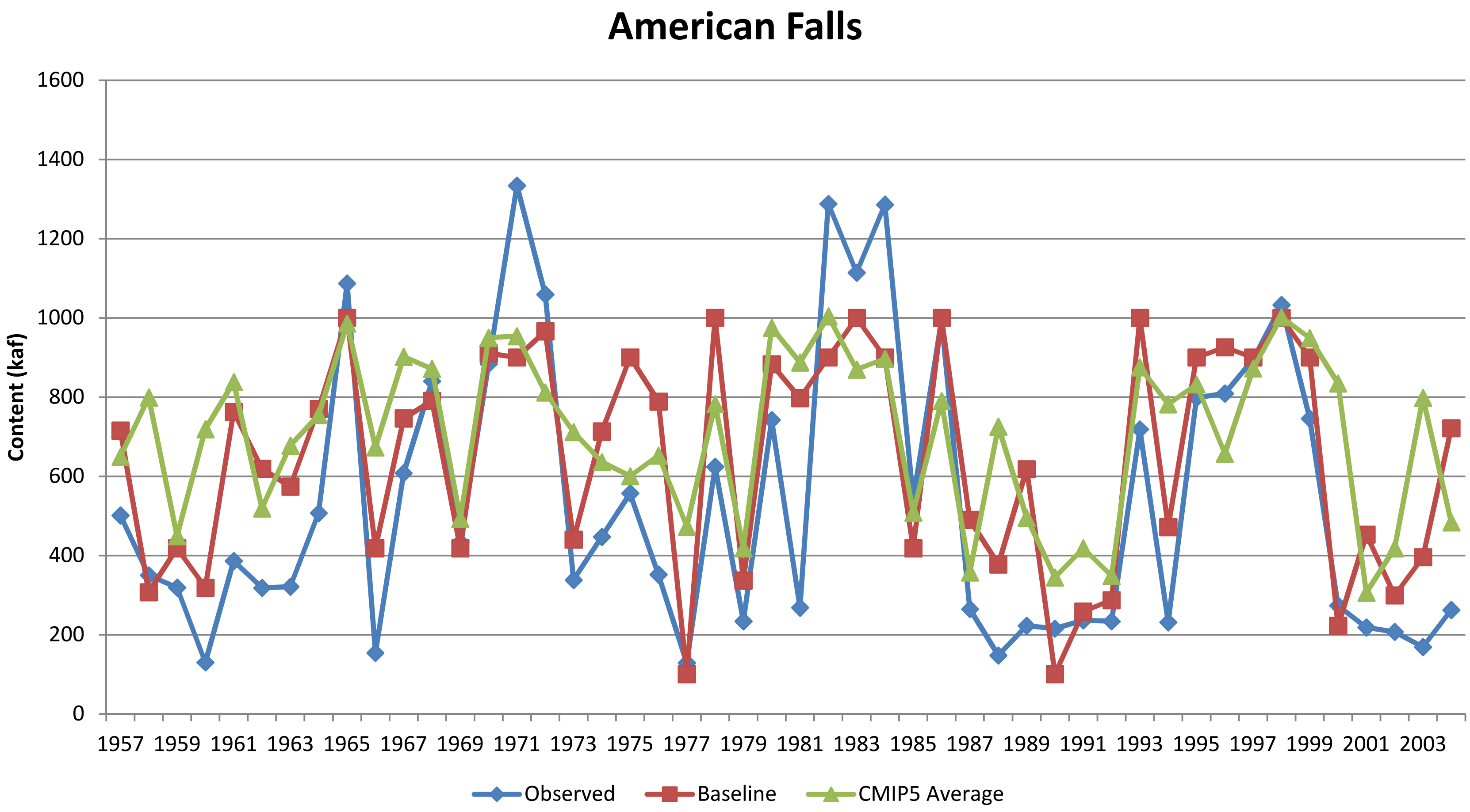


Figure 3.6 American Falls October end-of-month storage content (1956-2005)

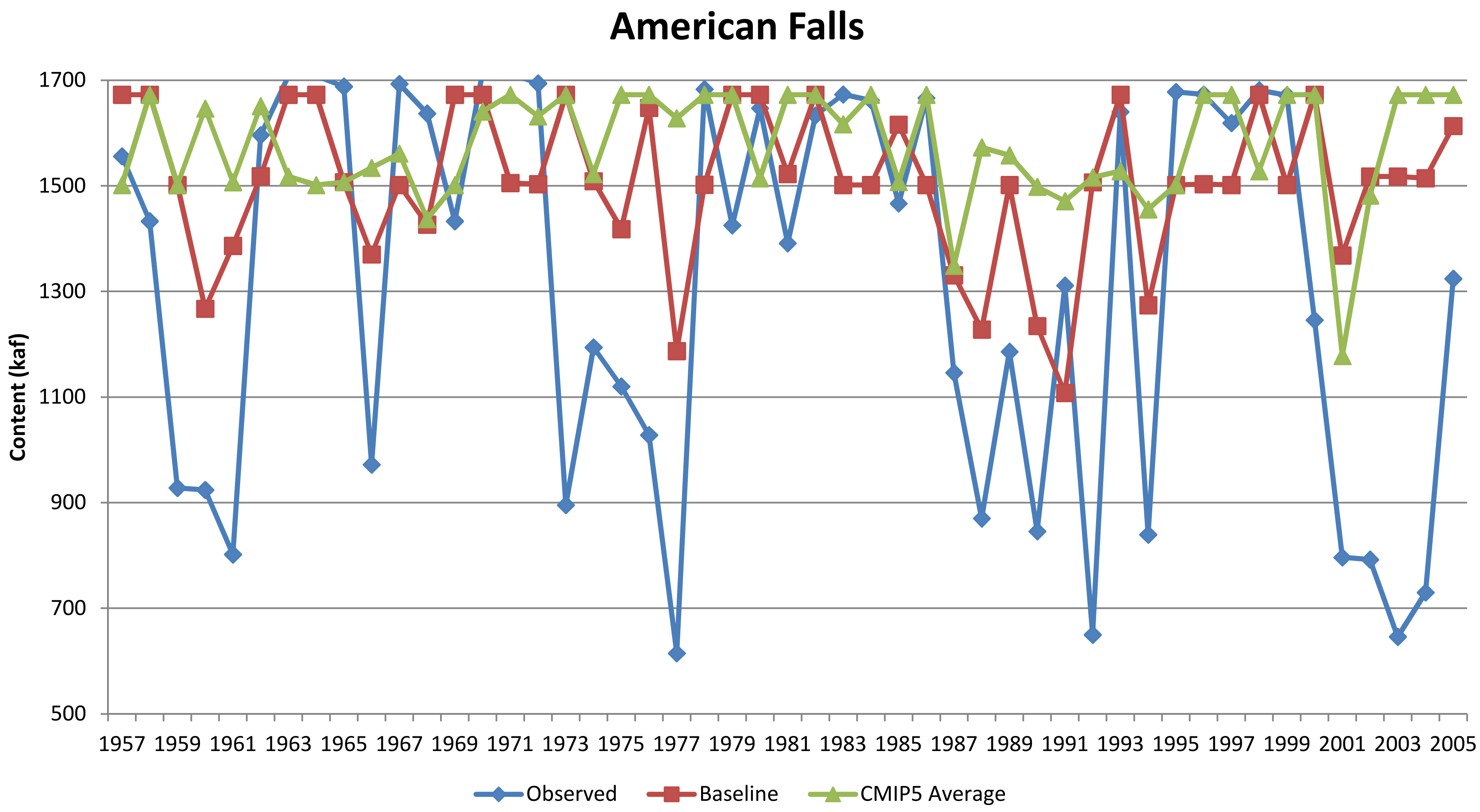


Figure 3.7 American Falls June end-of-month storage content (1956-2005)

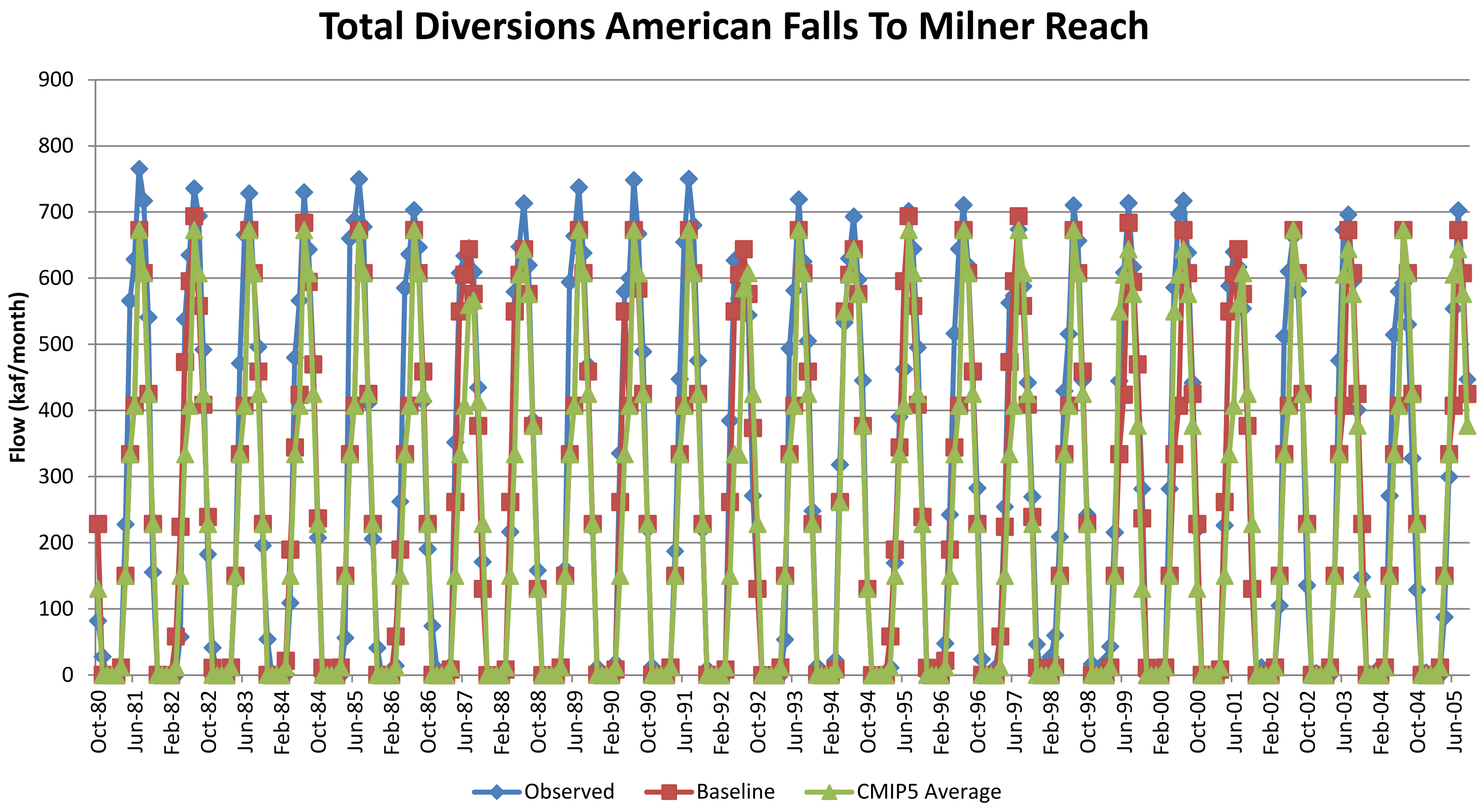


Figure 3.8 Total diversion from American Falls to Milner reach (1980-2005)

3.3.3 MODFLOW-VIC

The MODFLOW-VIC model results can be seen in Figure 3.9 and show the observed, VIC alone, and MODFLOW-VIC model output prior to bias correction. The results are not superior, but they do show a slight increase in spring discharge at King Hill, Idaho. Modeled spring discharge can be seen in Figure 3.10 and shows the total spring discharge above King Hill, Idaho. The modeled spring discharge is only accounting for 33% of the observed spring discharge, but the results do show that MODFLOW-VIC is capturing some spring discharge, around King Hill, Idaho. In Figure 3.11, the head in the aquifer can be seen. The results compare well with literature, suggesting that aquifer water table elevations have been decreasing. In some regions modeled by MODFLOW-VIC, the aquifer water tables have increased. This is not a true representation of the historic trends. These issues in aquifer head could be attributed to the Well Package, since no constant head boundaries are used in the model, the only water entering the system comes from the Well Package.

Finally, in Figure 3.12, a well near Minidoka, Idaho, shows the observed head and modeled head in the aquifer. The water table year-to-year variability is removed in the modeled aquifer head, since components of the aquifer are static, but the results showed we are capturing realistic aquifer head in this region of the aquifer. The trends of the aquifer head are decreasing, it is important to capture this trend, even if the variability is not present.

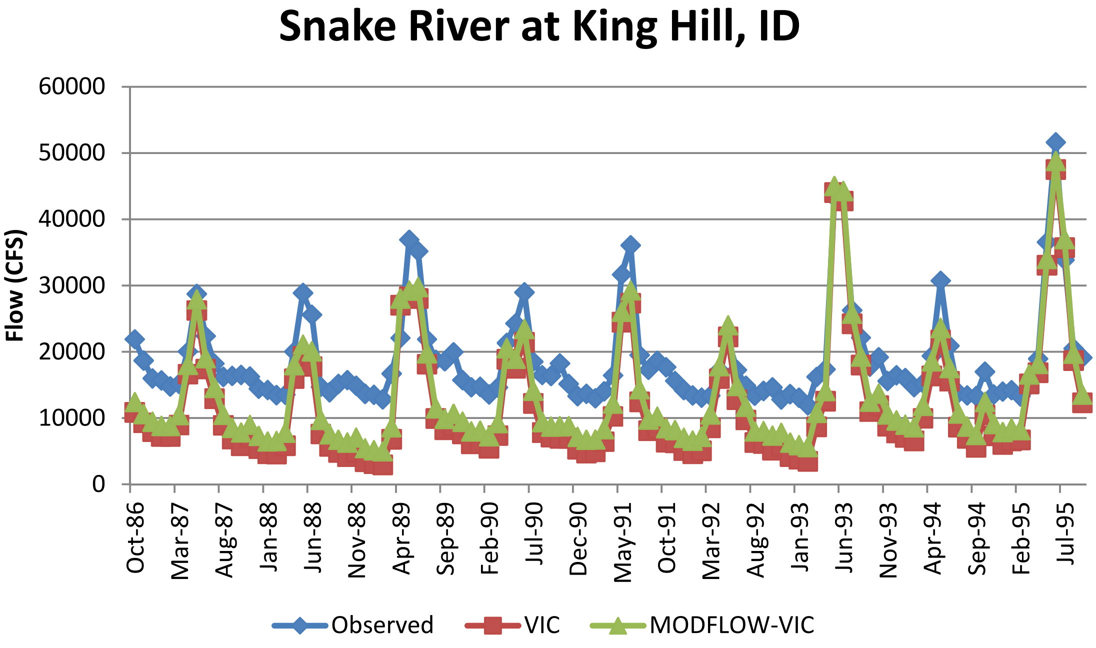


Figure 3.9 Comparison of the MODFLOW-VIC and VIC results with the observed natural flow (1986-1995)

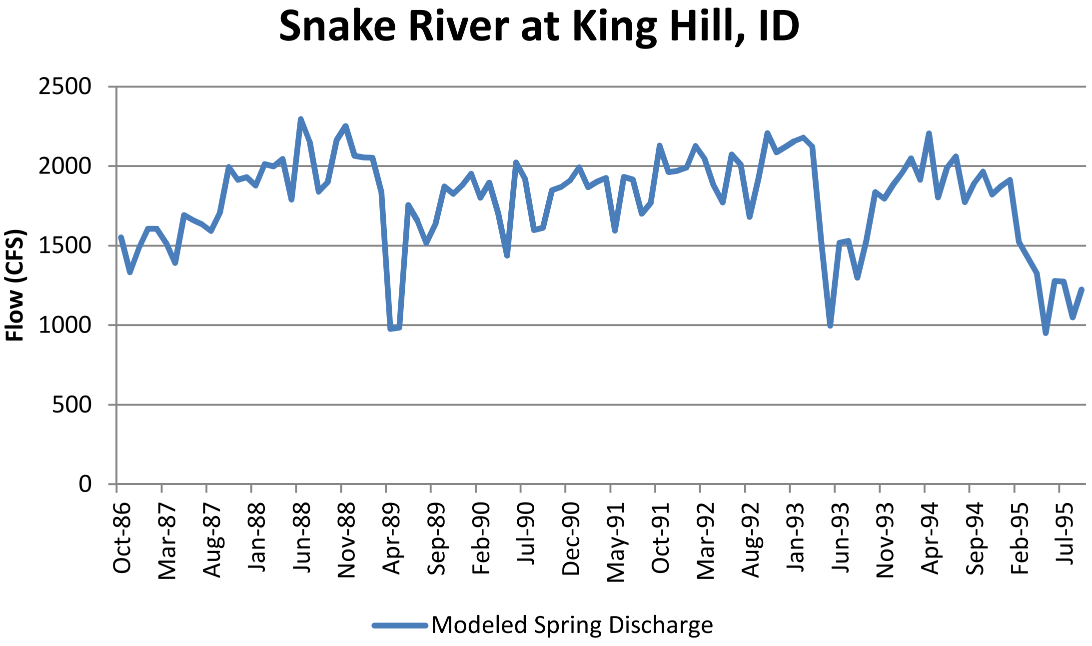


Figure 3.10 Modeled spring discharge at the Snake River at King Hill, Idaho (1986-1995)

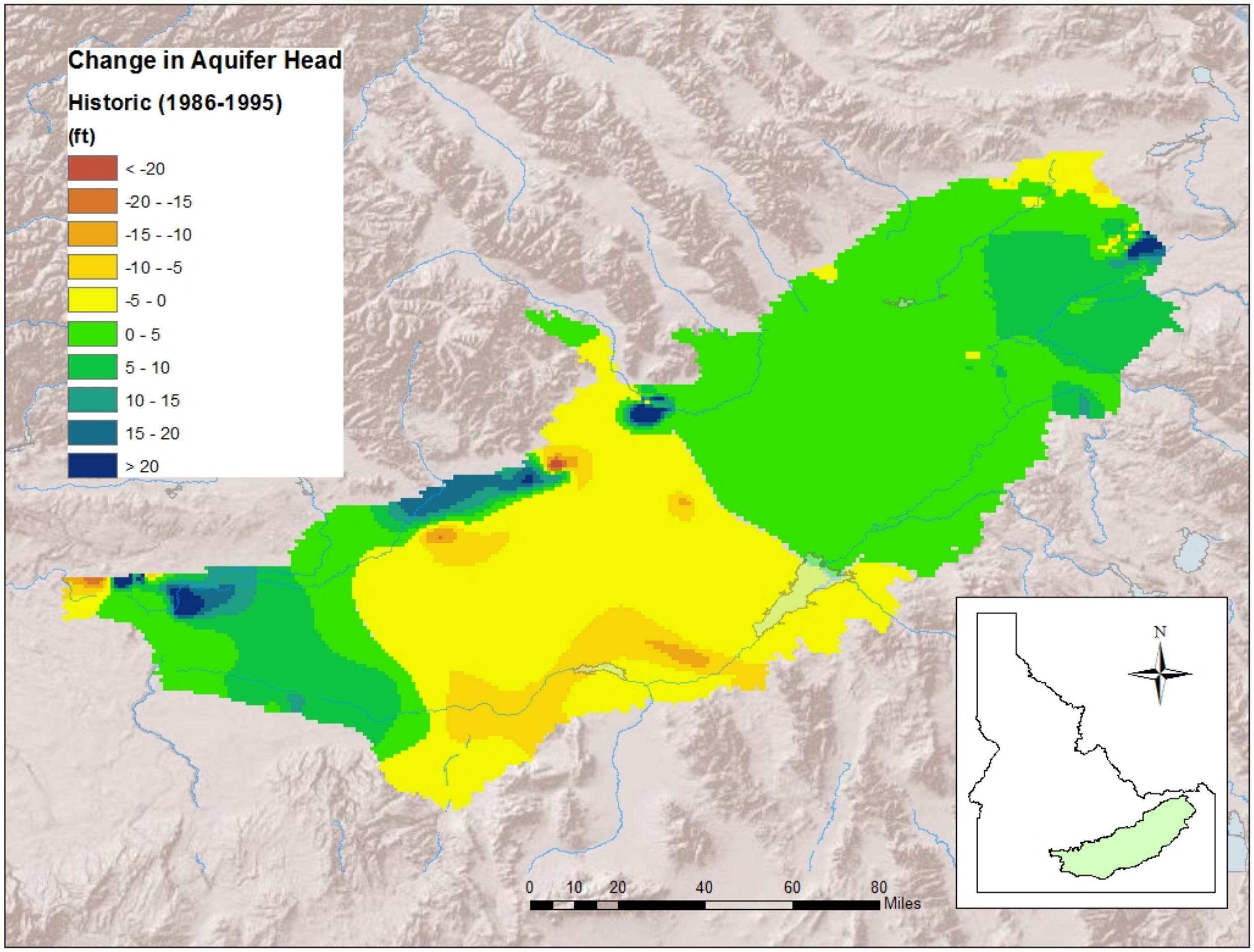


Figure 3.11 Eastern Snake River Plain Aquifer modeled change in aquifer head (1986-1995)

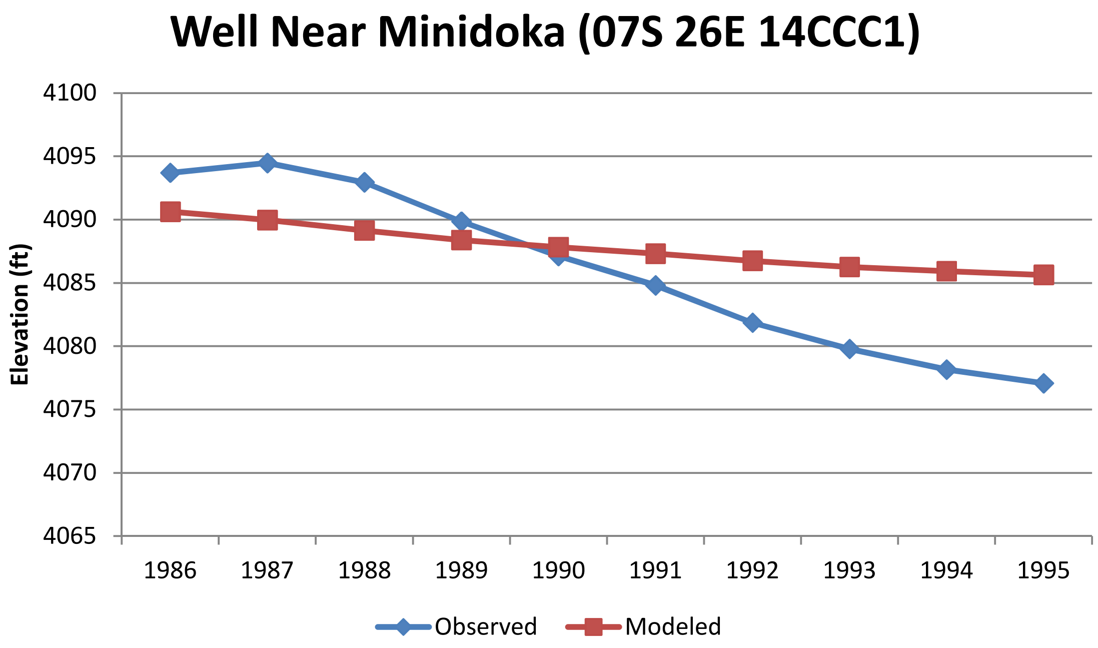


Figure 3.12 Observed and modeled water table elevation at well 07S 26E 14CCC1 in Minidoka, ID (1986-1995)

3.4 Discussion and Conclusion

From the results, we saw weak correlation from the SPM model when looking at end-of-month storage content and regulated streamflow. The causes of this weak correlation can be attributed to the flood forecasting method used, the averaging of the CMIP5 data, and the lack of streamflow locations fed into the model. These all cause issues with content and outflow of the reservoirs. Even though the correlation of the data is very weak, still it can be argued that the operations of the system are working properly. Even though the actual contents may vary on a year-by-year basis, the operations of years with that same volume preserve the operations. This is the justification for the use of this data into considering future operations. The comparison would look at modeled historic CMIP5 data and modeled future CMIP5 data to determine the changes. The only change between these comparisons would be the meteorological forcings. Hence, the differences observed in the operation of the system, due to changes in the meteorological forcings, would reflect the changes expected into the future. This can be thought of as conceptual model comparison, due to not appropriately capturing the past. This is the justification for the poor correlation, but it is reasonable to implement this framework with confidence that we can still force the model with future results and evaluate how it responds.

The MODFLOW-VIC model produced slightly preferable results in capturing the baseflow in the system, which VIC alone could not capture. The total volume of baseflow is not captured in this initial MODFLOW-VIC work, but the results show that with further calibration, the total volume of baseflow can be captured. One of the major reasons for the lack of baseflow is the elevation of the drains in the MODFLOW model. With an increase in the elevation of the drains, aquifer head would increase, which would cause an increase in the flux added to VIC. Another reason for the lack of baseflow is the conductance values for the Drain Package; if this value were increased, the model would cause greater baseflow. MODFLOW-VIC performed as expected and captured some baseflow, but the model needs to be calibrated again, due to the changes that occurred since initial models had been calibrated. To calibrate the MODFLOW-VIC model, the Drain Package should be used as a calibration parameter for capturing baseflow, and the Well Package should be used as a calibration parameter for capturing aquifer head.

CHAPTER FOUR: FUTURE SIMULATIONS INVESTIGATING THE MANAGEMENT OF THE UPPER SNAKE RIVER BASIN

4.1 Introduction

This chapter discusses the impacts of climate change over the next century on the Upper Snake River. The VIC model is forced with CMIP5 downscaled climate projections using the RCP45 and RCP85 scenarios from 2006-2099. The results of the bias-corrected streamflow from VIC are then used in the SPM to simulate river and reservoir operations in the Upper Snake River basin. The changes in hydrology of regulated and unregulated streamflow are evaluated based on the different RCPs. The changes to the Eastern Snake Plain Aquifer are investigated for the period of 2040-2049.

4.2 Methods

4.2.1 Future Dataset

The same technique from the historic GCM data will be used to project the future streamflow for use by the SPM. The data downloaded from Abatzoglou (2013) was used as inputs to the VIC model from 1/2006-12/2099. The same downscaling and upscaling techniques for the historic time periods are used for the future datasets. The datasets are from 2006-2099 on a 1/16th degree cell size over the Snake River Basin.

4.2.2 Experimental Design

The VIC model is used with the calibrated parameters from the historic calibration. The VIC model is run from 1/2006-12/2099. This will acquire a time series that is used by the SPM to project future climate change impacts on the Snake River Basin. The model will have two scenarios, RCP45 and RCP85, for 12 different models. The results of streamflow from each scenario will be ensemble together so a single time series will exist, and be the average of the 12 GCMs. This will then be used to force the SPM. Due to limitations of the SPM run time, the model will hold all past values except the locations of changed hydrology in the seven locations. The model will be run from 10/2010-9/2090, which will look at the changes into the future.

The MODFLOW-VIC model is forced with the CanESM2 GCM for RCP45 and RCP85. The MODFLOW-VIC model is run from 1/2040-12/2049. This will generate a future time series, which will be compared to the past to determine changes in spring discharge. The changes in aquifer head will also be looked at, which will investigate the change due to climate change.

4.3 Results

The results from the climate change projections will be divided into three sections, one section covers the future hydrology, another section covers the SPM, and the last section covers the MODFLOW-VIC results.

4.3.1 VIC

To understand the future hydrology of the system, VIC was forced with 12 different GCMs using RCP45 and RCP85 data to obtain 24 different time series of data.

These time series were then averaged to acquire one time series for RCP45 and one time series for RCP85. In Figures 4.1 and 4.2, the summary hydrographs for RCP45 and RCP85 can be seen for 12 locations above King Hill, respectively.

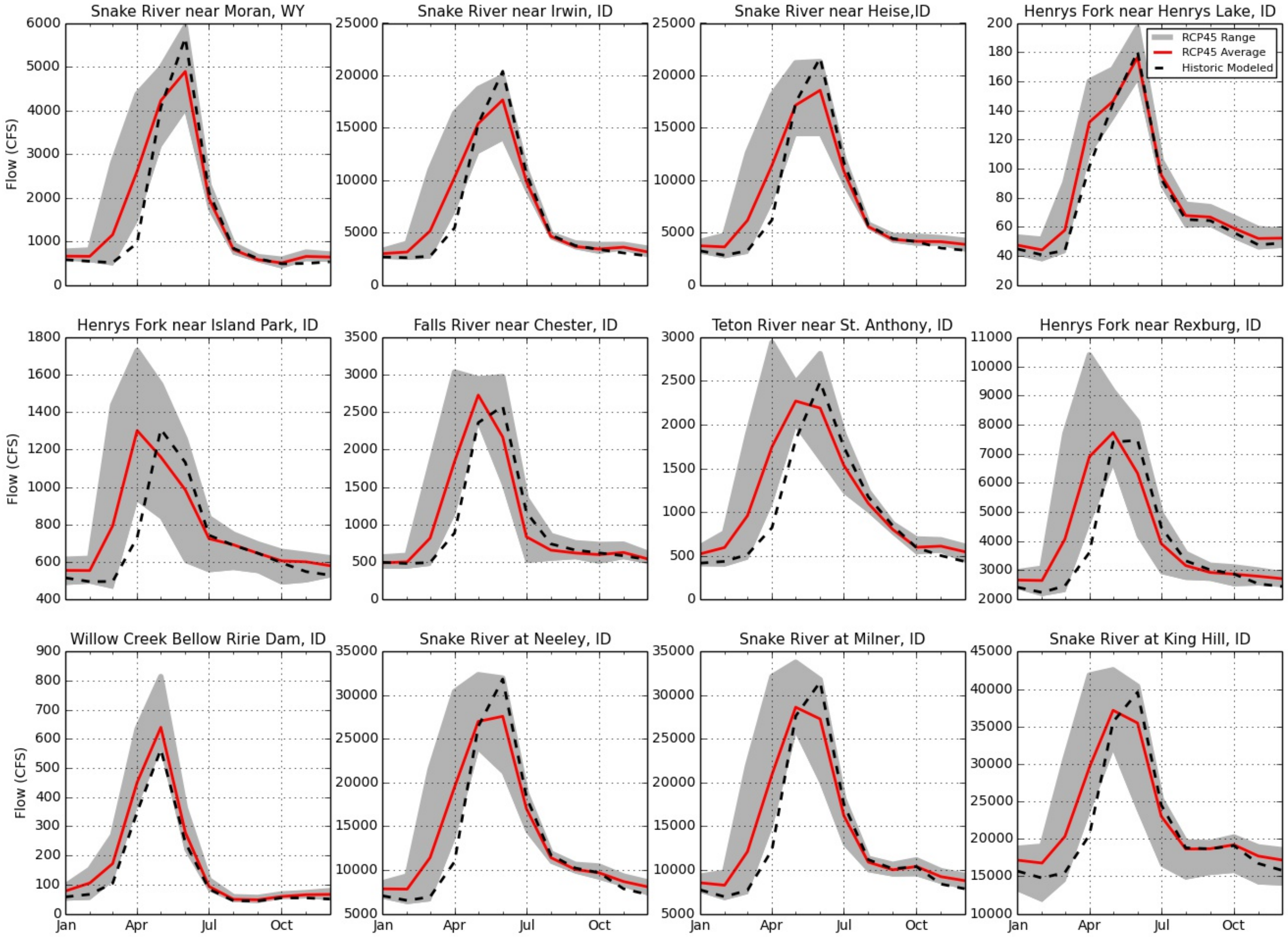
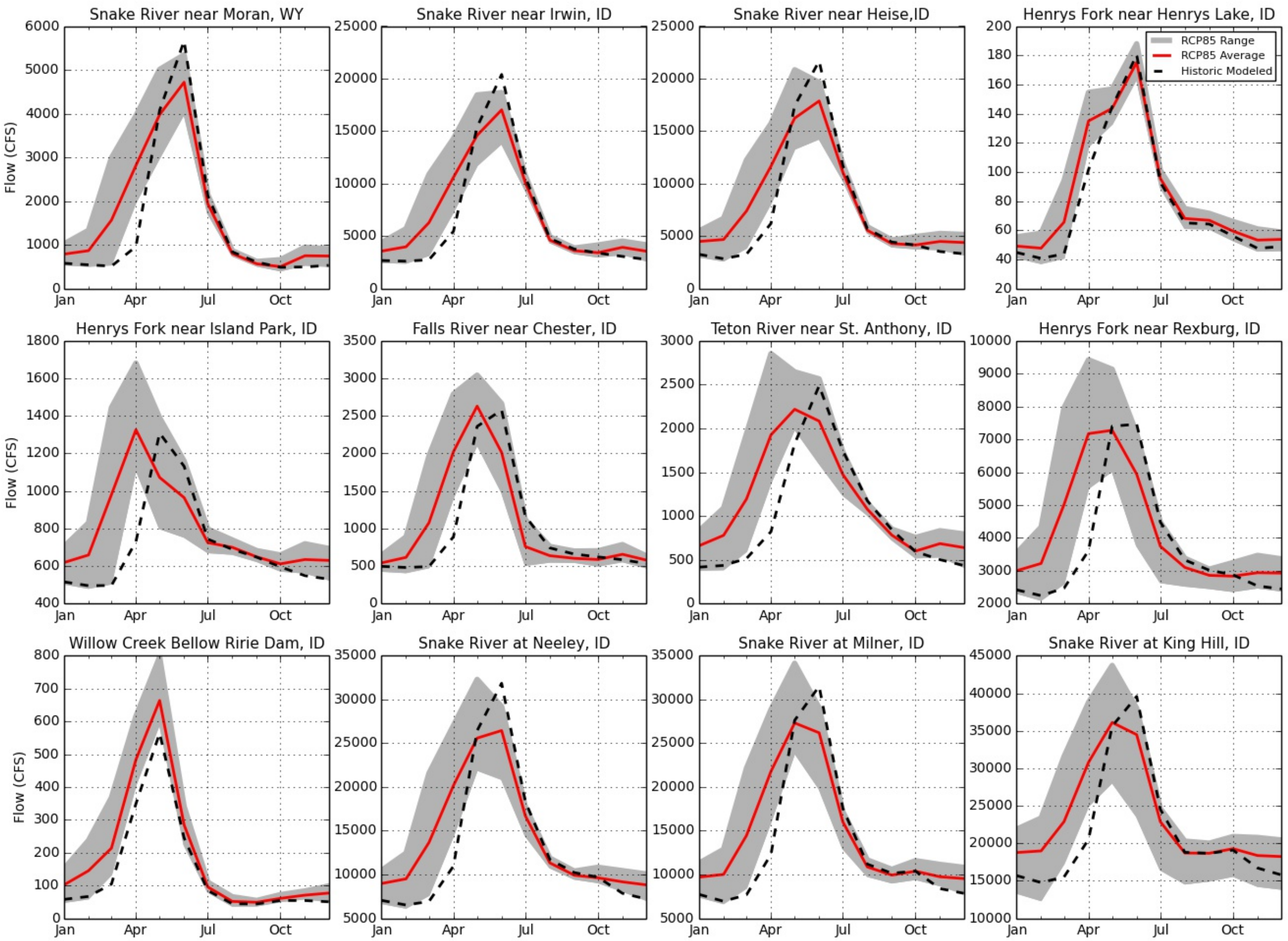


Figure 4.1 Summary hydrograph of the RCP45 model runs showing the average of the models (solid line), the range of the models (shaded region), and the historic modeled data (dashed line)



Snake River near Moran, WY

Snake River near Irwin, ID

Snake River near Heise,ID

Henrys Fork near Henrys Lake, ID

Henrys Fork near Island Park, ID

Falls River near Chester, ID

Teton River near St. Anthony, ID

Henrys Fork near Rexburg, ID

Willow Creek Bellow Ririe Dam, ID

Snake River at Neeley, ID

Snake River at Milner, ID

Snake River at King Hill, ID

Figure 4.2 **Summary hydrograph of the RCP85 model runs showing the average of the models (solid line), the range of the models (shaded region), and the historic modeled data (dashed line)**

The results from the summary hydrographs show how flow is shifting at different points in the Snake River and its tributaries. When investigating the Henrys Fork basin, the total volume during peak runoff is remaining constant into the future, but the peak runoff is occurring earlier by about 7-11 days. The Snake River from the headwaters down to King Hill displays similar trends when evaluating the summary hydrograph. The trends investigated in the Snake River are that the winter baseflow will increase due to the higher snow-line elevation in the basin. This causes more precipitation to fall as rain in the winter months, which cause higher streamflow. Due to this increase in streamflow in the winter, less snow is captured in the snow pack causing less snowmelt runoff in the spring. In all stations on the Snake River, the peak runoff is declined by about 12.5% of historic peak runoff.

In Figures 4.3, 4.4, and 4.5, major locations in the Snake River are evaluated to quantify how center of timing changes in the system. The first location is at Heise, which is a major flood-control point in the upper section of the Snake River. The second location displayed in Figure 4.4 is the Henrys Fork at Rexburg to investigate how the Henrys Fork changes. The third location displayed in Figure 4.5 is the Snake River at Hells Canyon, which shows the exit of the system before discharging into the Lower Snake River. In Appendix C, the center of timing figures can be seen for the remaining locations in the Snake River. The formula to determine the center of timing is Equation 4.1 where CT is the center of timing, t_i is the day of year timing occurs, and q_t is the total volume that has passed on day t_i of the year.

$$CT = \frac{\sum t_i q_t}{\sum q_t} \tag{4.1}$$

Figure 4.3 Center of timing for the Snake River at Heise, ID, showing shaded historic (1950-2005) and future (2006-2099)

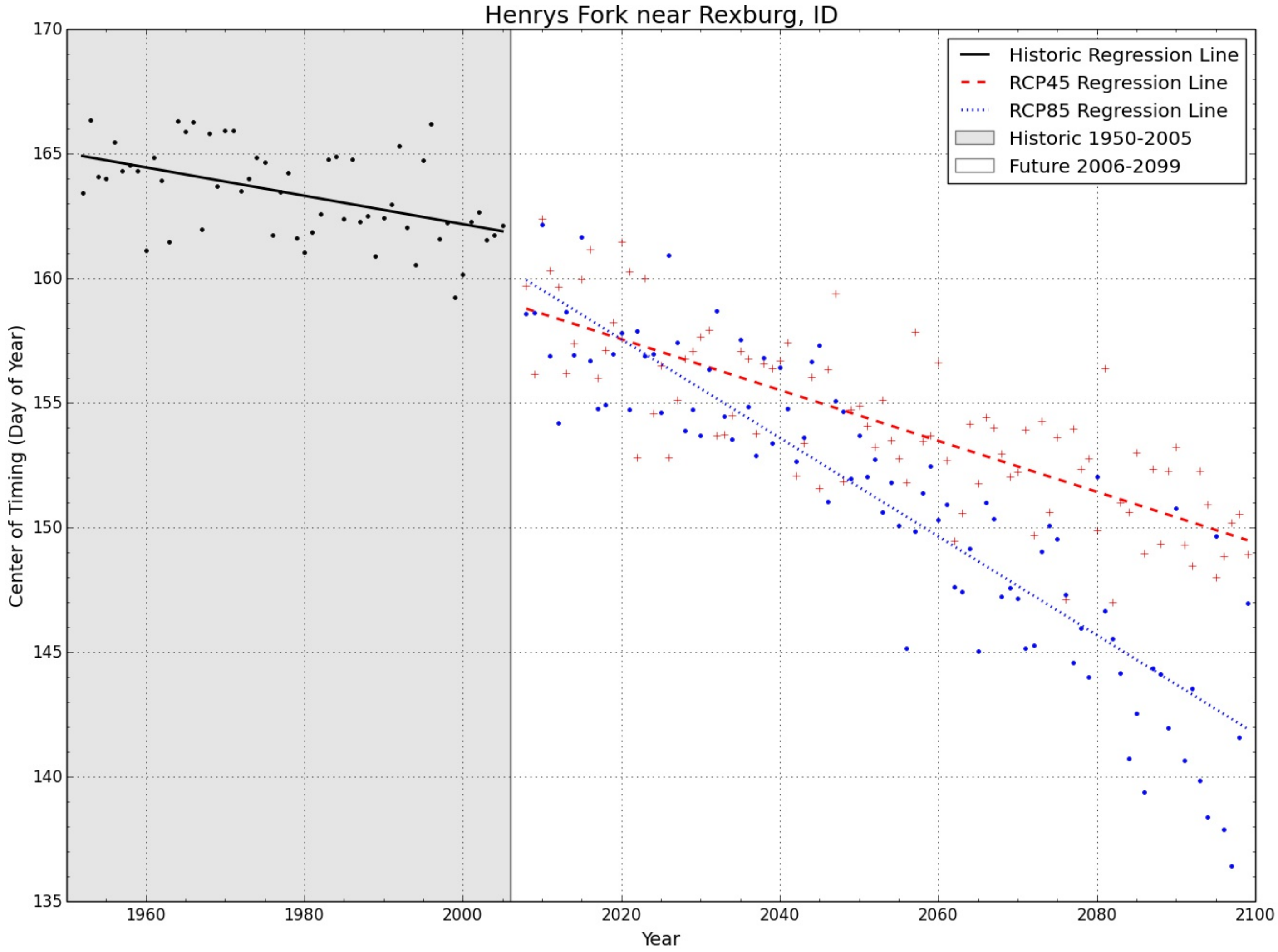


Figure 4.4 Center of timing for Henrys fork near Rexburg, ID, showing shaded historic (1950-2005) and future (2006-2099)

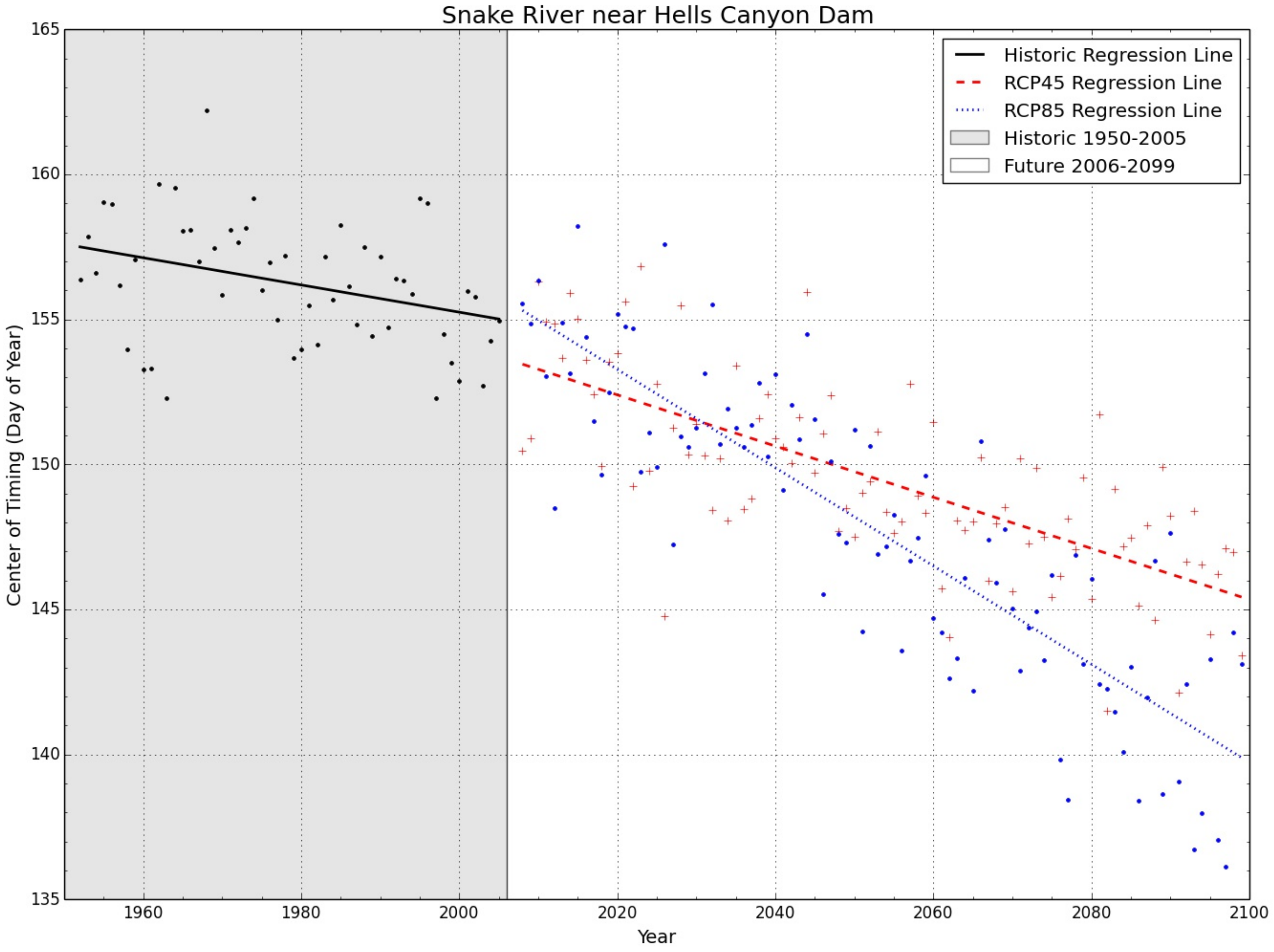


Figure 4.5 Center of timing at Snake River at Hells Canyon dam, ID-OR border, showing shaded historic (1950-2005) and future (2006-2099)

4.3.2 SPM

To understand the operations and the changes that may be seen in the future, RCP45 and RCP85 data are used to force the SPM model from 10/2010-9/2090. The forecasts used for Heise are the true volume that will be seen from the time series used to force the model. The following figures show how the reservoirs in the Snake River are operated looking at end-of-month storage content and regulated streamflow from climate change. Each time series is sectioned out, allowing the changes to be investigated as time progresses.

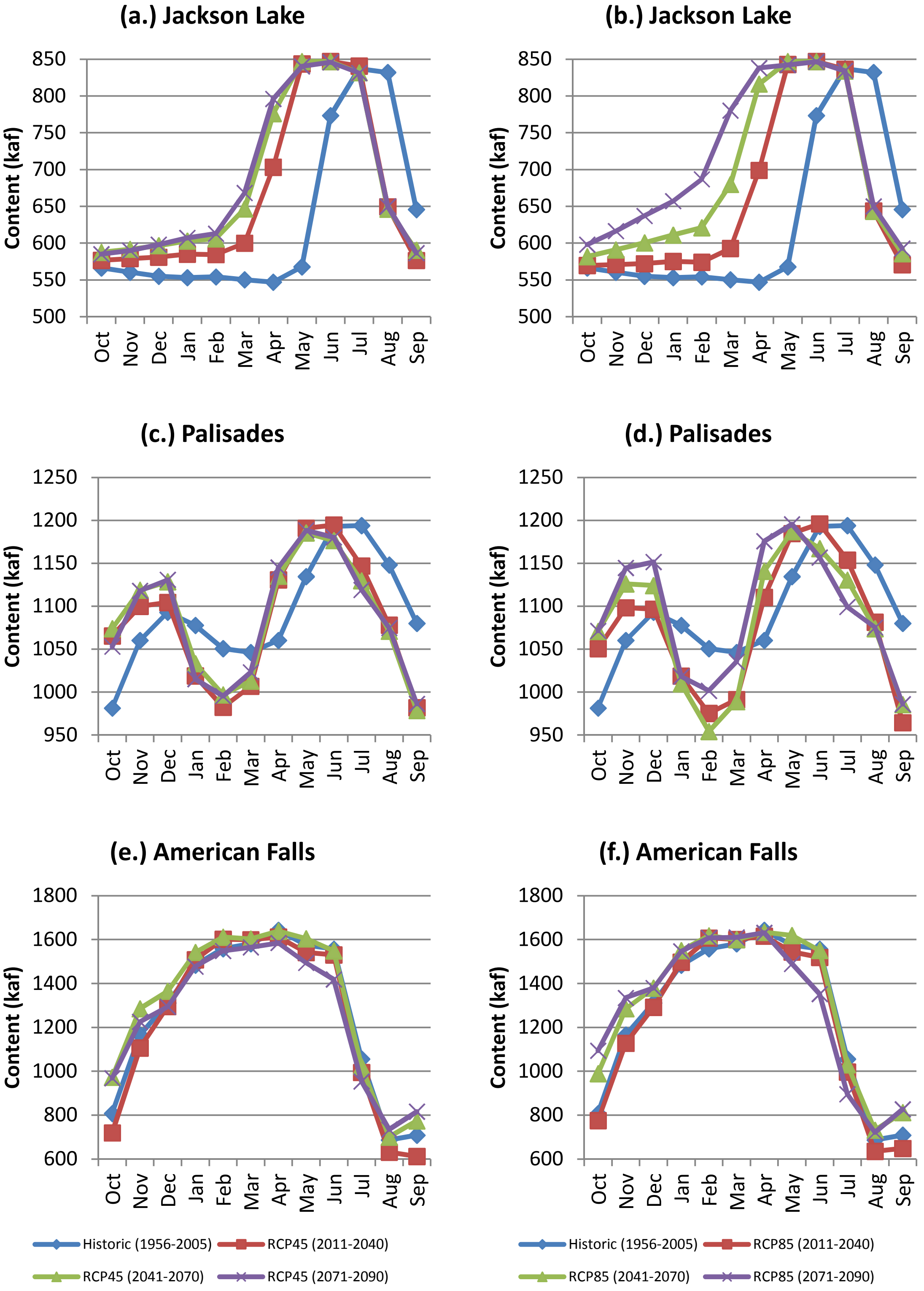


Figure 4.6 Comparison of EOM storage Content for Jackson Lake, Palisades, and American Falls with RCP45 on left and RCP85 on Right

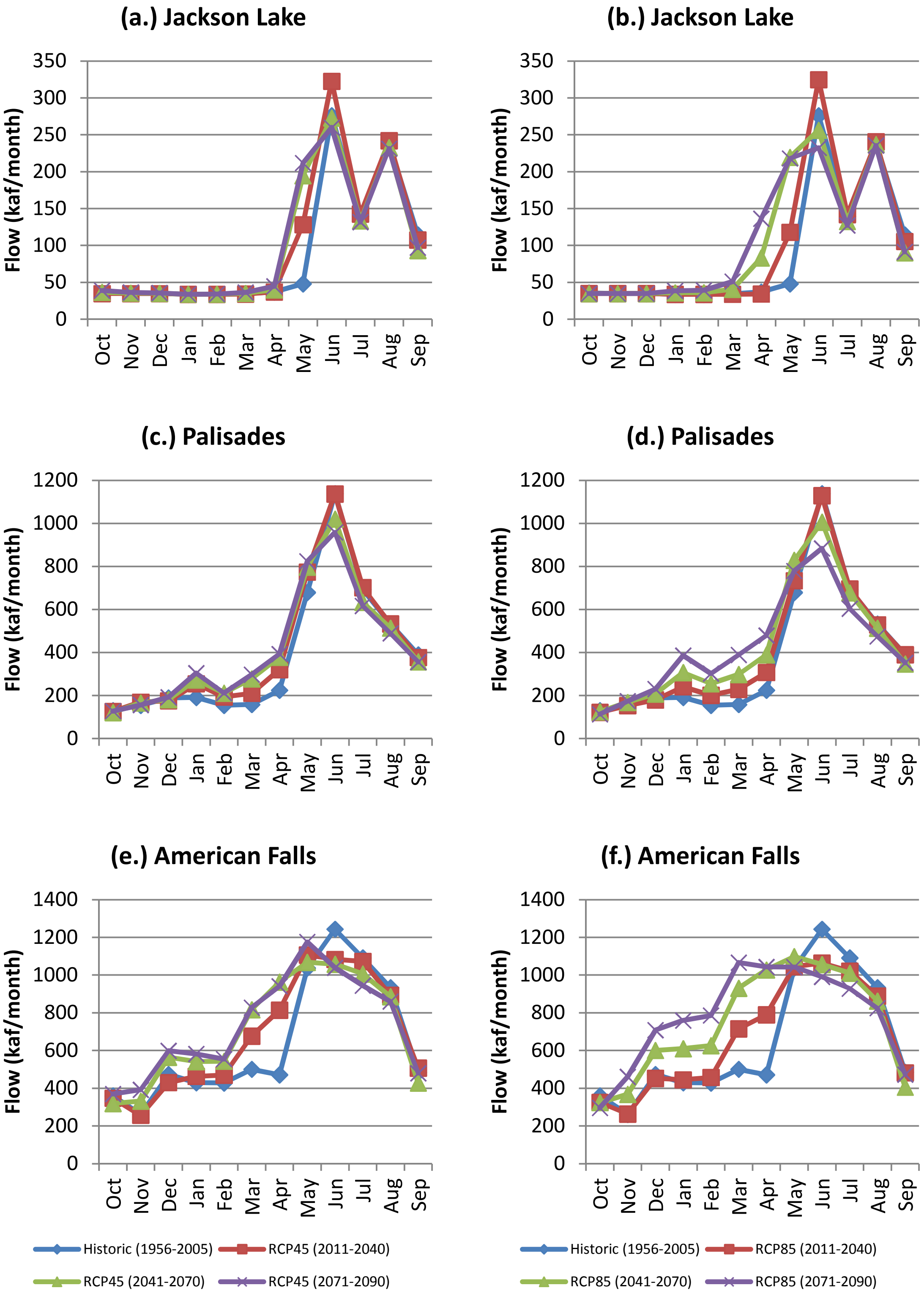


Figure 4.7 Comparison of regulated streamflow for Jackson Lake, Palisades, and American Falls with RCP45 on left and RCP85 on right

4.3.3 MODFLOW-VIC

To understand the future changes that may be seen in the Eastern Snake Plain Aquifer, the results from MODFLOW-VIC are presented. In Figure 4.8, the change in aquifer head is investigated for the RCP45, for 1/2040-12/2049. In Figure 4.9, the change in aquifer head is investigated for RCP85, for 1/2040-12/2049. The results show how the spatial distribution of declining aquifer head continues into the future. The magnitude of the decline in aquifer head is accentuated in the future scenarios compared to the historic 1986-1995 aquifer head, investigated in Figure 3.11. In Figure 4.10, the changes in spring discharge are investigated. The decline in aquifer head observed in Figures 4.8 and 4.9 is responsible for the decline in spring discharge in the aquifer.

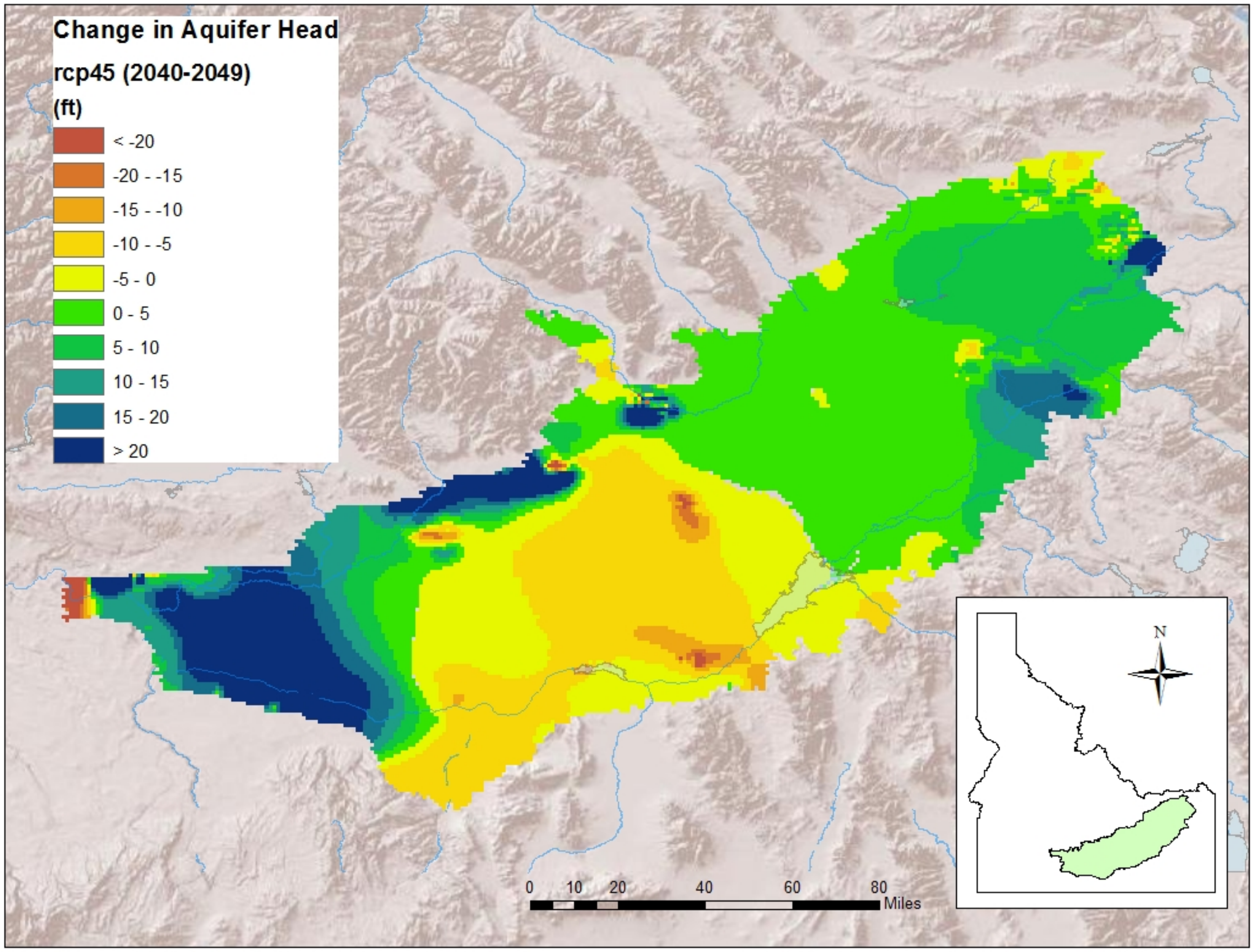


Figure 4.8 Eastern Snake River Plain Aquifer modeled change in aquifer head, for CanESM2 RCP45 (2040-2049)

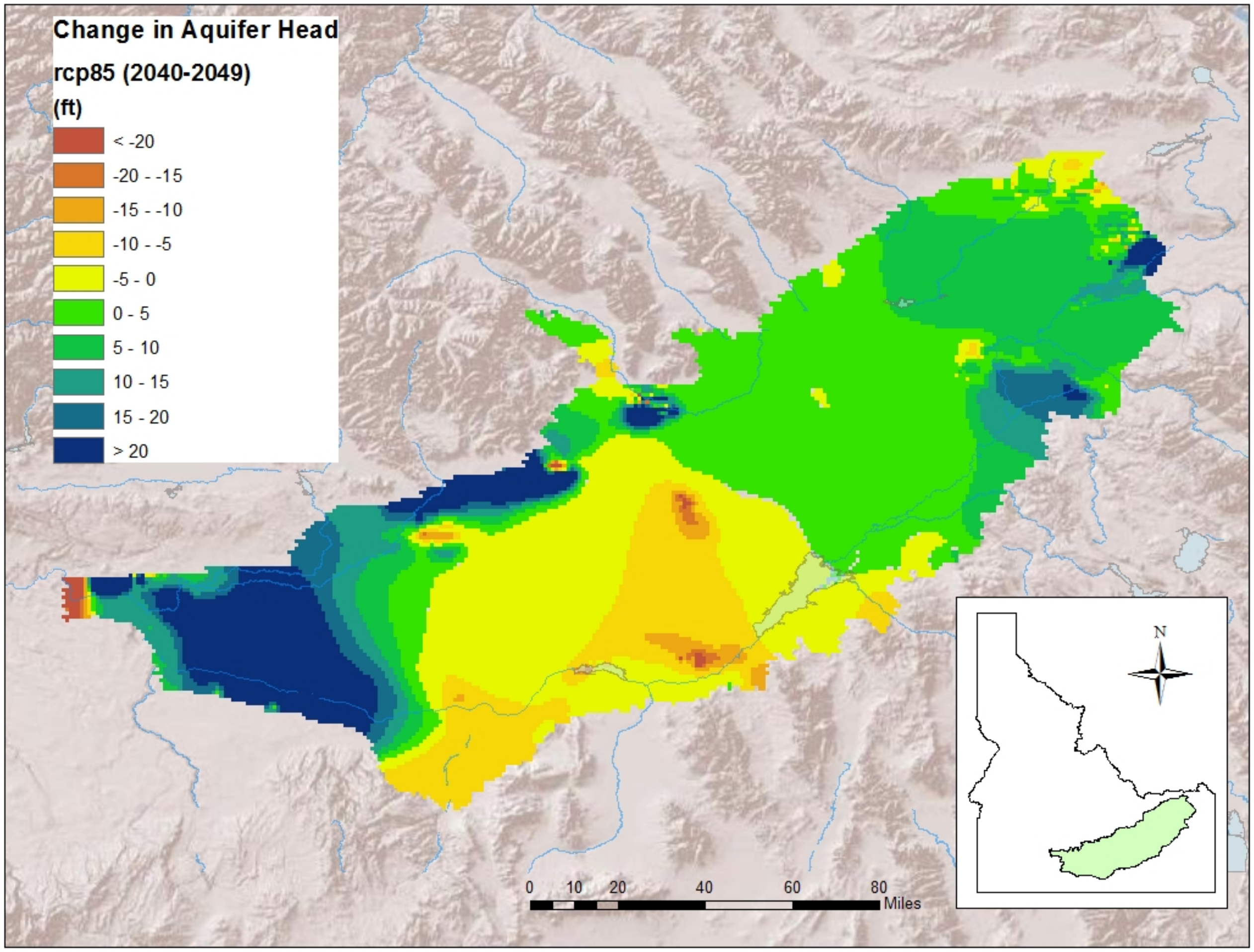


Figure 4.9 Eastern Snake River Plain Aquifer modeled change in aquifer head, for CanESM2 RCP85 (2040-2049)

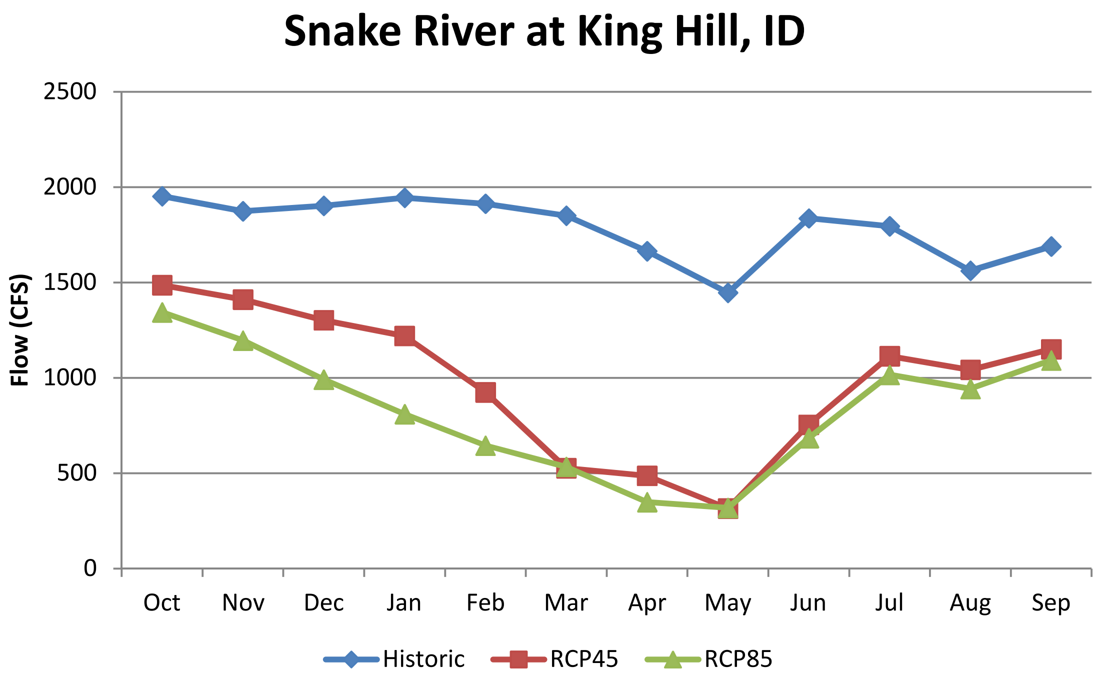


Figure 4.10 Comparison of modeled monthly average spring discharge, for the historic (1986-1995), CanESM2 RCP45 (2040-2049), and CanEXM2 RCP85 (2040-2049)

4.4 Discussion and Conclusion

The results show that the major change in operations comes at Palisades reservoir. With changes to the hydrology, Heise has a larger volume forecast in the January through March months than in the past hydrology. This requires the reservoir to be drawn down to a larger flood capacity to accommodate the total volume from flood control curves. A sizable volume will come off as runoff during the winter months since precipitation will be falling as rain, and the total runoff after March tends to be lower than historic volumes. This causes the reservoir to be drawn down farther in the winter than in the past and be refilled earlier than in the past. In addition, since the peak runoff occurs earlier, the reservoir is not supplemented with the same historic high inflows after refill, hence the reservoir starts to draft earlier than in the past. In the other two reservoirs, the flood control is not evident in the drawdown of the reservoir as is seen at Palisades, but the earlier drafting of the reservoir can be seen as a pattern in all the three reservoirs.

Based on our conclusions of how the hydrograph would shift to lower peak flow with higher winter flows, the results from the SPM seem to agree with what was expected. This has also been seen in other modeling studies, and it is encouraging to find that the newer CMIP5 models are similar to that of the CMIP3 models that were showing only slightly larger magnitude of streamflow volume.

The MODFLOW-VIC model showed that decreasing aquifer head will cause a decrease in spring discharge. These results are as we expected, the model had decreased aquifer head in the important reaches, which have surface-water and groundwater interactions. The results showed that RCP45 had the largest drawdown of aquifer head. This is because of the higher winter flows, from melting snow. The increase in winter snowmelt results in a greater recharge to the aquifer, during a period of less aquifer stress, and caused less drawdown of aquifer head.

CHAPTER FIVE: DISCUSSION AND CONCLUSION

The following sections describe the conclusions of each model and the future work needed to be performed to improve the results of this study. The final section discusses the physical conclusions about the Snake River and the hydrologic implications of climate change.

5.1 Selection of GCMs

The selection of the 12 GCMs used for this model proved to be sufficient for our study. The different models showed a good range in the time series and the averaging of the 12 time series seemed to reduce the swings in streamflow. The averaging of the time series caused the model to not display variability on a year-to-year basis, which is shown in Figure 3.3. This ensemble method reproduced did not reproduce the variability and should not be used in future studies. The best method would be to run each time series individually if time had permitted. Some uncertainties with our modeling were the lack of understanding of other CMIP5 GCM outputs. Since many GCMs exist it would have been preferred to follow in the tracks of previous modeling studies where every model in the CMIP phase was run to generate streamflow. This would be preferred to have, but currently the data is not available for the 1/16th degree VIC modeling.

5.2 Calibration of VIC

The calibration of VIC was successful at the 13 locations in the Snake River, showing very good correlation with the observed natural flow. The locations chosen for calibration were not ideal for input into the SPM. In the SPM, the input locations from the previous study should have been exactly matched. Due to confusing naming convention from CIG, the locations were thought to be the same but later in the study it was learned that the Henrys Fork at Island Park was actually down river from Island Park at the Henrys Fork near Ashton. This caused a huge difference between our Island park time series and the CIG time series. Since the spreadsheet used to partition flow was created for CIG data, this caused instability in the model, which required the Henrys Fork section not to be evaluated in the SPM.

It was the initial plan of this work to generate the streamflow for the Falls River and Teton River in the Henrys Fork, which would have reduced the error in the partitioning of the streamflow into SPM. Since these points did not match the CIG locations, the streamflow generated for input, at these locations, to the SPM had to be eliminated. If more time had been available, the spreadsheet would have been completely rebuilt for inclusion of these additional locations. However, since time became a constraint, the spreadsheet could not be changed, hence the additional calibration points could not be used.

5.3 SPM

As mentioned in Section 5.2, the SPM model might have produced better results if the exact locations from the CIG study had been selected throughout the basin. The response of the system to the future hydrology was as predicted. This study helps predict how the river and reservoir operations will continue in the future. Because no significant changes in flood frequency or surface-water delivery were detected in the model, it is a fair assumption to conclude that current operations, as they exist today, will still be valid and able to cope with climate change. Although we will see different patterns that might exist in the reservoirs response to these operations, the overall delivery of surface water may not be threatened by climate change. River and reservoir operations are ever-evolving dynamic management practices that need real-time decisions. The optimization of the system should be expected to continue under current operating procedures.

Other issues that could have been fixed to improve SPM results are the inclusion of the flood forecasts. In the RMJOC study, the USBR developed techniques to replicate current forecasting methods from parameters of VIC. In this method, variables from VIC at the forecast point are generated from VIC-modeled parameters, then used to generate forecasts. This method has errors induced into the flood forecasts, which show better response by the reservoirs to historic conditions. In our flood forecasts, we used the exact volume to make the forecasts perfect every time. This caused the reservoirs not to be drawn down more than needed, caused refill to happen at most reservoirs every year, and also prevented the reservoirs from flooding. This is not a true representation of the system and ideally an error-induced forecast would be a better method for generating forecasts.

5.4 MODFLOW-VIC

The MODFLOW-VIC model demonstrated the capturing of the baseflow and the response of the aquifer system desired by this study. Although the magnitude of the baseflow was not totally captured, the results are still a slight improvement in capturing baseflow. To improve this model, calibration of the MODFLOW-VIC model, once combined, could significantly improve the capturing of baseflow and the aquifer head in the system. The Well Package could be calibrated for improvement of the aquifer head in the system, and the Drain Package could be calibrated for improvement of the baseflow. The conclusion of this study, as it relates to MODFLOW-VIC, is that coupling of the MODFLOW and VIC model was successful but still needs further calibration.

The results of the MODFLOW-VIC run for the future showed that the aquifer drawdown seen in the past will continue into the future at an increased rate. The results showed that a decrease in spring discharge may be seen in the future. The decrease in spring discharge is directly related to the decrease in aquifer head in the model.

5.5 Conclusion

Climate change will impact Snake River in a variety of ways. The results of this research shows that under climate change projections peak streamflow will decrease by 12.5%; the peak streamflow will shift 7-11 days earlier; baseflow is expected to decrease by 5% in the late summer months; and flows are expected to increase by 25% in the winter months. Overall, the total annual volume of streamflow is expected to increase in the basin on average. This will cause changes to the historic operations of the Snake River. The reservoirs in the system show that as snowmelt advances to an earlier melt, earlier drafting of the reservoirs will occur. The drafting causes the reservoirs storage to be depleted earlier than in historic time periods. This will impact water users who have low-priority dates and could in the future cause curtailment of these junior water-right users due to lack of storage and natural flow rights in the basin.

5.6 Recommendations for Water Managers

From the results, two recommendations can be made to water managers in the Upper Snake River. The first recommendation is for federal river and reservoir operators.

The recommendation is to have adaptive management plans, while taking into account these changes in hydrology. Although historic operating plans appear to be acceptable, the changes in hydrology could be utilized for an advantage to the system. This study did not look into the advantages that could occur from climate change, but if individual managers had adaptation strategies for utilizing this larger volume of water, it would benefit them to have plans in place for this potential change in hydrology.

The second recommendation is for irrigation districts. The recommendation is to be prepared for lower natural flow, and to have sufficient storage-water rights to supplement their demand. Districts that cannot secure these rights need to look at water conservation tactics. This could include changing crop types, lining of canals, and planning for shorter irrigation seasons. The irrigation districts need to be adaptive to the changing environment in order to survive.

5.7 Recommendations for Future Work

A lot of additional work could be done to improve upon this research. The incorporation of the SPM could be improved by routing of the flow in the system to more locations. By better partitioning of flow through a combination of manual and automated procedures, SPM implementation can be revised. Another improvement for further research is to run the SPM for each GCM, without averaging the time series. This would investigate the ability of the model to handle year-to-year variability of streamflow.

The development of the MODFLOW-VIC model, for the Snake River, can be improved through further calibration of baseflow and aquifer heads. To calibrate the baseflow, the Drain Package could be used as a calibration parameter. To calibrate the aquifer head, the Well package could be used as a calibration parameter. Calibrating these parameters could significantly improve the MODFLOW-VIC results.

REFERENCES

Abatzoglou, J. T. (2013). “Development of gridded surface meteorological data for ecological applications and modelling.” *International Journal of Climatology*, 33(1), 121–131.

Barnett, T., Malone, R., Pennell, W., Stammer, D., Semtner, B., and Washington, W. (2004). “The Effects of Climate Change on Water Resources in the West: Introduction and Overview.” *Climatic Change*, 62(1-3), 1–11.

Bates, B., Kundzewicz, Z. W., Wu, S., and Palutikof, J. (2008). *Climate change and water.* Intergovernmental Panel on Climate Change (IPCC).

Brekke, L. D., Dettinger, M. D., Maurer, E. P., and Anderson, M. (2008). “Significance of model credibility in estimating climate projection distributions for regional hydroclimatological risk assessments.” *Climatic Change*, 89(3-4), 371–394.

Chaney, E. (1977). “The Desert Land and Carey Act in Idaho.” *Idaho Conservation League. Agricultural Lands Project Summary Report, June*.

Christensen, N. S. and Lettenmaier, D. P. (2007). “A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin.” *Hydrology and Earth System Sciences Discussions*, 11(4), 1417–1434.

Clark, G. M. (2010). “Changes in Patterns of Streamflow From Unregulated Watersheds in Idaho, Western Wyoming, and Northern Nevada.” *JAWRA Journal of the American Water Resources Association*, 46(3), 486–497.

Cosgrove, D. M., Contor, B. A., and Johnson, G. S. (2006). “Enhanced Snake Plain aquifer model final report.” *Idaho Water Resources Research Institute Technical Report*, 2.

Duan, Q. Y., Gupta, V. K., and Sorooshian, S. (1993). “Shuffled complex evolution approach for effective and efficient global minimization.” *Journal of Optimization Theory and Applications*, 76(3), 501–521.

Gao, H., Tang, Q., Shi, X., Zhu, C., Bohn, T. J., Su, F., Sheffield, J., Pan, M., Lettenmaier, D. P., and Wood, E. F. (2010). “Water budget record from Variable Infiltration Capacity (VIC) model.” *Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records*.

Gilbert, J. D., Ostenaa, D., and Wood, C. (1983). *Seismotectonic Study Jackson Lake Dam and Reservoir, Minidoka Project, Idaho-Wyoming*. US Department of the Interior, Bureau of Reclamation.

Greer, R. and Pair, C. H. (1966). “Sprinkler Irrigation Development on the Snake River Plain.”

Harbaugh, A. W. (2005). *MODFLOW-2005, the U.S. Geological Survey modular ground-water model: The ground-water flow process*. U.S. Geological Survey, Reston, Virginia.

Hoekema, D. J. and Sridhar, V. (2011). “Relating climatic attributes and water resources allocation: A study using surface water supply and soil moisture indices in the Snake River basin, Idaho.” *Water Resources Research*, 47(7).

IDWR. (2012). “State Water Plan.” *Idaho Water Resource Board*, <http://www.idwr.idaho.gov/waterboard/WaterPlanning/Statewaterplanning/State_Planning.htm> (Nov. 7, 2013).

Jin, X. and Sridhar, V. (2010). “An integrated model coupling VIC and MODFLOW to study the hydrological prediction at the Snake River Basin.”

Jin, X. and Sridhar, V. (2012). “Impacts of Climate Change on Hydrology and Water Resources in the Boise and Spokane River Basins.” *JAWRA Journal of the American Water Resources Association*, 48(2), 197–220.

Johnson, F. and Sharma, A. (2012). “A nesting model for bias correction of variability at multiple time scales in general circulation model precipitation simulations.” *Water Resources Research*, 48(1), W01504.

Knutti, R. and Sedláček, J. (2012). “Robustness and uncertainties in the new CMIP5 climate model projections.” *Nature Climate Change*, 3(4), 369–373.

Labadie, J. and Larson, R. (2007). “MODSIM 8.1: River Basin Management Decision Support System User Manual and Documentation.” Colorado State University.

Labadie, J. W. (2006). “MODSIM: decision support system for integrated river basin management.” *Summit on Environmental Modeling and Software, the International Environmental Modeling and Software Society, Burlington, VT USA*.

Leavesley, G. H., Lichty, R. W., Troutman, B. M., and Saindon, L. G. (1983). *Precipitation-runoff modeling system: User’s manual*. US Geological Survey.

Leavesley, G. H., Stannard, L. G., and Singh, V. P. (1995). “The precipitation-runoff modeling system-PRMS.” *Computer models of watershed hydrology.*, 281–310.

Li, H., Sheffield, J., and Wood, E. F. (2010). “Bias correction of monthly precipitation and temperature fields from Intergovernmental Panel on Climate Change AR4 models using equidistant quantile matching.” *Journal of Geophysical Research: Atmospheres*, 115(D10), 1–20.

Liang, X., Lettenmaier, D. P., Wood, E. F., and Burges, S. J. (1994). “A simple hydrologically based model of land surface water and energy fluxes for general circulation models.” *Journal of Geophysical Research: Atmospheres*, 99(D7), 14415–14428.

Livneh, B., Rosenberg, E. A., Lin, C., Mishra, V., Andreadis, K. M., and Lettenmaier, D. P. (2012). “Extension and spatial refinement of a long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States.” *Journal of Climate (in review).*

Lohmann, D., Raschke, E., Nijssen, B., and Lettenmaier, D. P. (1998). “Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model.” *Hydrological Sciences Journal*, 43(1), 131–141.

Lovin, H. T. (1987). “The Carey Act in Idaho, 1895-1925: An Experiment in Free Enterprise Reclamation.” *The Pacific Northwest Quarterly*, 78(4), 122–133.

Maurer, E. P., Wood, A. W., Adam, J. C., Lettenmaier, D. P., and Nijssen, B. (2002). “A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States.” *Journal of Climate*, 15(22), 3237–3251.

Miller, S. A., Johnson, G. S., Cosgrove, D. M., and Larson, R. (2003). “Regional Scale Modeling of Surface and Ground Water Interaction in the Snake River Basin.” *JAWRA Journal of the American Water Resources Association*, 39(3), 517–528.

Mote, P. W. (2003). “Trends in snow water equivalent in the Pacific Northwest and their climatic causes.” *Geophysical Research Letters*, 30(12), Letter.

Mote, P. W., Parson, E. A., Hamlet, A. F., Keeton, W. S., Lettenmaier, D., Mantua, N., Miles, E. L., Peterson, D. W., Peterson, D. L., Slaughter, R., and Snover, A. K. (2003). “Preparing for Climatic Change: The Water, Salmon, and Forests of the Pacific Northwest.” *Climatic Change*, 61(1-2), 45–88.

Mote, P. W. and Salathé, E. P. (2010). “Future climate in the Pacific Northwest.” *Climatic Change*, 102(1-2), 29–50.

NRCS. (2001). “Idaho Natural Resource Trends.” NRCS Boise, ID.

Payne, J. T., Wood, A. W., Hamlet, A. F., Palmer, R. N., and Lettenmaier, D. P. (2004). “Mitigating the Effects of Climate Change on the Water Resources of the Columbia River Basin.” *Climatic Change*, 62(1-3), 233–256.

Pierce, D. W., Barnett, T. P., Hidalgo, H. G., Das, T., Bonfils, C., Santer, B. D., Bala, G., Dettinger, M. D., Cayan, D. R., Mirin, A., Wood, A. W., and Nozawa, T. (2008). “Attribution of Declining Western U.S. Snowpack to Human Effects.” *Journal of Climate*, 21(23), 6425–6444.

Pierce, D. W., Westerling, A. L., and Oyler, J. (2012). “Future humidity trends over the western United States in the CMIP5 global climate models and variable infiltration capacity hydrological modeling system.” *Hydrology and Earth System Sciences Discussions*, 9(12), 13651–13691.

Piety, L. A., Wood, C. K., Gilbert, J. D., Sullivan, J. T., and Anders, M. H. (1986). “Seismotectonic study for Palisades Dam and Reservoir, Palisades Project.” *US Bureau of Reclamation Seismotectonic Report 86*, 3, 198.

Puma, M. J. and Cook, B. I. (2010). “Effects of irrigation on global climate during the 20th century.” *Journal of Geophysical Research: Atmospheres*, 115(D16).

Simonds, W. J. (1997). *The Boise Project*. Bureau of Reclamation History Program.

Slaughter, R. A. (2004). “Institutional history of the Snake River 1850-2004.” *Climate Impacts Group, University of Washington, Seattle, WA*, 98195–5672.

Snover, A. K., Hamlet, A. F., and Lettenmaier, D. P. (2003). “Climate-Change Scenarios for Water Planning Studies: Pilot Applications in the Pacific Northwest.” *Bulletin of the American Meteorological Society*, 84(11), 1513–1518.

Stoll, S., Hendricks Franssen, H. J., Butts, M., and Kinzelbach, W. (2011). “Analysis of the impact of climate change on groundwater related hydrological fluxes: a multi-model approach including different downscaling methods.” *Hydrol. Earth Syst. Sci.*, 15(1), 21–38.

Sulis, M., Paniconi, C., Marrocu, M., Huard, D., and Chaumont, D. (2012). “Hydrologic response to multimodel climate output using a physically based model of groundwater/surface water interactions.” *Water Resources Research*, 48(12).

Sulis, M., Paniconi, C., Rivard, C., Harvey, R., and Chaumont, D. (2011). “Assessment of climate change impacts at the catchment scale with a detailed hydrological model of surface-subsurface interactions and comparison with a land surface model.” *Water Resources Research*, 47(1), W01513.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A. (2009). "A summary of the CMIP5 experiment design." *WCRP, submitted*.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A. (2012). "An overview of CMIP5 and the experiment design." *Bulletin of the American Meteorological Society*, 93(4), 485–498.

Thyer, M., Kuczera, G., and Bates, B. C. (1999). "Probabilistic optimization for conceptual rainfall-runoff models: A comparison of the shuffled complex evolution and simulated annealing algorithms." *Water Resources Research*, 35(3), 767–773.

US EPA, O. of W. (2013). "Importance of Water to the United States Economy." Overviews & Factsheets, <http://water.epa.gov/action/importanceofwater/index.cfm> (Nov. 6, 2013).

USGS. (2013). "USGS ** USGS 13290450 SNAKE RIVER AT HELLS CANYON DAM ID-OR STATE LINE." *USGS Water Data*, <http://waterdata.usgs.gov/id/nwis/nwisman/?site_no=13290450&agency_cd=USGS> (Nov. 7, 2013).

Vrugt, J. A., Gupta, H. V., Bouten, W., and Sorooshian, S. (2003). "A Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters." *Water Resources Research*, 39(8).

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., and Lamarque, J.-F. (2011). "The representative concentration pathways: an overview." *Climatic Change*, 109(1-2), 5–31.

Williams, M. H. (1970). *The History of Development and Current Status of the Carey Act in Idaho: Special Report*. Idaho Department of Reclamation.

Wood, A. W., Leung, L. R., Sridhar, V., and Lettenmaier, D. P. (2004). "Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs." *Climatic Change*, 62(1-3), 189–216.

Wulfhorst, J. D. and Glenn, E. (2002). "Irrigation, community, and historical development along the upper Snake River." *Agricultural history*, 76(2), 434–447.

APPENDIX A

Code Changes

In order to link VIC and MODFLOW, the following source codes changed.

vicNl_function.c

- This function evolves from vicNl.c by changing it to a subroutine in order to be called by MODFLOW. Replace “int main(int argc, char *argv[])” with “int vic_(int* timestep, int* next_month, int* next_day, int* next_year, int* next_hr)”
- Line 169, assign VIC command line arguments
- Line 193, set VIC parameters, e.g., row, col
- Line 222, update the startyear, startmonth, startday using the parameter passed from the function argument.
- Line 283, get next day and return to MODFLOW for calling VIC next time.
- Line 472, getwc_(), getting the upward flow entering VIC root zone and update the soil moisture in the VIC zone.
- Line 568, create a file for recharge.(note: in the code, we still call it “espa.uzf.XXX”, but it is unrelated to UZF now)

disp_prec.c

- Add one more argument “leak” for pass the upward flux

put_data.c

- Add one more argument “leak” for pass the upward flux

write_data.c

- Line 221, output infiltration(nrow, ncol) into an array for each
- Set baseflow to zeros

get_global_param.c

- Line 858, change the output state file name

cmd_proc.c

- Change for command line arguments change in vicNl_function.c

vicNl.h

- Added a few variables and prototype declaration of a few functions.

mf2005.f

- Line 23, add a few variables for code modification
- Line 146, initialize the starting month, day and year
- Line 497, call VIC function

gwf2drn7.f

- Line 336, add code for upward flux output

APPENDIX B

1950-2005 observed natural flow vs. baseline modeled natural flow

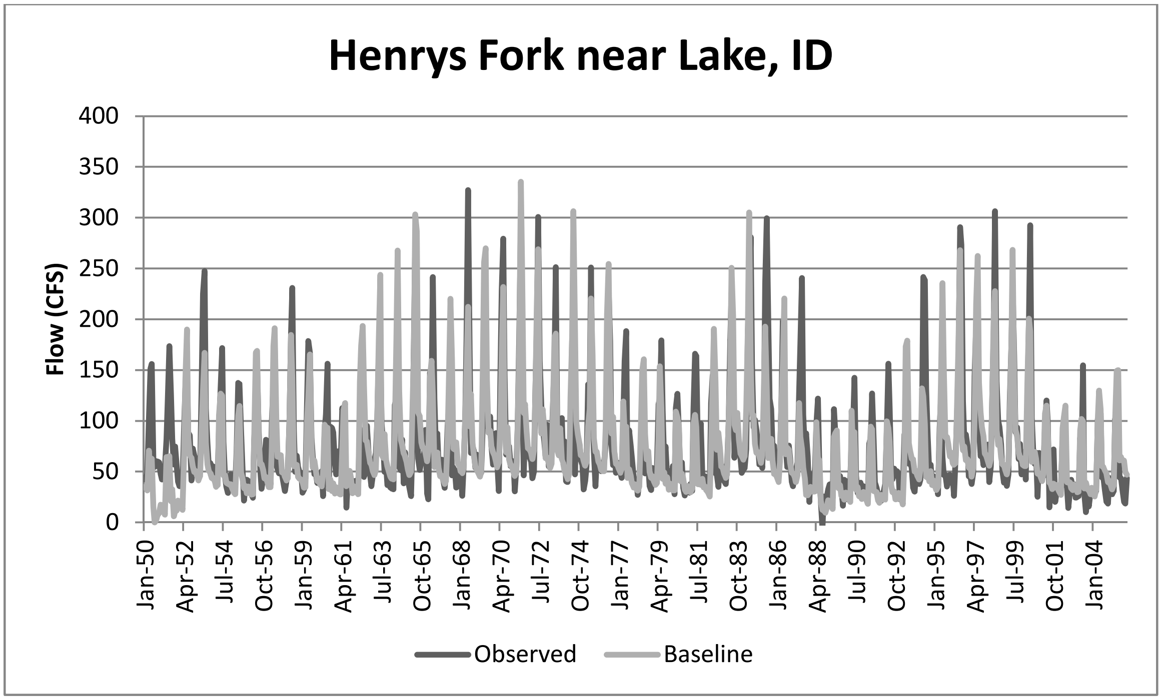


Figure B.1 Comparison of observed and baseline natural flow, for Henrys Fork near Lake, ID (1950-2005)

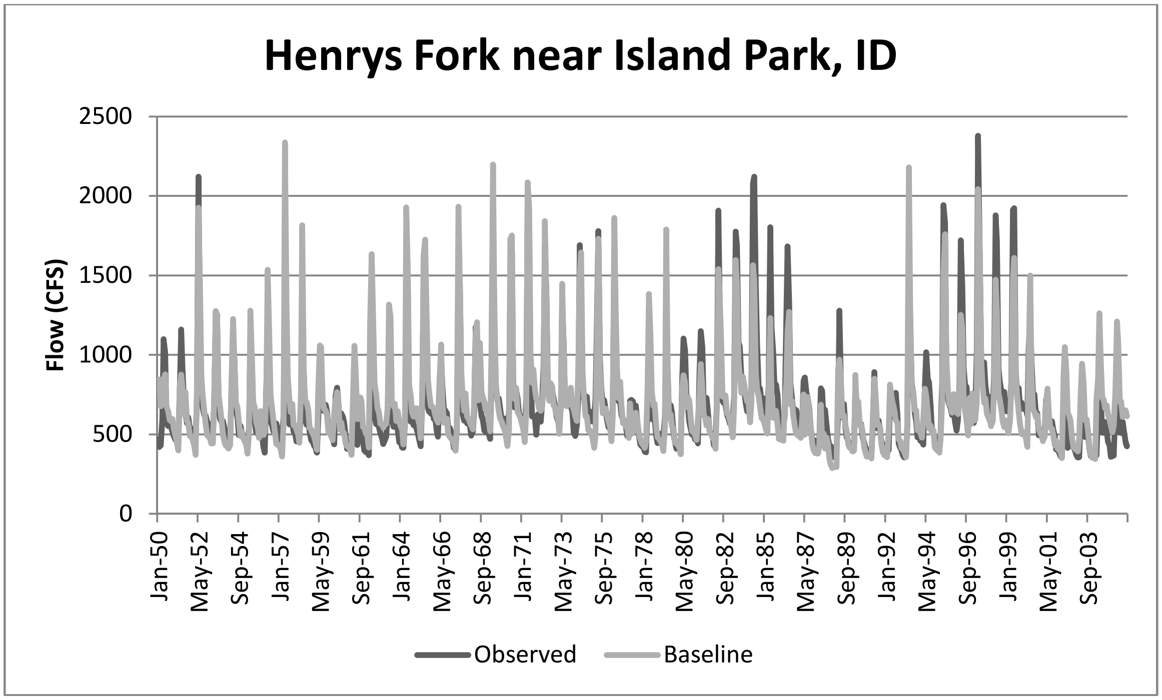


Figure B.2 Comparison of observed and baseline natural flow, for Henrys Fork near Island Park, ID (1950-2005)

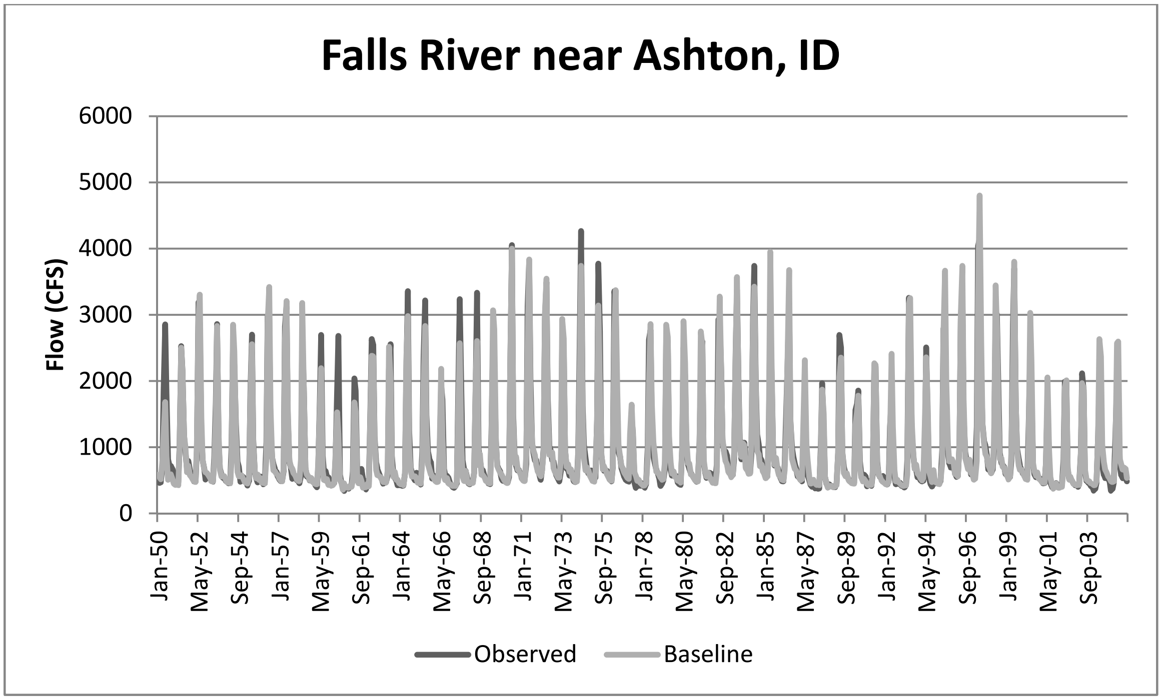


Figure B.3 Comparison of observed and baseline natural flow, for Falls River near Ashton, ID (1950-2005)

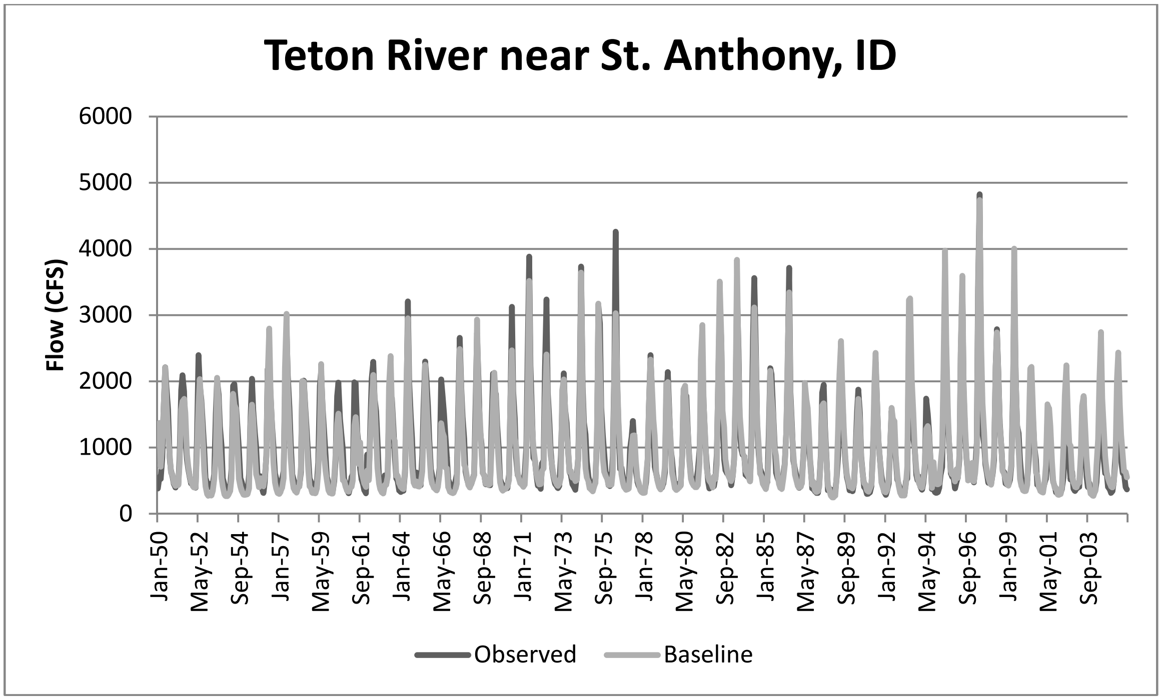


Figure B.4 Comparison of observed and baseline natural flow, for Teton River near St. Anthony, ID (1950-2005)

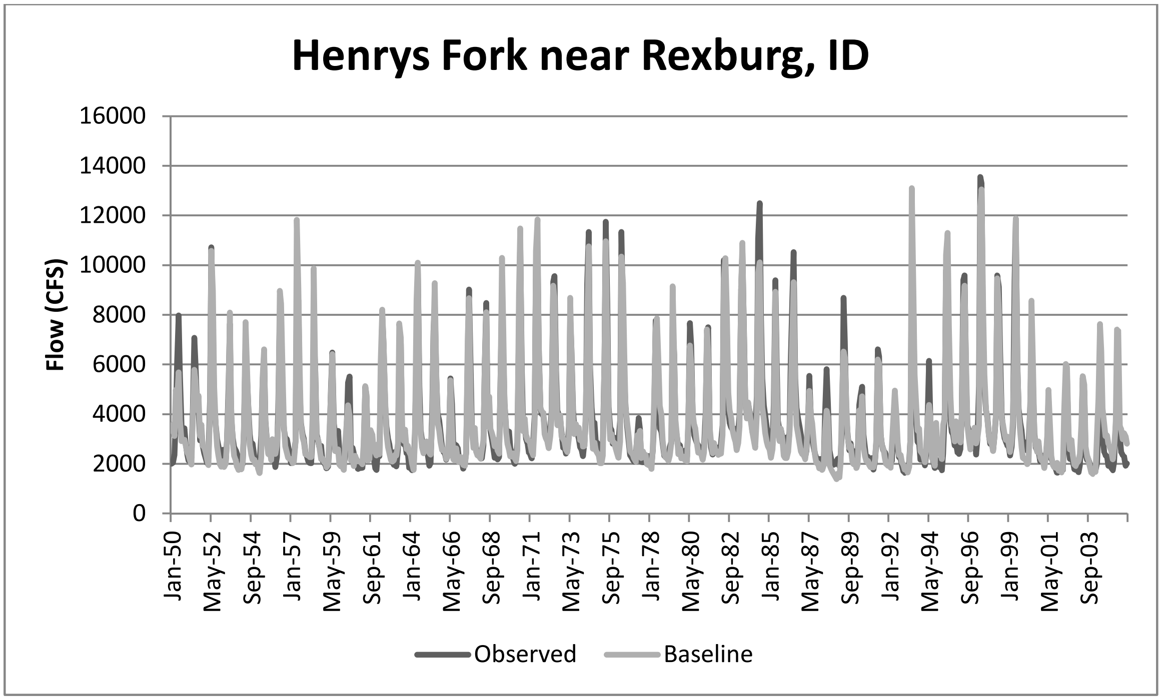


Figure B.5 Comparison of observed and baseline natural flow, for Henrys Fork near Rexburg, ID (1950-2005)

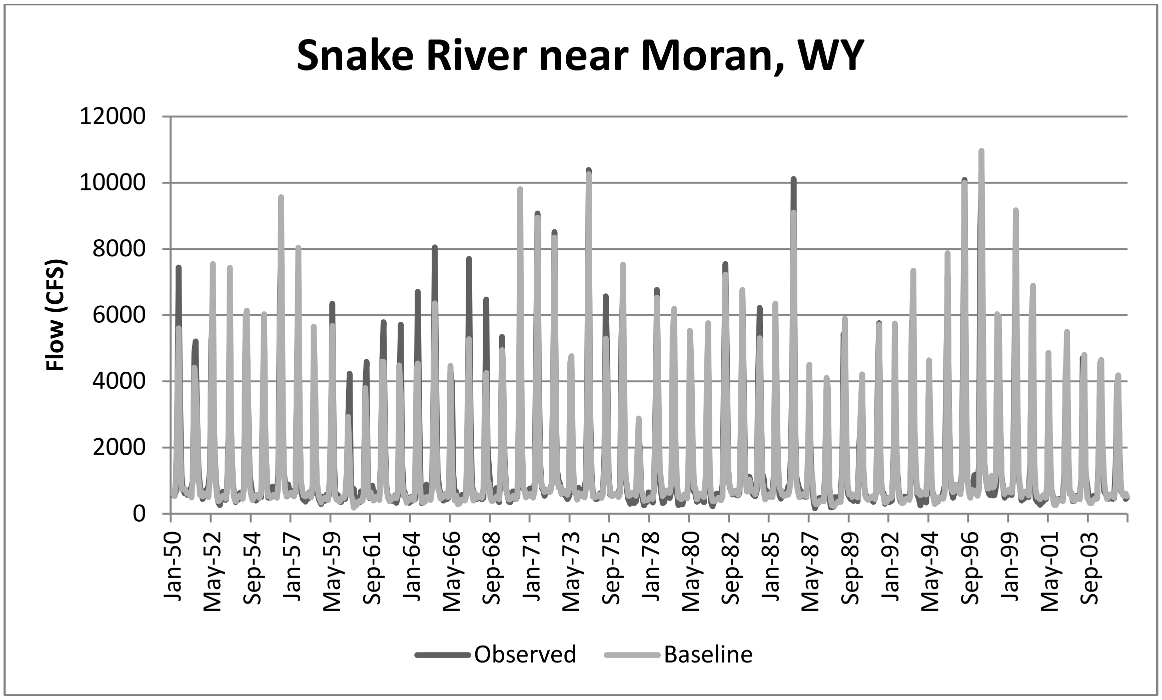


Figure B.6 Comparison of observed and baseline natural flow, for Snake River near Moran, WY (1950-2005)

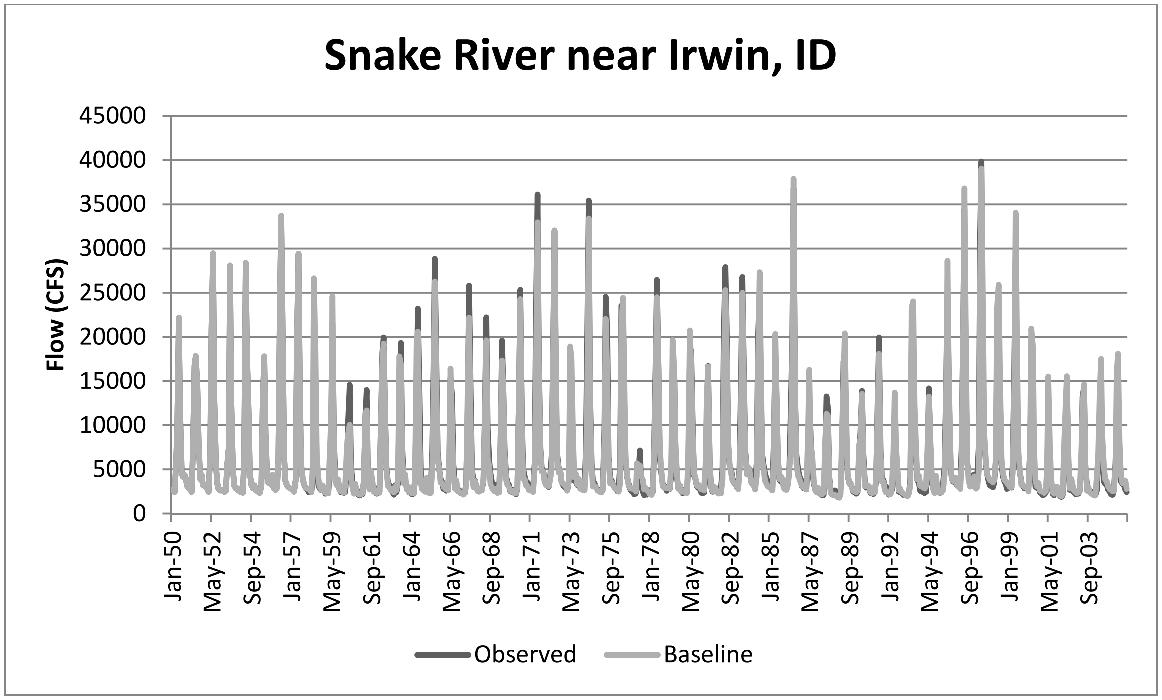


Figure B.7 Comparison of observed and baseline natural flow, for Snake River near Irwin, ID (1950-2005)

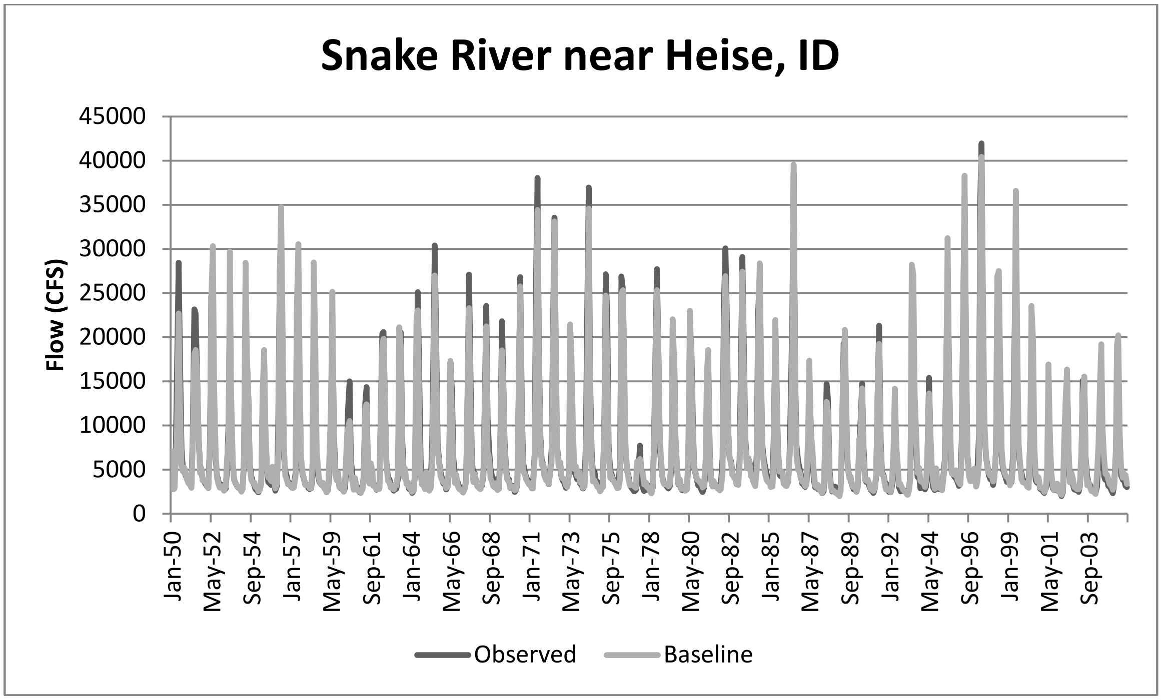


Figure B.8 Comparison of observed and baseline natural flow, for Snake River near Heise, ID (1950-2005)

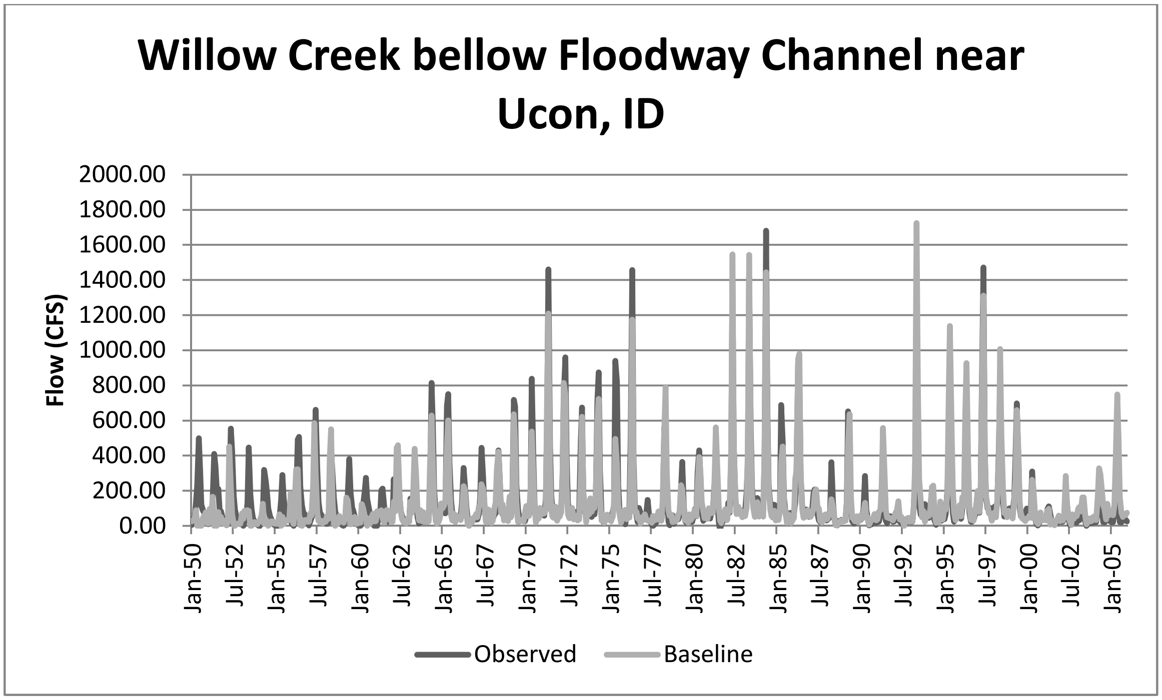


Figure B.9 Comparison of observed and baseline natural flow, for Willow Creek bellow Floodway Channel near Ucon, ID (1950-2005)

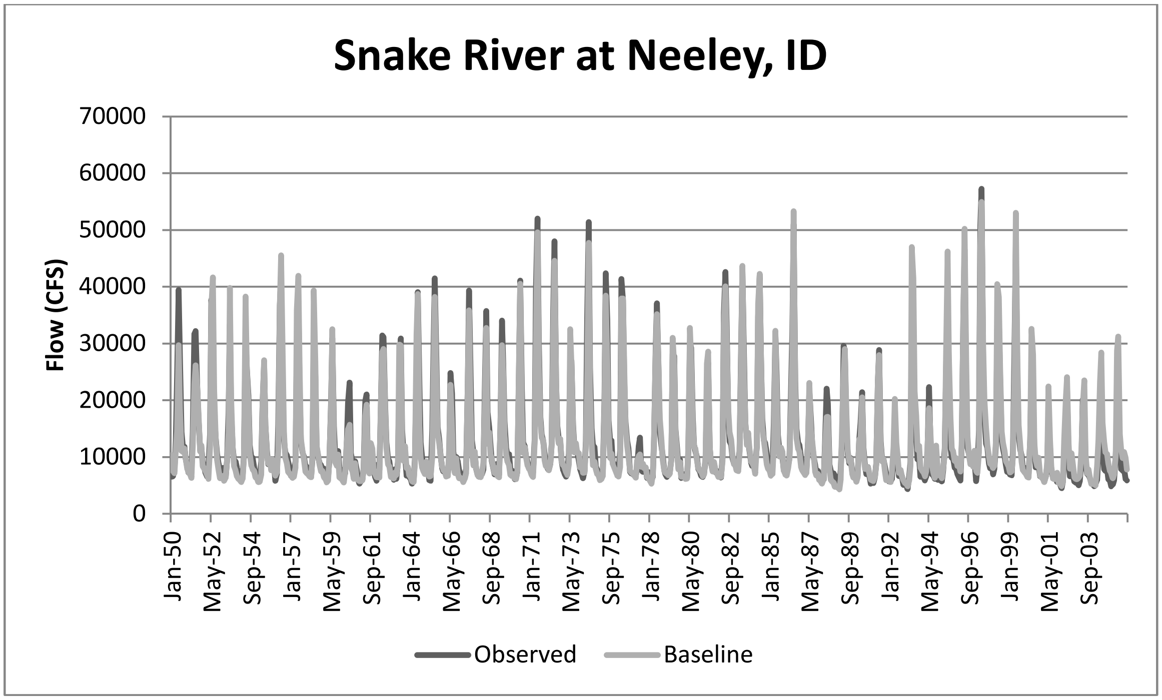


Figure B.10 Comparison of observed and baseline natural flow, for Snake River near Neeley, ID (1950-2005)

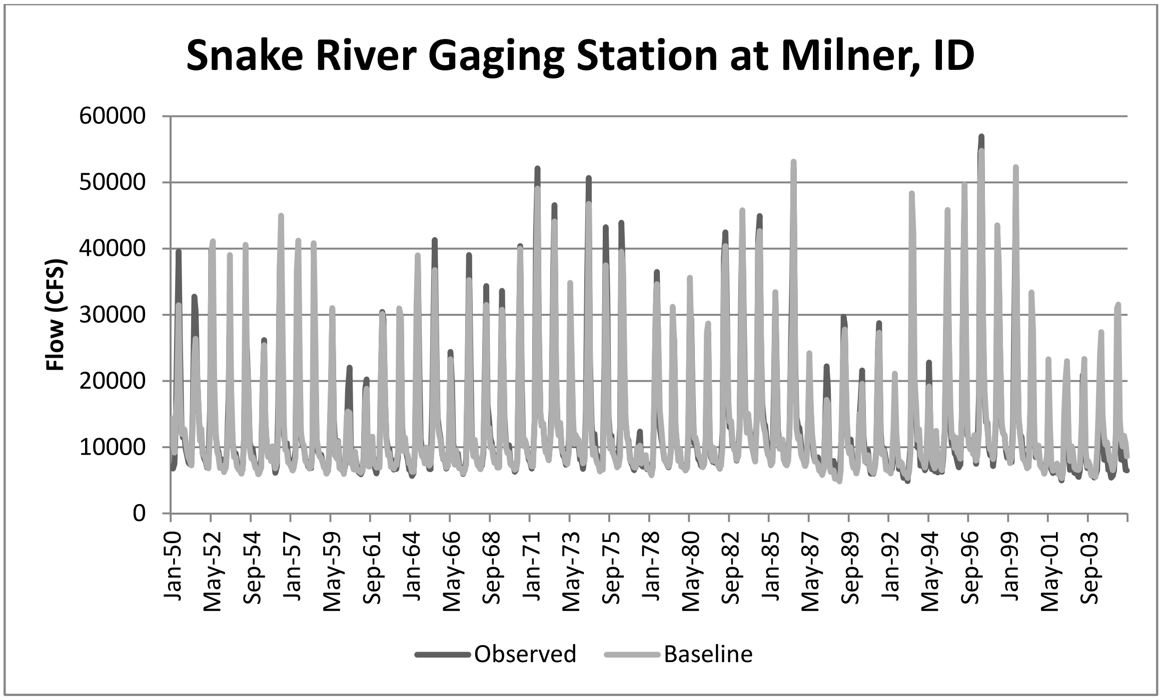


Figure B.11 Comparison of observed and baseline natural flow, for Snake River Gaging Station at Milner, ID (1950-2005)

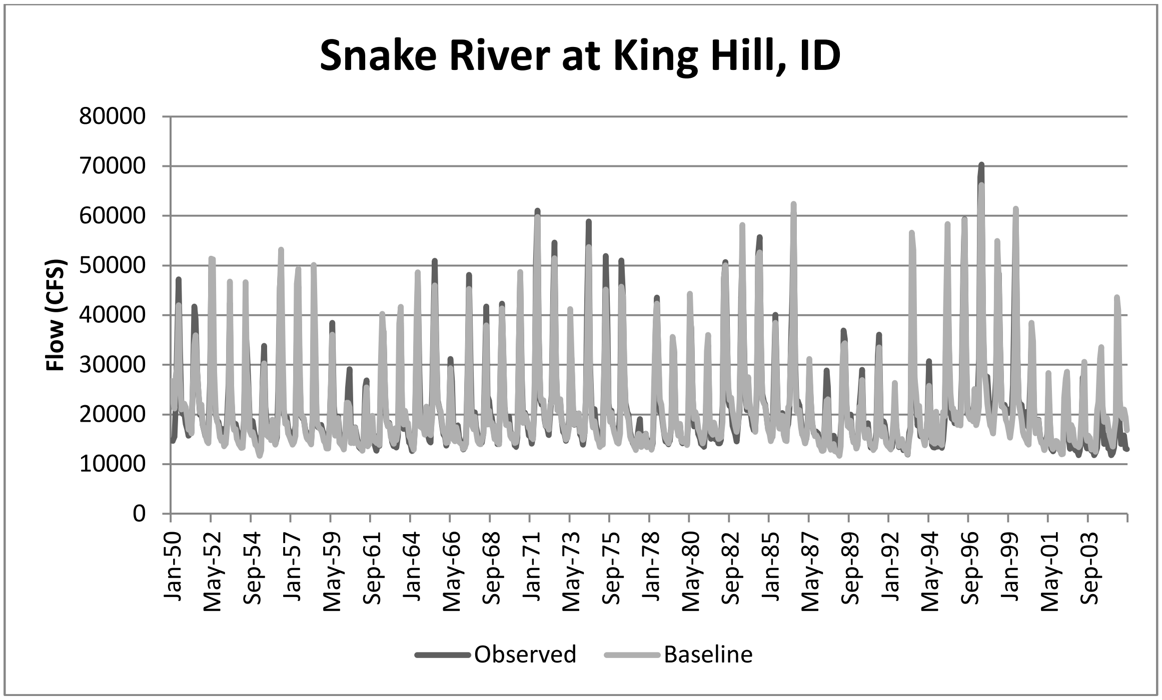


Figure B.12 Comparison of observed and baseline natural flow, for Snake River at King Hill, ID (1950-2005)

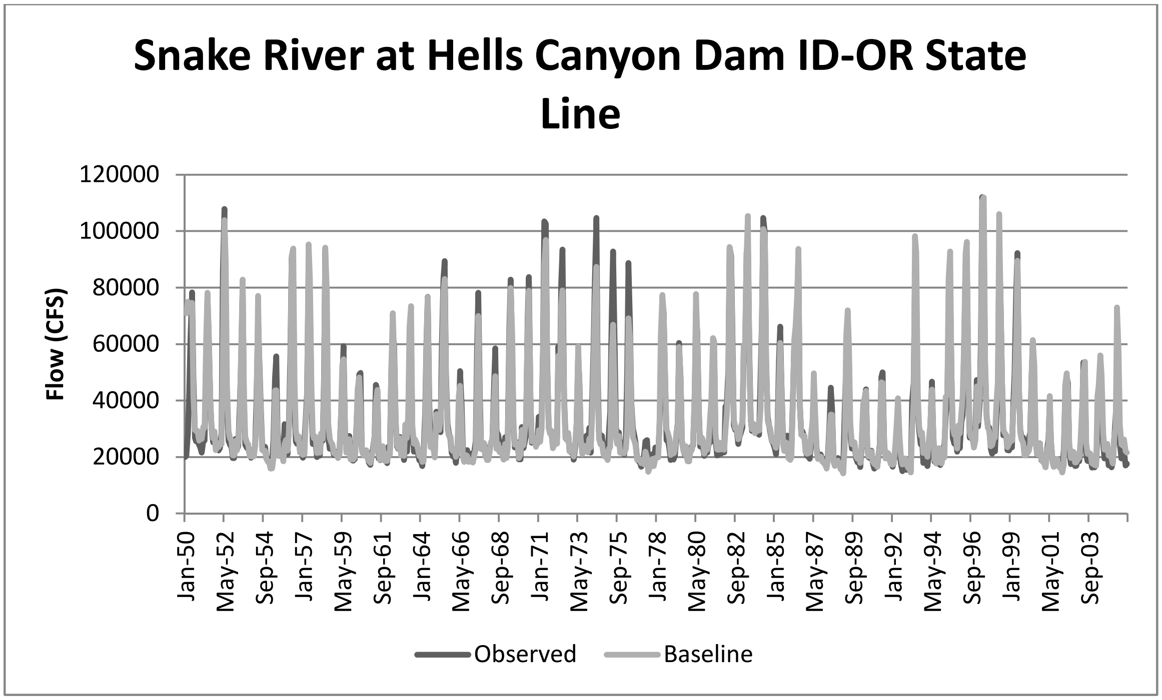


Figure B.13 Comparison of observed and baseline natural flow, for Snake River at Hells Canyon Dam ID-OR State Line (1950-2005)

APPENDIX C

1950-2099 Center of Timing Change

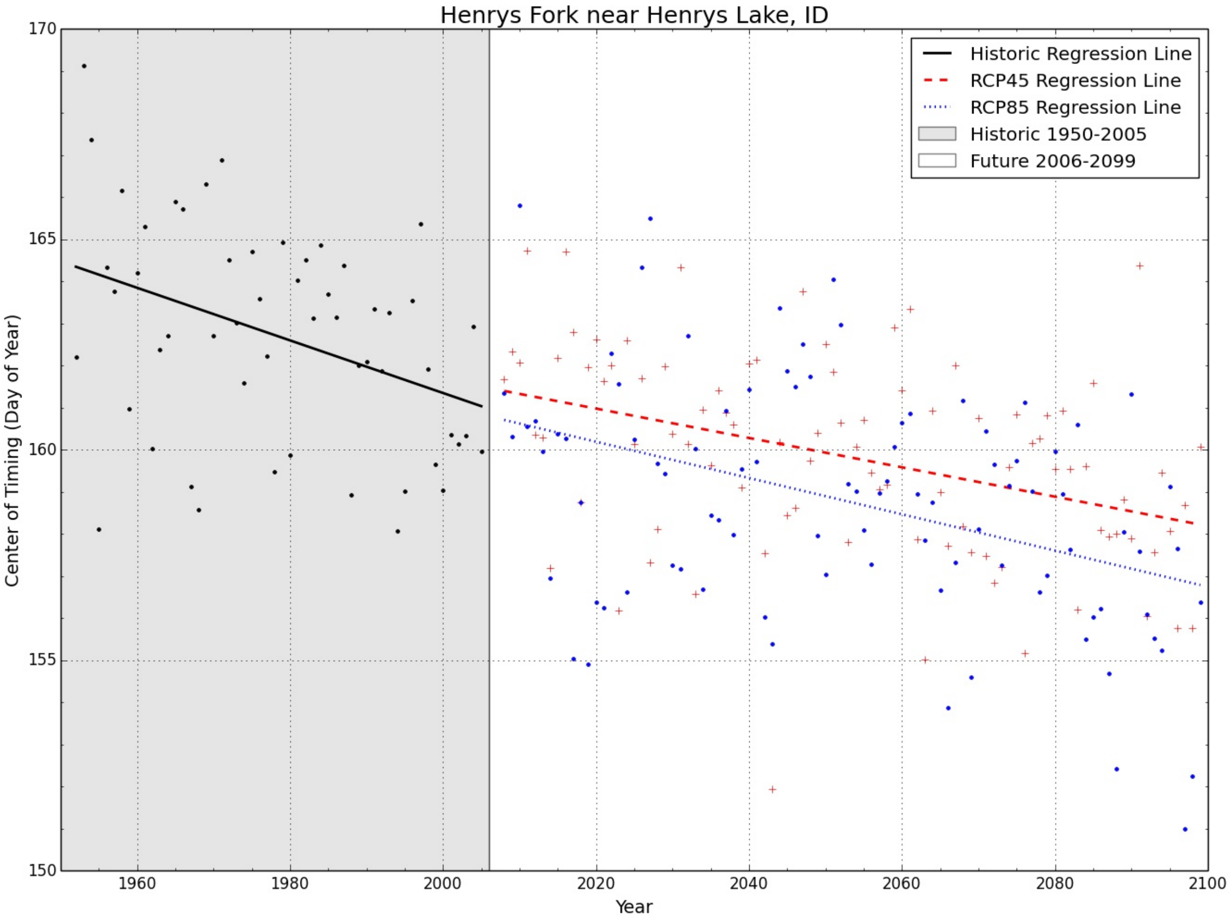


Figure C.1 Center of timing for Henrys Fork near Lake, showing shaded historic (1950-2005) and future (2006-2099)

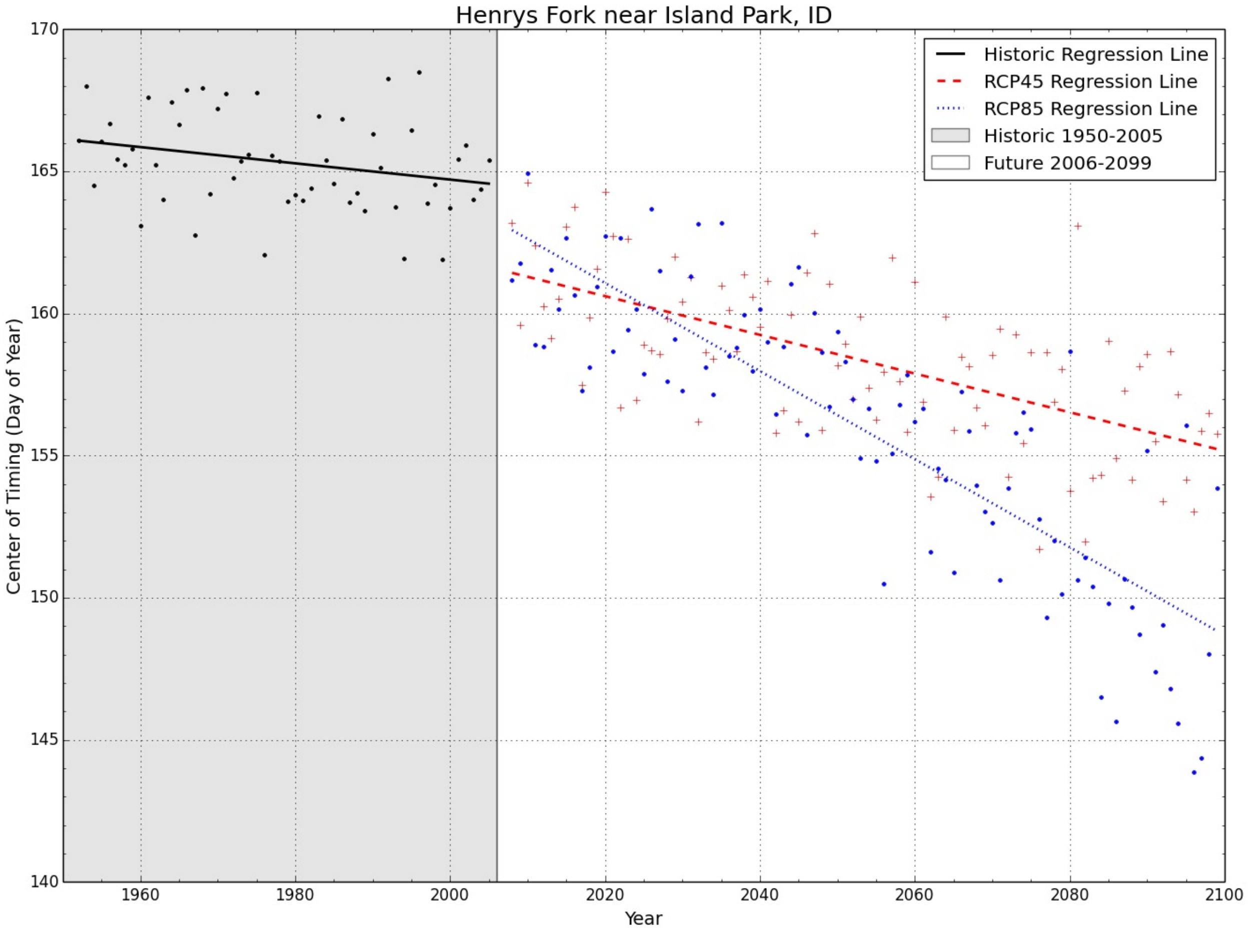


Figure C.2 Center of timing for Henrys Fork near Island Park, showing shaded historic (1950-2005) and future (2006-2099)

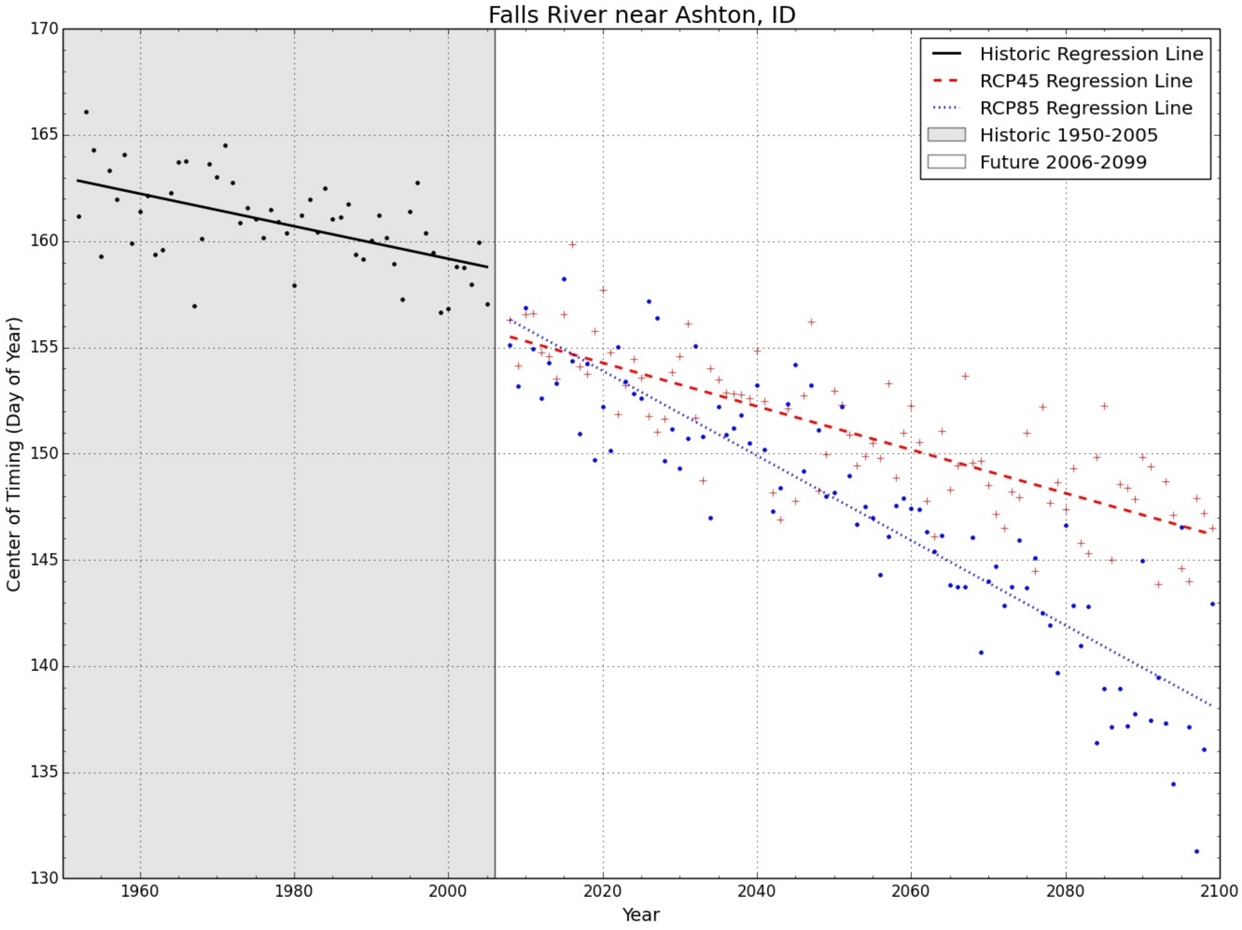


Figure C.3 Center of timing for Falls River near Ashton, showing shaded historic (1950-2005) and future (2006-2099)

Figure C.4 Center of timing for Teton River near St. Anthony, showing shaded historic (1950-2005) and future (2006-2099)

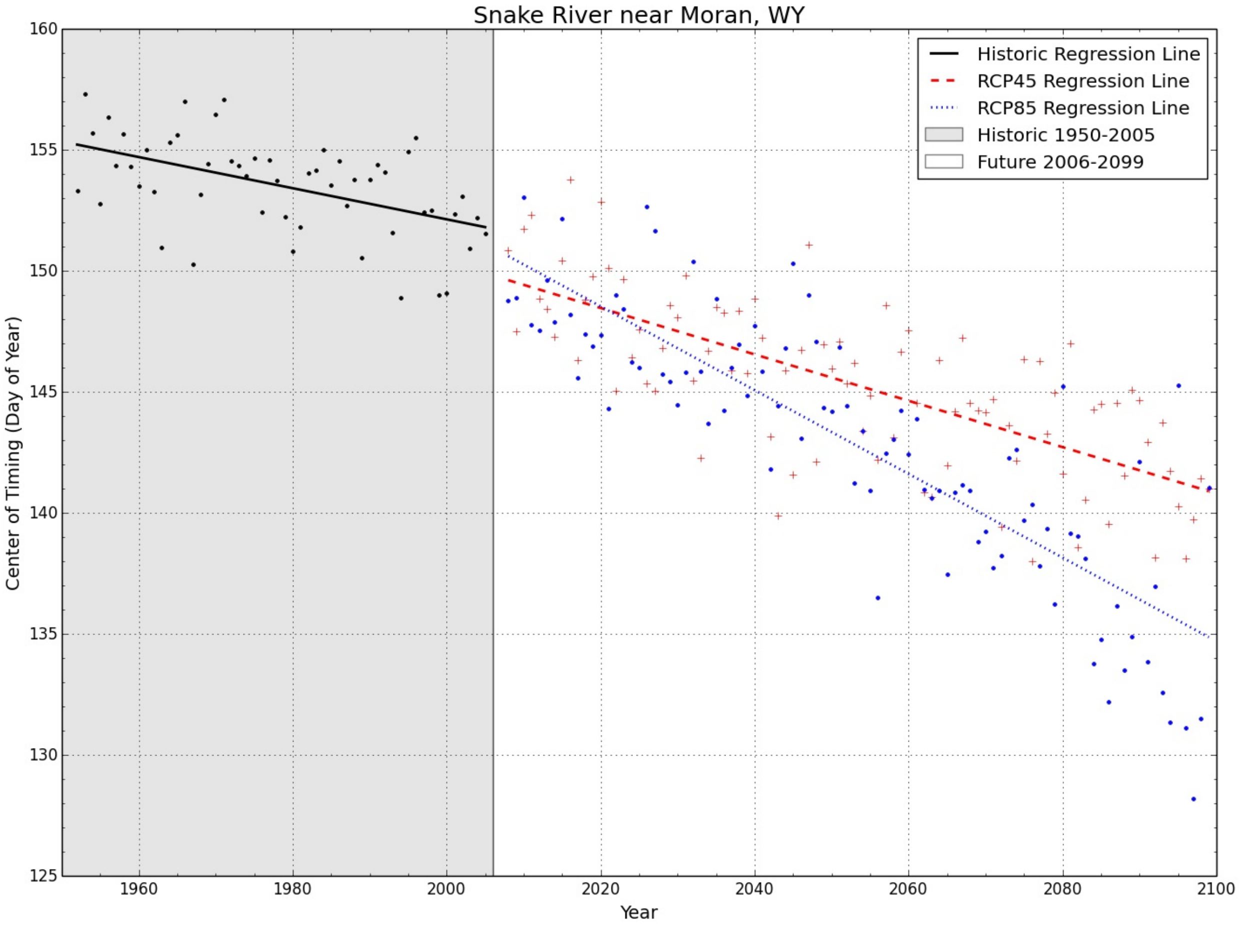


Figure C.5 Center of timing for Snake River near Moran, showing shaded historic (1950-2005) and future (2006-2099)

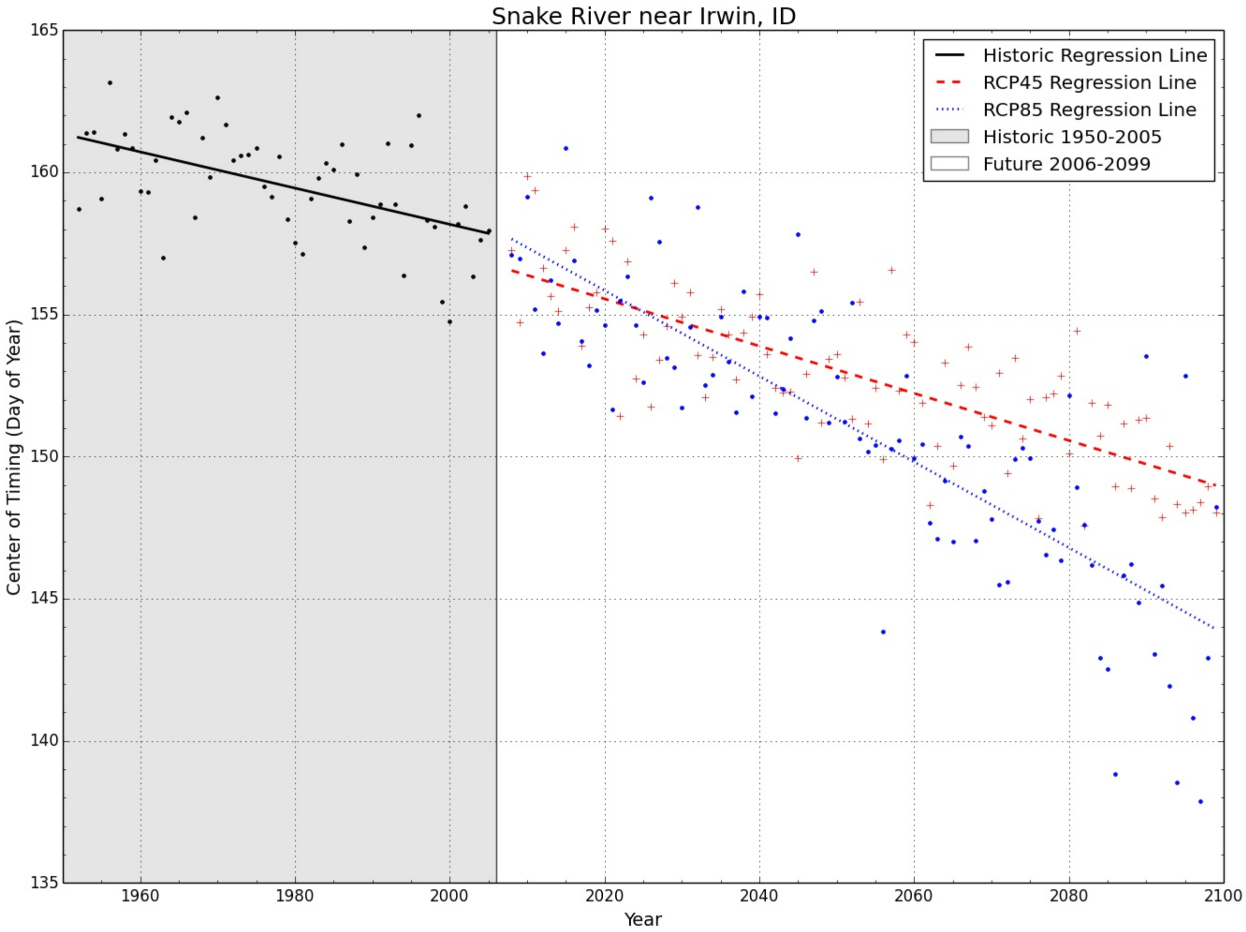


Figure C.6 **Center of timing for Snake River near Irwin, showing shaded historic (1950-2005) and future (2006-2099)**

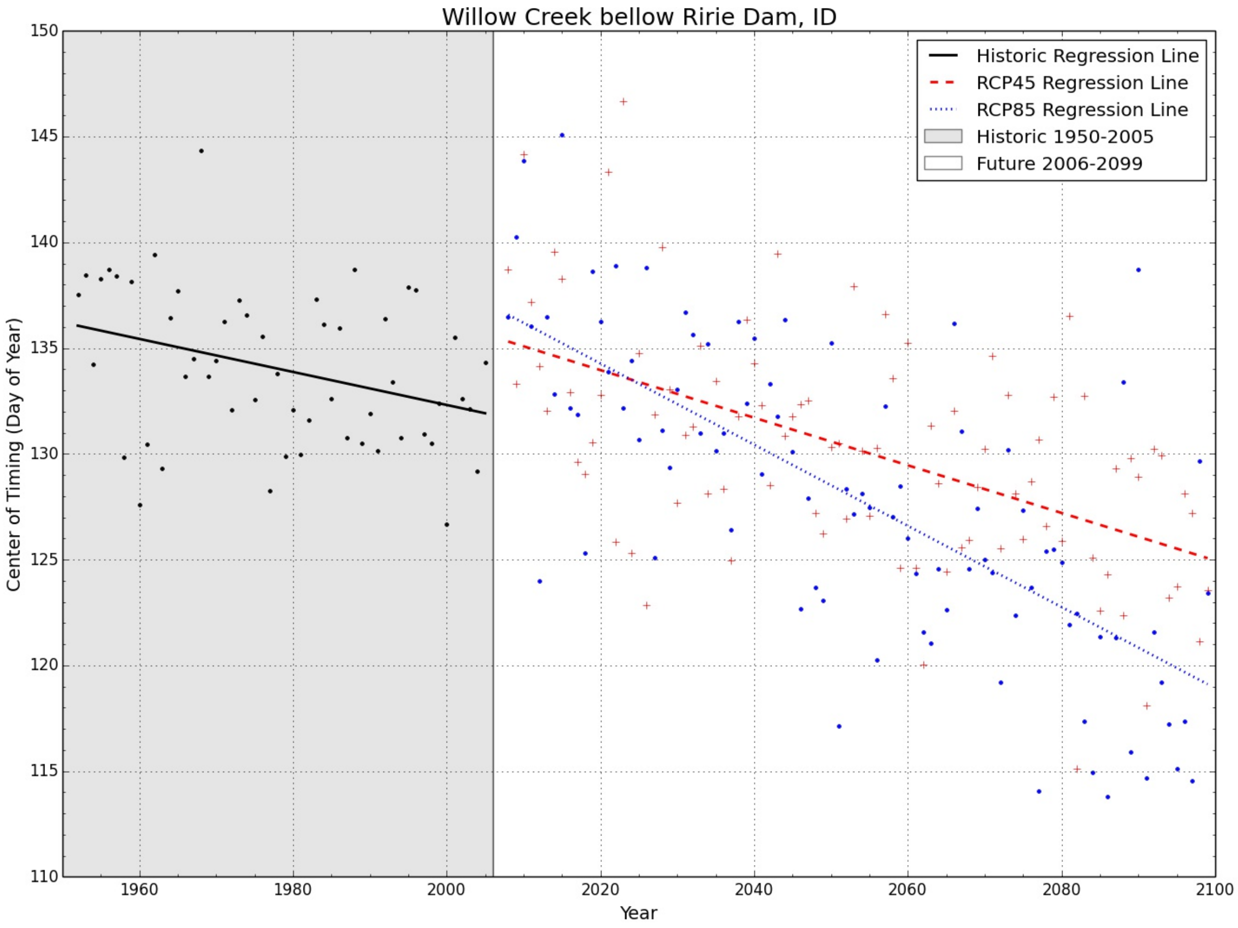


Figure C.7 Center of timing for Willow Creek bellow Ririe, showing shaded historic (1950-2005) and future (2006-2099)

Figure C.8 Center of timing for Snake River at Neeley, showing shaded historic (1950-2005) and future (2006-2099)

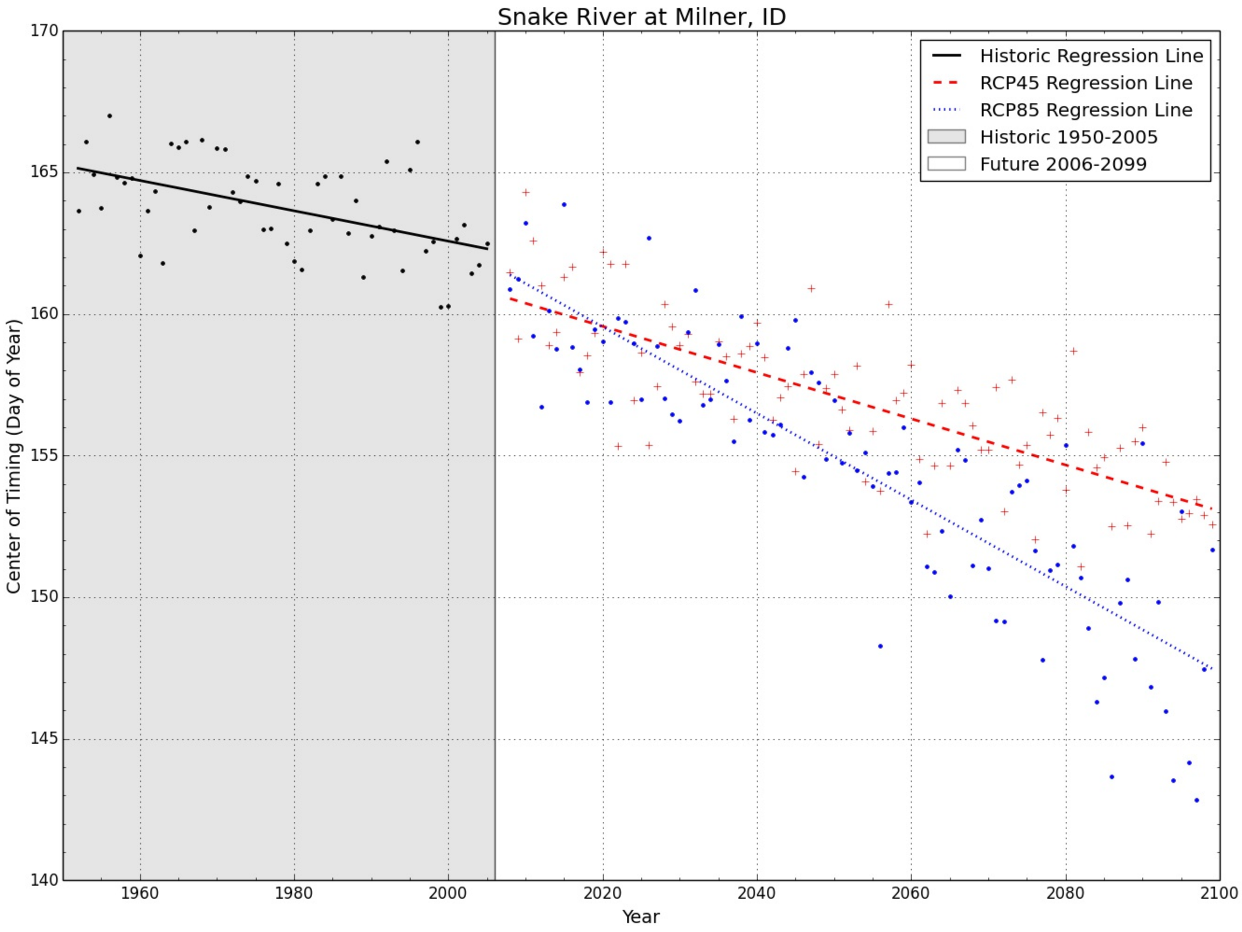


Figure C.9 Center of timing for Snake River at Milner, showing shaded historic (1950-2005) and future (2006-2099)

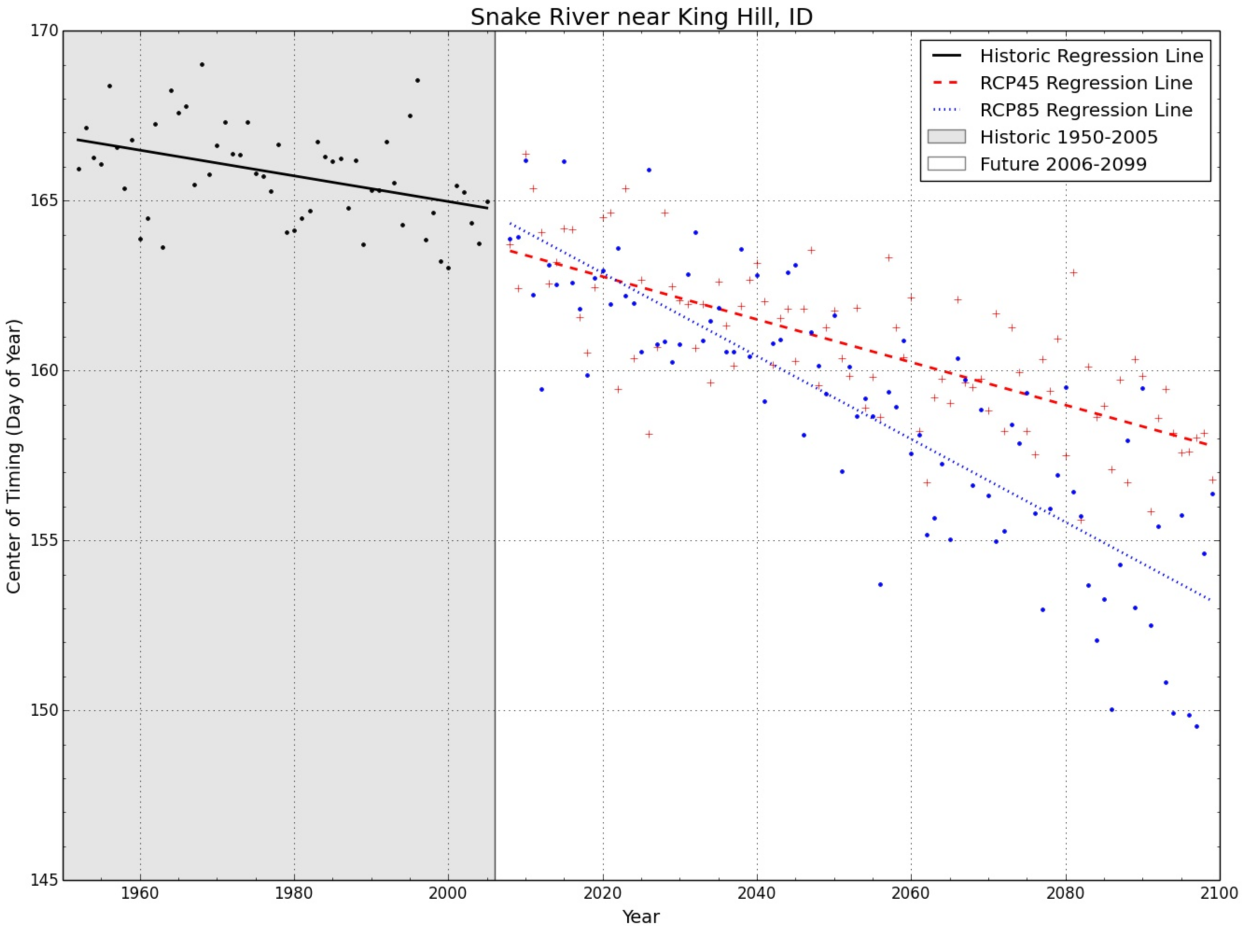


Figure C.10 Center of timing for Snake River at King Hill, showing shaded historic (1950-2005) and future (2006-2099)