EXPLORING THE IMPACT OF CLIMATE AND LAND COVER CHANGE ON REGIONAL HYDROLOGY IN A SNOWMELT-DOMINATED WATERSHED: THE UPPER BOISE RIVER BASIN, IDAHO

by

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DEDICATION

This thesis is dedicated to the memory of my grandmother, Phyllis Steimke Couey, for her everlasting support of all my pursuits.

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ABSTRACT

Seasonally snow-dominated, mountainous watersheds supply water to many human populations globally. However, the timing and magnitude of water delivery from these watersheds has already and will continue to change as climate is altered. Associated changes in watershed vegetation cover further affect the runoff responses of watersheds, from altering evapotranspiration rates to changing surface energy fluxes, and there exists a need to incorporate land cover change in hydrologic modeling studies. However, few land cover projections exist at the scale needed for watershed studies, and current models may be unable to simulate key interactions that occur between land cover and hydrologic processes.

To help address this gap in the literature, we explored the impacts of climate and land cover change on hydrologic regimes in the Upper Boise River Basin, Idaho. Using a multiagent simulation framework, Envision, we built a hydrologic model, calibrated it to historic streamflow and snowpack observations, and ran it to year 2100 under six diverse climate scenarios. Under present land cover conditions, average annual discharge increased by midcentury (2040-2069) with 13% more runoff than historical (1950-2009) across all climate scenarios, with ranges from 6-24% of increase. Runoff timing was altered, with center of timing of streamflow occurring 4-17 days earlier by midcentury. Our modeled snowpack was more sensitive to warming at lower elevations, and maximum snow water equivalent decreased and occurred 13-44 days earlier by midcentury. Utilizing metrics applicable to local water managers, we see the date that

junior water rights holders begin to be curtailed up to 14 days earlier across all models by the end of the century, with one model showing this could occur over a month earlier. These results suggest that current methods of water rights accounting and management may need to be revised moving into the future.

To test the sensitivity of our hydrologic model to changes in land cover, we selected a projected future land cover from the FORE-SCE (FOREcasting SCEnarios of land-use change) model. Our future land cover produced less evapotranspiration and more runoff, which stemmed from misclassification of high elevation regions between the FORE-SCE model and our initial land cover dataset, due to changes in the NLCD (National Land Cover Database) classification methodology. Additionally, FORE-SCE does not explicitly model wildfire or vegetative response to climate, both of which will likely be major drivers of landscape change in the mountainous, forested, western U.S., potentially making it insufficient for land cover projections in these areas. With evapotranspiration being the only parameter changing between land cover types in our hydrologic model, we were unable to capture the totality of hydrologic response to land cover change and other models may be better suited for such studies. This study highlights the necessity for better land cover projections in natural ecosystems that are attuned to both natural (e.g., climate, disturbance) and anthropogenic (e.g. management, invasive species) drivers of change, as well as better feedback in hydrologic models between the land surface and hydrological processes.

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LIST OF ABBREVIATIONS

AF	acre-feet
CanESM2	2nd generation Canadian Earth System Model
cfs	cubic feet per second
CMIP5	5th Coupled Model Intercomparison Project
CNRM-CM5	Centre National de Recherches Meteorologiques Climate Model
CONUS	Contiguous United States
CT	center of timing (of streamflow)
DOA	day of allocation
ET	evapotranspiration
FAO56	Food and Agricultural Organization Paper 56
FORE-SCE	FOREcasting SCEnarios of land-use change
GCM	Global Climate Model
GFDL-ESM2M	Geophysical Fluid Dynamics Lab Earth System Model
HBV	Hydrologiska Byråns Vattenbalansavdelning
HRU	Hydrologic Response Unit
HUC	Hydrological Unit Codes
IDU	Integrated Decision Unit
IGBP-DIS	Global Gridded Surfaces of Selected Soil Characteristics
IPCC	Intergovernmental Panel on Climate Change

MACA	Multivariate Adaptive Constructed Analogs
METDATA	Meteorological Data
NLCD	National Land Cover Database
NSE	Nash-Sutcliffe Efficiency
RCP	Representative Concentration Pathway
SNOTEL	SNOw TELemetry
SWE	Snow Water Equivalent
UBRB	Upper Boise River Basin
USGS	United States Geological Survey
USBR	United States Bureau of Reclamation
USACE	United States Army Corps of Engineers
VE	Volume error

1. PROJECT MOTIVATION AND OVERVIEW

1.1 Introduction

Water resources infrastructure and management are stressed globally, beset by combined pressures of growing populations and climate change (Vörösmarty et al., 2000; Oki and Kanae, 2006). Climate change is increasingly altering the spatiotemporal distribution of water availability (Mote et al., 2005; Regonda et al., 2005; Knowles et al., 2006). At the same time humans are modifying the Earth's surface at high rates, with one study suggesting humans have converted 40% of earth's surface to a human-modified coverage (Sterling and Duchame, 2008). Changes in land use and land cover are known to affect various components of the water cycle (Brauman et al., 2007; Sterling et al., 2013). Because land cover change and climate change interact to alter water resources across a range of spatial scales, there is a need to understand how both changing land cover and climate change will affect hydrologic regimes to ensure water security (National Research Council, 2012).

Numerous studies (Adam et al., 2009; Jin and Sridhar, 2012; Ficklin et al., 2013) have projected how regional hydrologic regimes will change in the future, with most taking a hydrologic modeling approach. However, many of these studies assume a static landscape, meaning they examine interactions between climate forcings (e.g., precipitation, temperature, humidity, etc.) on hydrology alone. By ignoring land cover change these studies miss potential interactions between vegetation, climate, and hydrology that could either modulate or amplify impacts of climate change on hydrologic response. With a better understanding of the role land cover plays in hydrology, local communities and land management agencies may be able to develop policies that mitigate against the impacts of climate change on hydrologic regimes while also enhancing water security.

There are not many straightforward methods to predict the timing, rate, and spatial extent of land cover change at the spatial resolutions that would be required to facilitate meaningful inferences about the impacts of land cover change on hydrologic regimes. The lack of broadly accepted techniques arises, in part, because land cover change prediction requires thorough understanding and representations of both natural (e.g., climate, disturbance) and anthropogenic (e.g., management, invasive species) drivers of change and the interactions between the two. Extrapolating past trends into the future is potentially misleading because of the possible nonlinear disruptions of human intervention and climate change. Several models do provide spatial projections of land cover (Bierwagen et al., 2010; Sohl et al., 2016), but there is a high amount of variability between models and they may not be well parameterized for all regions. For example, more emphasis is typically placed on land conversion stemming from urbanization or agriculture. However, in the western United States federal land ownership makes up nearly half of all lands (Gorte et al, 2012), and so land cover change likely occurs, in part, through different modes than the rest of the country.

Even with adequate projections of land cover change, many of our commonly used hydrologic models may not be well suited to model how changing land cover affects hydrologic variables. For example, many conceptual models use land cover as an input, but different land cover may only affect one hydrologic process, such as evapotranspiration. Numerous field studies have demonstrated that vegetation change correspondingly affects other variables, particularly those that characterize the soil, and that are likely to affect hydrologic response. Therefore, there is at present no singular framework capable of capturing the true effects of land cover conversion on hydrologic regimes. Hence, when studying the mutual interactions of climate change, land cover change, and regional hydrology, it is critically important to understand the limitations of the modeling framework being used.

In this thesis we use the Envision multiagent modeling framework (Bolte et al., 2007) to assess how future water resources may be affected by the interactions of climate and land cover change in a snowmelt-dominated, western U.S. watershed, the Upper Boise River Basin, ID. We explore the interactions between climate, land cover, and hydrology by running a hydrologic model through a combination of six climate scenarios and two land cover scenarios through the end of the century. We see that the majority of climate projections indicate slightly greater overall water availability, but that the timing and phase of the water is altered substantially, which will have ramifications for regional water management. Using a different land cover changed the hydrologic response of our study area, but after further investigation, this was primarily due to a mismatch between classifications of our two land covers, instead of specific drivers of change. At present, there does not exist any robust projections of vegetation distributions for our study area based upon the unique drivers of change that occur in these mountainous, natural ecosystems and at the resolution needed for watershed-scale studies. We discuss the limitations of both the land cover change model used, as well as our modeling framework, to capture feedbacks between the two. Additionally, we provide a literature review to understand some of the factors involved in federal land management decision-making, in hopes to spur future research to further understand how and why land management decisions are made and to incorporate management actions into models.

1.2 Impact

The results of this study complement and reinforce other work being done to assess climate change in Idaho. As a direct impact, the modeled streamflow outputs will serve as an upper boundary condition for modeling efforts in the Lower Boise River Basin. Recent efforts in this region have focused on creating models of population growth and the associated water use and availability under different development and climate scenarios (Han et al., 2017). Other related work uses a process-based model to understand how crop yield, irrigation demand, and farm management practices may change as the climate warms (Leonard., *in prep*). Water resources for irrigation in the Lower Boise River Basin are scarce and primarily stem from upper basin storage reservoirs; therefore, future projections of lower basin water resources must rely on robust projections from the watershed above.

Other work is being done to assess aspects of scale in hydrological studies. As we show in Chapter 3, there currently are no adequate projections of land cover change in topographically complex, natural ecosystems for hydrological studies on the scale of this study. While there are models at present to forecast projected vegetation (Shafer et al., 2015; Sheehan et al., 2015), they are limited by the scale of their input datasets, which affects their ability to capture smaller drivers of vegetation distribution, particularly along ecotones where subtle changes in aspect can play a large role in the distribution of vegetation types (Gelb, *in prep*). However, as we gain greater computational ability, we may be able to generate input datasets to these models that are at more appropriate and higher spatial resolutions (e.g., particularly chracterizing climate forcings). Current work is being done to create a historical dataset over our study area domain using the Weather Research and Forecasting model (Skamarock et al., 2008) at spatial and temporal resolutions of 1 km and 1 hour, respectively (Flores et al., 2016). For watershed-scale studies, finer-scaled forecasts of climate and other input datasets are needed to better constrain ecohydrological studies.

There is an increased need to more accurately capture the joint feedback of climate and land cover change on the replumbing of the hydrological system. As we show in this study, our conceptual models may not be able to accurately reflect those complex hydrologic processes. Moving forward, researchers should experiment with physically-based hydrologic models, such as WRF-HYDRO (Gochis et al., 2013), which may be able to more truly capture the reality of changing land cover (e.g. vegetation surface roughness, albedo) and its feedback to hydrologic processes.

1.3 Objectives

The objectives of this thesis are the following:

1. Identify a range of global climate model projections and assess how they affect hydrologic parameters;
2. Identify how current water management practices may be affected by changes in hydrologic regimes;
3. Determine if there is a significant change in hydrologic variables when modeled with a different land cover;

4. Investigate if changes in hydrologic variables due to land cover change vary between contrasting climate futures;
5. Assess the ability of our chosen modeling framework and setup to represent interactions between climate, land cover, and hydrology; and
6. Identify factors that affect federal land managers' decision-making.

1.4 Organization

This thesis is composed of four chapters and two appendices. Chapter 1 provides an overview for the project. Chapter 2 addresses objectives 1 and 2 above, provides an overview of the modeling framework used in this study, and is titled "Impacts of climate change on regional hydrology and water management in a snowmelt-dominated watershed." Chapter 3 addresses objectives 3-5 and is titled "Testing the sensitivity of hydrologic variables to modeled land cover change in an agent-based modeling framework." Chapter 4 concludes the thesis and provides suggestions for future studies.

Appendix A stems from an independent study performed in fall 2015, in which we explored the literature to understand the current knowledge of the types of factors that affect federal land managers' decision-making. The original objective was to be able to gain sufficient insight in different types of land management styles to be able to model them within Envision. While the knowledge gained from that exercise ultimately did not make it into our model, we felt it was necessary to include this paper to provide a baseline of information for others that may attempt such a study in the future. This appendix addresses objective six and is titled "How do public land managers decide to manage their land? A synthesis on current literature and the factors involved in decision-making." Appendix B provides locations of model runs, scripts, and data products.

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2. IMPACTS OF CLIMATE CHANGE ON REGIONAL HYDROLOGY AND WATER MANAGEMENT IN A SNOWMELT-DOMINATED WATERSHED

2.1 Abstract

Climate change directly affects the hydrologic cycle in mountainous watersheds, which has consequences for downstream users. Improved water projections under diverse potential climate futures are critical to improve water security and management in these watersheds. Here, we examine potential hydrologic changes to a semi-arid, snowmelt-dominated, mountainous watershed, the Upper Boise River Basin, ID, which supplies water to an agriculturally intensive and rapidly urbanizing region. Using the Envision integrated modeling framework, we created a hydrologic model that was calibrated to several hydrologic metrics and ran it to year 2100 under six diverse climate scenarios. By 2050, annual discharge increased from historical values by an average of 13% across all climate scenarios with a range of increase of 6-24%. Runoff timing was altered, with peak discharge occurring 4-33 days earlier and center of timing of streamflow occurring 4-17 days earlier by midcentury. Modeled snowpack was more sensitive to warming at lower elevations, and maximum snow water equivalent decreased and occurred 13-44 days earlier by midcentury. We calculated the "Day of Allocation", a metric used by local water managers, which represents the date that junior water rights holders begin to be curtailed. We found that, by 2100, the Day of Allocation occurs up to 14 days earlier across all climate scenarios, with one scenario suggesting this date could occur over a

month earlier. These results suggest that current methods and policies of water rights accounting and management may need to be revised moving into the future.

2.2 Introduction

Climate change exerts a significant control on global hydrologic regimes by influencing the timing, magnitude, phase, and seasonal variability in precipitation (Mote et al., 2005; Regonda et al., 2005; Knowles et al., 2006). Changes in temperature further influence how that precipitation moves through a watershed by affecting snowmelt timing, soil moisture, and evapotranspiration rates (Barnett et al., 2005). While there is general consensus among scientists that the Earth is warming and will continue to do so, there remain significant uncertainties regarding the impacts of global warming on the water cycle and how those changes will be distributed regionally in the future (Huntington, 2006; Turral et al., 2011).

Significant changes in the water cycle can have serious consequences for water users and management across many sectors. It is estimated that more than two billion people currently live in highly water-stressed regions (Oki and Kanae, 2006), with this number likely to increase moving into the future (Schewe et al., 2014). Agriculture is vulnerable to changes in hydrologic regimes, especially in regions that rely on surface water resources for irrigation and in rain-fed systems (Turral et al., 2011). Flooding could intensify, putting stress on current water management infrastructure as well as lessening the effectiveness of hydropower generation as runoff arrives earlier (Markoff and Cullen, 2008). However, the effectiveness of the natural capital, physical infrastructure, and legal and social frameworks comprising current water management systems under changing hydrologic regimes is not well understood.

Snowmelt-dominated systems, located primarily in the western U.S., are especially vulnerable to climate change (Barnett et al., 2005; Stewart, 2009). Significant reservoirs, in the form of snow, develop at times (i.e. winter) and locations (i.e. high elevations) where that water cannot be used to grow crops and produce hydroelectricity. This snowpack at high elevations provides a natural reservoir that holds water in reserve and, ideally, slowly releases it into the spring and summer, into downstream valleys with fertile agricultural soils. Physical and legal infrastructure has been developed to store springtime runoff, mitigate flooding, and direct it to other locations when there is a demand for irrigation. This current water management infrastructure and protocols are set up to account for the historical range of hydrologic variability; however, they may not be adequate to adapt to future hydrologic regimes (Palmer et al., 2008). With sufficient changes in the timing and magnitude of water delivery, as is projected with climate change, current management practices may be inadequate to meet the dual needs of flood control and late-season irrigation demand (Barnett et al., 2005). However, it is uncertain to what extent current management practices may be insufficient under future hydrologic regimes or when water management agencies can expect those practices to begin coming into conflict with the reality of altered runoff regimes.

Many previous modeling studies have investigated how water resources will change in snowmelt-dominated systems (Adam et al., 2009; Jin and Sridhar, 2012; Ficklin et al., 2013). However, results from these studies are typically not presented in a way that is usable to water managers. Here we provide an example of how hydrologic modelers can generate additional results that are meaningful for management decisions. For example, in the American West, there are different hierarchies of water rights users who may be affected differently by projected changes in water availabity (Vicuna et al., 2007). Such results require more in-depth knowledge of location-specific water management and distribution, and provide more relevant information to a wider group of audiences.

The overarching objective of this study is to better understand and quantify how climate change will impact future water resources and management. We perform our study in the upper Boise River Basin, ID, an ideal location because it is a relatively undisturbed high mountain watershed that provides water resources to a region where agriculture is being rapidly displaced by urban development. We explore this connected biophysical and social system by combining a surface water hydrologic model with diverse climate projections to project potential changes in future regional hydrologic regimes. Furthermore, we translate our model outputs into a metric that is directly applicable to downstream water users and managers. Our specific research objectives are to:

1. Identify a range of climate projections and assess how they affect hydrologic parameters such as center of timing of streamflow, volume of annual water delivery, and snowpack levels through 2100; and
2. Identify how current water management practices may be affected by changes in hydrologic regimes.

2.3 Study Area

The upper Boise River Basin (BRB) is located in southwest Idaho (Figure 2.1) and supplies water for downstream users in the populated Boise metropolitan region. This watershed encompasses an area of 6935 km^2 with elevation ranging from 930 to 3000+

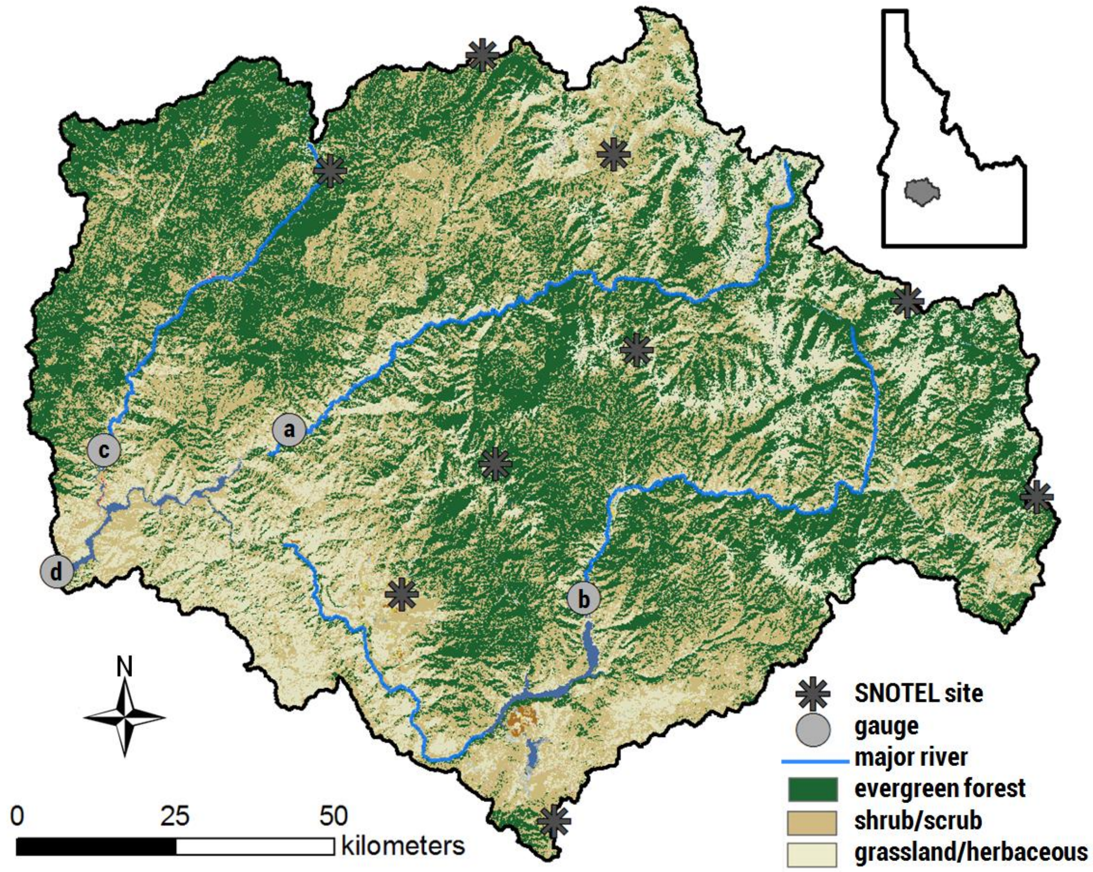

Figure 2.1: Overview of the study area with major land cover types and locations of SNOTEL stations and gauge locations (see Table 6 for names of gauges).

meters. It is bounded by the Sawtooth range in the east, the Payette River Basin to the north, and the Snake River Plain to the southwest. We delineated the study area by combining three Hydrologic Unit Code (HUC) 8 watersheds: the North and Middle Forks Boise (17050111), the South Fork Boise (17050113), and Boise-Mores (17050112). Due to the large variation in topography throughout the study area, regions shift from semi-arid grasslands and shrublands in the lowlands to coniferous forests in the highlands. In the BRB, the dominant land covers are forest (43.0%), shrubland (34.6%) and grassland (20.9%). Additional land covers make up the remaining 1.5% of area, and there has been little development within the BRB. The climate in this region is a continental Mediterranean climate (Köppen *Dsb*) with cold winters, warm summers, and the majority of precipitation falling in winter as snow. The overall average precipitation is ~800 mm, with averages ranging from ~400 mm in low elevations and over 1300 mm at high elevations (PRISM climate group; Daly et al., 1994).

The BRB is the primary source of water for the downstream Treasure Valley region, which contains the state's three largest cities (Boise, Nampa, and Meridian) and roughly 40% of the state's total population. The Treasure Valley is an agriculturally intensive region and contains approximately 1300 km^2 of farmlands, many of which rely on irrigation water from the BRB. Like many other snowmelt-dominated watersheds in the West, the BRB is heavily managed to fulfill the needs of flood control and downstream uses, especially for direct consumption in the Treasure Valley. There are three large storage reservoirs within the study area providing flood control with secondary uses of irrigation and hydropower (Table 2.1). Similar to other western states, water rights in this region follow the prior appropriation doctrine, also known as "first in time – first in right." This doctrine states that the earliest beneficial users (i.e. senior water rights) retain their full water right, and those that came later (i.e. junior water rights) may retain their water rights as long as they do not infringe on those that came beforehand. As such, many junior water rights are curtailed during low water years.

Table 2.1: Dams located within the study area

Name	**Owner**	**Watercourse**	**Active Capacity (AF)**
Lucky Peak	USACE	Boise River, Mores Creek	264,400
Arrowrock	USACE	Boise River	271,700
Anderson Ranch	USBR	South Fork Boise River	413,100

Previous studies indicate that the UBRB has already begun to respond hydrologically to climate change, noting an increase in summer streamflow temperatures (Isaak et al., 2010), earlier timing of streamflow (Clark 2010), lengthened growing season (Kunkel et al, 2004), and declining extreme low flow discharges (Kormos et al., 2016). Additionally, there have been previous modeling studies that have used this basin to anticipate changes in hydrology under climate change (Jin and Sridhar, 2012; Bureau of Reclamation, 2008). However, both of the aforementioned studies used an older generation of global climate models as their climate input and calibrated their models to streamflow alone. This study extends those previous works by making use of climate projections from the 5th Couple Model Intercomparison Project (CMIP5; Taylor et al., 2012), calibrating the hydrologic model to multiple hydrologic metrics, and producing results that may provide additional meaning to water users.

2.4 Methods

2.4.1 Modeling framework

Here we employ the Envision framework, a multiagent-based, spatially explicit modeling framework, to examine how regional hydrology may change with climate. Envision was created to examine the relationships between human and natural environmental systems by integrating scenarios, data, and component models to assess regional landscape change (Bolte et al., 2007). To this end, the modeling framework and software infrastructure of Envision supports integration of a variety of social and biophysical models in a spatiotemporally dynamic way. It is freely available and users can extend and enhance model capabilities by adding additional models as plugins. It has been extensively used recently in a wide variety of studies, from understanding urbanization impacts on streamflow (Wu et al., 2015) to projecting climate change impacts of land cover and land use (Turner et al, 2015), and even to understand when fire occurrence and size is 'surprising' (Hulse et al, 2016). Additionally, it has been used to integrate water rights to spatially allocate irrigation in the agriculturally intensive region below the BRB (Han et al., 2017).

In this study, we use Envision version 6.197 and utilize the Flow extension to model future hydrology under various climate scenarios (Figure 2.2). In the following sections, we provide an overview of the modeling structure and the inputs needed for the various components.

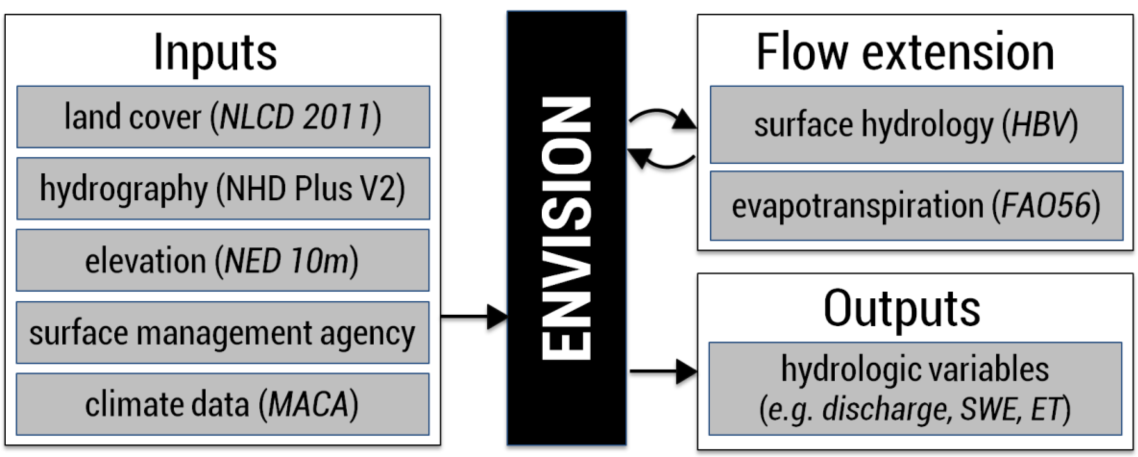

Figure 2.2: An overview of the inputs and submodels used in this study.

2.4.1.1 Spatial coverage in Envision

In Envision, the most refined spatial elements where model algorithms are applied are referred to as Integrated Decision Units (IDUs). The size and geometry of these polygons is dependent on the type of modeling being performed and the geospatial datasets required as input to those model. As such, there is no universally accepted method for creating IDU coverage. In this project, we used three datasets to form the IDU geometry: surface management agency, land cover, and HUC 12 stream catchments (Table 2.2).

The datasets were processed in ArcMap 10.1. To shorten Envision's computation time, we coarsened the land cover dataset from 30 to 100 m in increments of 10 m. We used the raster resampling tool and recorded the areal percentage each major land type covered during this process in order to ensure that coarsening the dataset did not significantly change the overall amounts of each land cover type (Figure 2.3). We used a nearest neighbor algorithm to resample land cover types to more accurately capture the original distribution of coverage in the land cover dataset. The other two datasets were polygon geospatial datasets that required very little processing besides renaming attributes to be consistent with the Envision framework requirements.

Table 2.2: Data sources used for spatial coverage in Envision

Input Data (*resolution*)	**Data Sources**	**Used in**
Surface Management Agency	Bureau of Land Management	IDU
Land Cover (*30 m*)	National Landcover Database (*2011*)	IDU, ET
Streams & Catchments (*HUC 12*)	NHD Plus V2	IDU, HBV
Elevation (*30 m*)	National Elevation Dataset	HRU

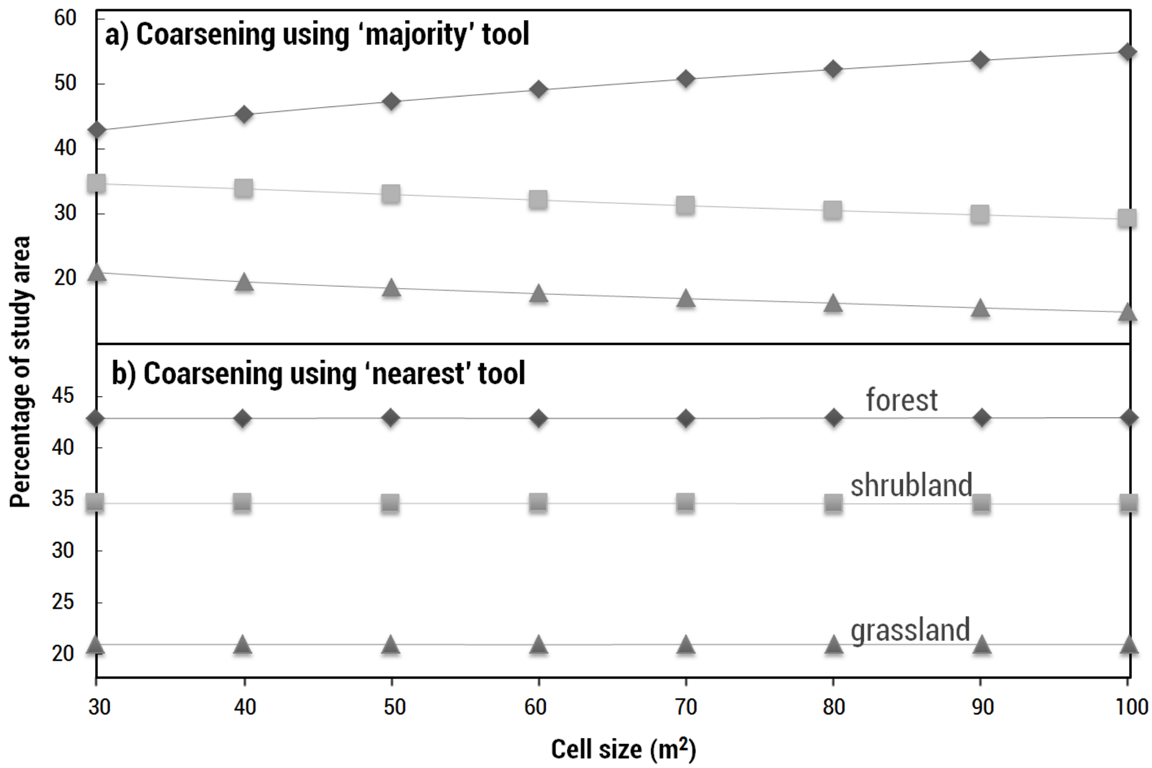

Figure 2.3: Results of using different methods to resample rasters in ArcGIS showing the three major land cover types. A bias is introduced when the 'majority' tool is used, and so the 'nearest' tool was used instead.

We created our IDU coverage by intersecting the three aforementioned datasets, creating 31,625 polygons. We extracted the average elevation for each IDU and assigned an elevation class from 1-4, corresponding to 0-1500, 1500-2000, 2000-2500, and >2500 meters. Additionally, to aid in analysis and querying we created a land cover hierarchy ranging from general (e.g. Natural Vegetation) to more specific (e.g. Evergreen Forest), which was formed by grouping NLCD classifications that are similar (Figure 2.4).

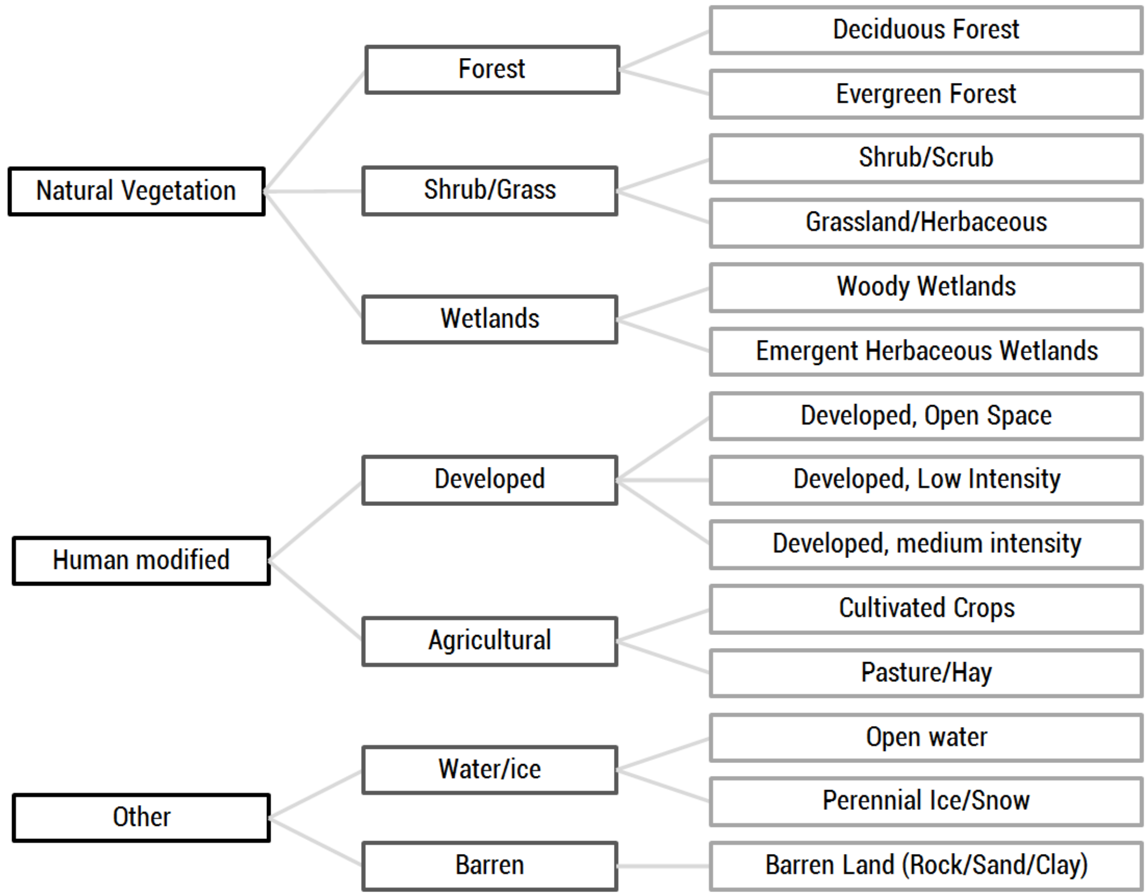

Figure 2.4: Land use / land cover tree developed for Envision. The tree allows for modeling algorithms to be applied at different hierarchy levels, from more general to more specific land types. The finest categories on the right correspond to the NLCD land classification system.

The hydrologic model in Envision applies algorithms to Hydrologic Response Units (HRUs; Jin and Sridhar, 2012; Turner et al., 2017), which are an aggregation of IDUs that would theoretically behave hydrologically similar. To create the HRU coverage, we grouped polygons that had the same intermediate land cover (Figure 2.4), identical elevation class, and were located in the same HUC 12 catchment. This resulted in 9465 HRUs.

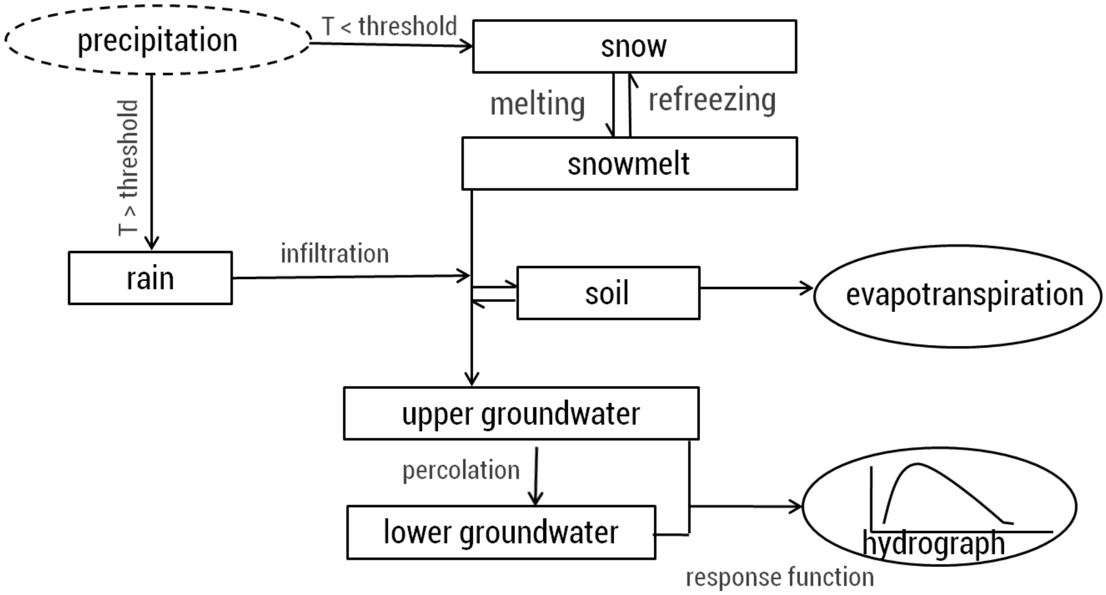

Figure 2.5: Flowchart of the different hydrologic processes and reservoirs within the Flow model in Envision, (modified from Han et al., 2017).

2.4.1.2 Flow description

Flow is an extension in Envision that supports plug-ins to allow flexibility in modeling hydrology and the use of different model representations of hydrologic processes. In this study, we use a modified version of the HBV (Hydrologiska Byråns Vattenbalansavdelning) rainfall-runoff model (Bergström, 1976) for surface hydrology. HBV is a commonly used conceptual model (Seibert 2000, Woodsmith et al., 2007; Abebe et al., 2010; Bergström and Lindström, 2015) but has been modified by Envision's developers to be spatially distributed. Each HRU is conceptualized as a linked reservoir with five layers of storage: snowpack, lakes, soil, upper groundwater and lower groundwater (Figure 2.5). Runoff from each HRU is routed to streams using HUC12 flowlines from NHDplus V2 (Table 2.2). The water balance in Flow is described by the following equation:

$$P - ET - Q = \frac{d}{dt}\,[SP + SM + UZ + LZ + lakes] \qquad \text{(eq. 1)}$$

where P = precipitation, ET = evapotranspiration, Q = runoff, SP = snow storage, SM = soil moisture storage, UZ = upper groundwater storage, LZ = lower groundwater storage, and $lakes$ = lake storage. A more thorough description of the HBV model can be found in other papers (Seibert, 1999; Bergström and Lindström, 2015) and a more detailed description of Flow can be found on Envision's website (http://envision.bioe.orst.edu/).

Evapotranspiration (ET) is calculated via a modified Penman-Monteith approach described in the Food and Agriculture Organization's Irrigation and Drainage paper 56 (FAO56) where a crop coefficient is applied to the ET of a reference plant (Allen et al., 1998) and was later developed specifically for Idaho (Allen and Robison, 2007) using the following equation:

$$ET = ET_r * K_c \qquad \text{(eq. 2)}$$

where ET = evapotranspiration, ET_r = reference evapotranspiration (alfalfa, for Idaho), and K_c = crop coefficient.

We used this equation and applied crop coefficient curves that either matched our land cover type directly or estimated crop coefficient curves based upon similarities of crops to land cover types (Table 2.3). Crop coefficients were obtained from AgriMet and Allen and Robison (2007), with a few modified land cover coefficients from Inouye (2014).

Table 2.3: Land cover type in Envision and the associated crop used to calculate evapotranspiration

Land cover	Crop substituted for land cover	Source
Forest	3rd year poplar * 3	Agrimet, Inouye
Shrubland	Sagebrush	Allen & Robison
Grassland	Bunch grass	Allen & Robison
Wetlands	Poplar * 3	Agrimet, Inouye
Developed	Lawn * 0.21	Agrimet, Inouye
Agricultural	Alfalfa (mean)	Agrimet
Water/ice	Open Water	Allen & Robison
Barren	Lawn * 0.21	Agrimet, Inouye

2.4.2 Climate inputs

We used statistically downscaled climate data using the MACA (Multivariate Adaptive Constructed Analogs) method version 1.0 for both historic and future simulations (Abatzaglou and Brown, 2011). This data has a spatial resolution of 4 km across the continental U.S. and is available daily for 1950-2100. Downscaled data is available for 20 Global Climate Models (GCMs) from CMIP5 for both Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios. RCPs are a consistent set of projections that are named according to their radiating forcing level at 2100, such that RCP 4.5 equates to 4.5 W/m^2 net radiative forcing at the end of the century (Figure 2.6).

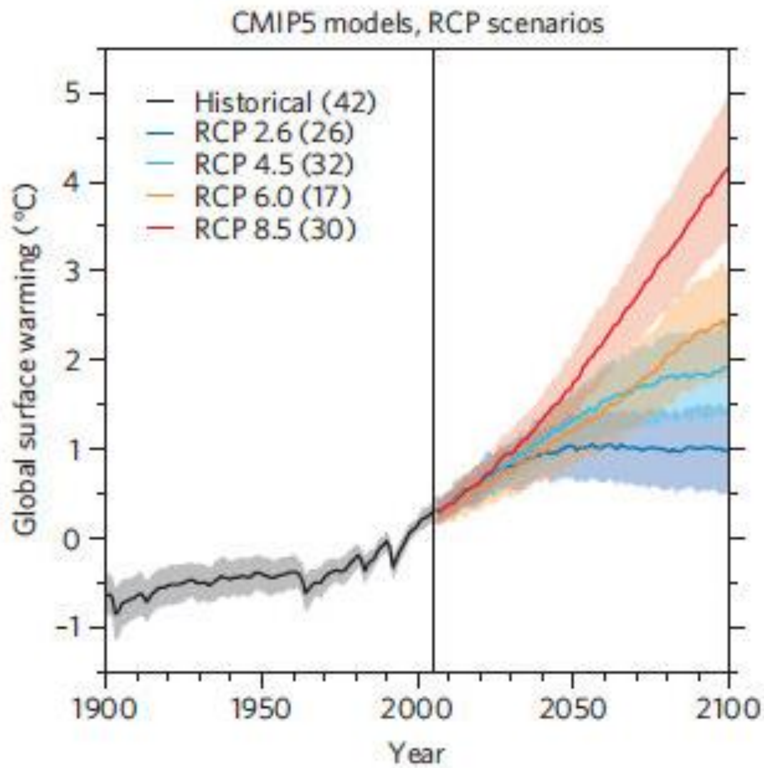

Figure 2.6: Mean projections of global temperature change (shaded area is 1σ) for CMIP5 GCMs under the RCP scenarios relative to 1986-2005. Figure was taken from Knutti and Sedláček, 2013.

For future simulations, we selected GCMs that both captured the range of variability between models (Figure 2.7) and that also performed relatively well when ran over the historical period in the Pacific Northwest (Rupp et al., 2013). To save on computational time, we selected three climate models: CanESM2 (hotter, wetter), CNRM-CM5 (warmer, slightly wetter), and GFDL-ESM2M (less warm, drier), and ran each one for RCP 4.5 and 8.5 scenarios, which results in six total future climate scenarios (Figure 2.8). We also used a historical climate dataset, METDATA (Abatzaglou, 2013) to force our model in the historical period from 1980-2014. Table 2.4 provides a naming convention for these six future climate scenarios to ease in discussing results and implications.

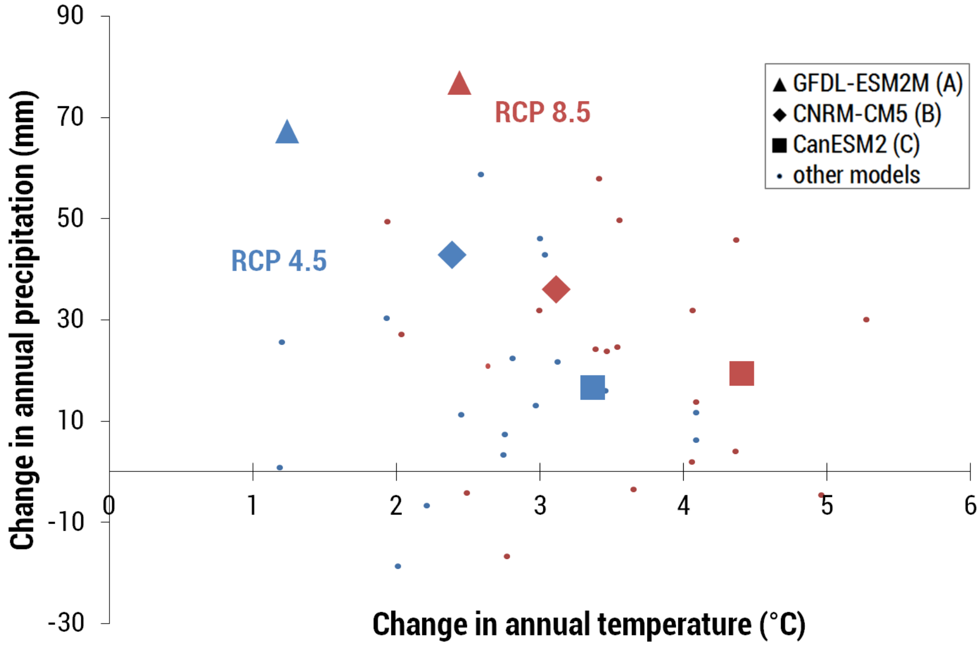

Figure 2.7: Change in climate variables from 1979-2000 to 2040-2069 for MACA downscaled GCMs (Abatzoglou and Brown, 2012). Blue and red points represent RCP 4.5 and 8.5 scenarios, respectively. The larger icons represent the GCMs selected for this study.

The downscaled variables Envision requires for Flow are daily maximum, minimum, and average temperature, precipitation amount, specific humidity, daily downward shortwave radiation, and wind speed. The datasets required minor processing (e.g. changing units, averaging variables, subsetting annually) to preprocess the files and variables to the format required by Envision.

Table 2.4: Naming convention for the six climate scenarios used in this study

	GFDL-ESM2M (warm)	**CNRM-CM5** (warmer)	**CanESM2** (warmest)
RCP 4.5	A-45	B-45	C-45
RCP 8.5	A-85	B-85	C-85

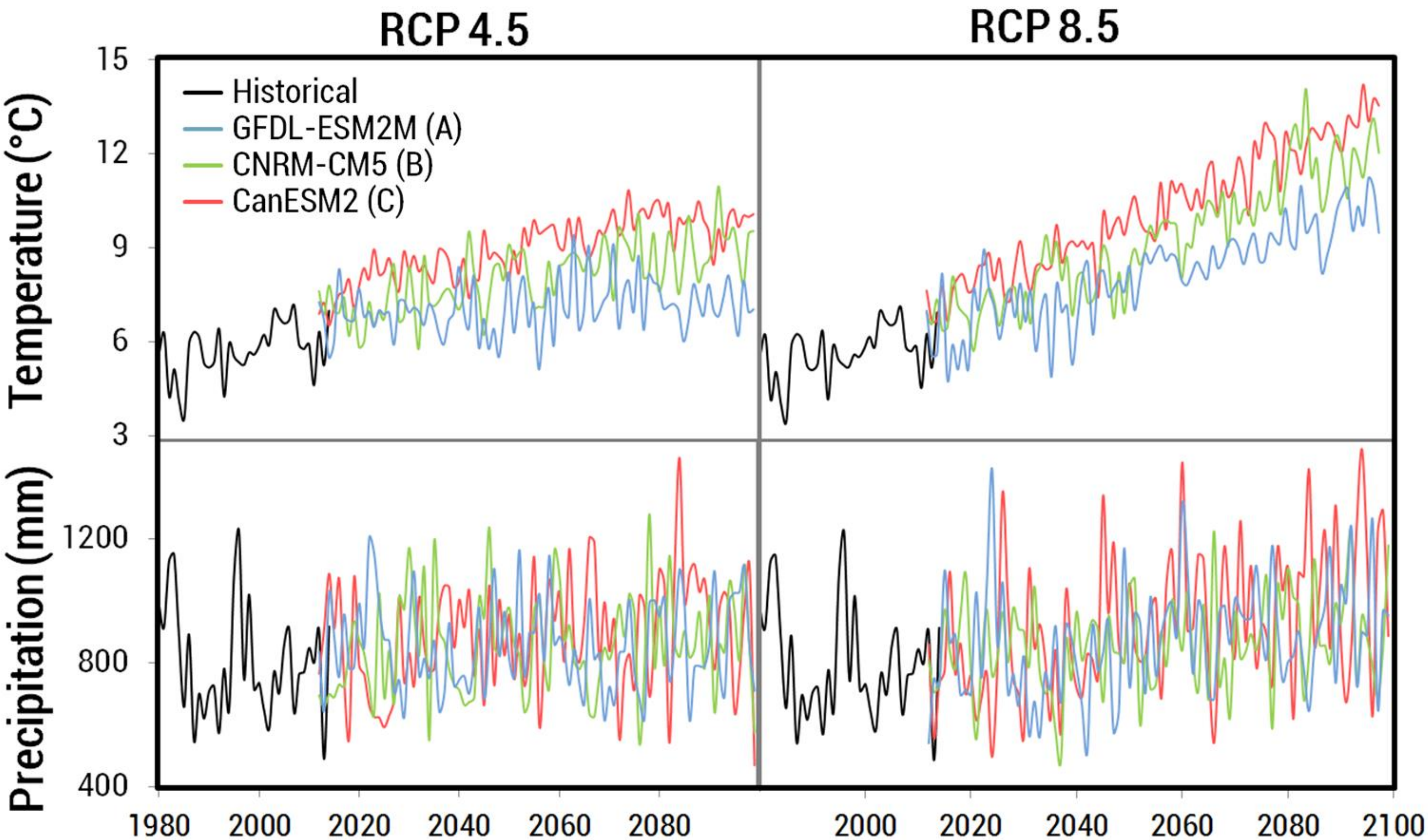

Figure 2.8: Temporal projections for annual mean temperature and precipitation for the six climate scenarios used in this study. Temperature increases in all scenarios, but precipitation is more variable.

2.4.3 Calibration and validation

HBV is a semi-conceptual model, and as such, is parameterized through calibration because most parameters cannot be physically measured (Bergström and Lindström, 2015). Numerous combinations of parameter values can yield equally good results (i.e. the equifinality issue; Beven, 2006; Gupta et al., 2005), which makes it difficult to select the best parameter set. To combat this issue, some studies (Madsen, 2003; Inouye, 2014) build an objective function to find an adequate parameter set based on the type of information they want to yield from the model (e.g. streamflow volume, timing, snowpack, etc.). Typically, the calibration-validation procedure takes the form of a data-denial experiment. The model is run over a calibration period to select best parameter sets, and then re-run over a validation period to ensure that the selected parameter set performs well during this period for which data was not used to calibrate the model.

Fourteen parameters are included within the HBV model and govern rates of exchange between reservoirs. We held five of them constant, while the remaining nine were calibrated. CFR and CWH are insensitive parameters and were held constant as is often done in HBV applications (Seibert, 1997). While many of the parameters are conceptual and cannot be measured, three of them are based on physical properties, so we fixed those parameters to better represent the reality of our study area. We used the Global Gridded Surfaces of Selected Soil Characteristics (IGBP-DIS) dataset (Hope and Peck, 1994) and took the average of values for the study area. We used the following datasets from IGBP-DIS: soil field capacity, soil profile available water capacity, and soil wilting point for the parameters FC, LP, and WP, respectively (Table 2.5). In each model run, we randomly selected the remaining nine parameters from a uniform distribution between ranges of possible values (Table 2.5) defined based on previous studies (Inouye, 2014; Han et al., 2017).

Table 2.5: Parameters for FLOW and the ranges/values considered for calibration

Routine	Parameter	Description	Units	Range	Value
Snow Routine	TT	Threshold temperature	°C	-0.5 – 2.0	1.335
	CFMAX	Degree-day factor	mm $°C^{-1}$ day^{-1}	1.0 – 6.0	1.489
	SFCF	Snowfall correction factor	-	0.7 – 1.2	0.568
	CFR	Refreeze coefficient	-	-	0.05
	CWH	Water holding capacity of snowpack	-	-	0.1
Soil and Evaporation Routine	FC*	Max depth of water in soil water reservoir	mm	-	399.7
	LP*	Soil moisture value where actual ET=PET	mm	-	247.2
	WP*	Wilting point in soil for ET to occur	mm	-	156.2
	BETA	Shaping Coefficient	-	1.0 – 6.0	2.015
Ground-water and Response Routine	PERC	Percolation coefficient	day^{-1}	0.1 – 2.0	1.272
	UZL	Threshold for K0 to outflow	mm	1.0 – 400.0	365.4
	K0	Recession coefficient	day^{-1}	0.1 – 1.0	0.339
	K1	Recession coefficient	day^{-1}	0.01 – 0.5	0.079
	K2	Recession coefficient	day^{-1}	0.001 – 0.15	0.004

*values obtained from ORNL DAAC SDAT

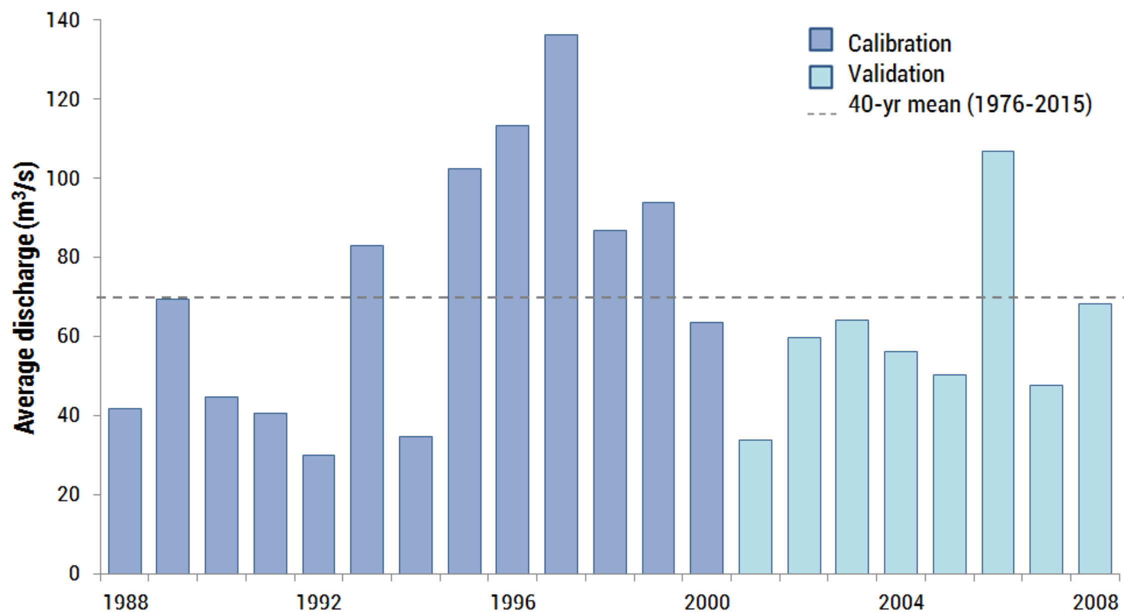

Figure 2.9 Average unregulated discharge at Lucky Peak over the calibration and validation years. Both wet and dry years are present.

We ran the model for 1000 simulations at a daily time step over the years 1988-2000 (12 years + 1 spin-up year). We selected this time interval for calibration because it encompasses a reasonably long time period that includes both wet and dry years (Figure 2.9). We compared model output to historical stream discharge records from three long-term USGS gaging stations and snowpack observations from nine SNOTEL (SNOw TELemetry) stations, omitting all leap days from these datasets (Table 2.6). For each run, we calculated the Nash-Sutcliffe Efficiency (NSE; Nash & Sutcliffe, 1970), log NSE, and a volume error (VE) using the following equations:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_{obs}^{t} - Q_{sim}^{t})^2}{\sum_{t=1}^{T}(Q_{obs}^{t} - \overline{Q_{obs}})^2} \quad \text{(eq. 3)}$$

$$logNSE = 1 - \frac{\sum_{t=1}^{T}(\ln(Q_{obs}^{t}) - \ln(Q_{sim}^{t}))^2}{\sum_{t=1}^{T}(\ln(Q_{obs}^{t}) - \ln(\overline{Q_{obs}}))^2} \quad \text{(eq. 4)}$$

$$VE = \frac{\sum_{t=1}^{T}(Q_{obs}^{t} - Q_{sim}^{t})}{\sum_{t=1}^{T}(Q_{obs}^{t})} \quad \text{(eq. 5)}$$

where Q_{obs} is the observed value and Q_{sim} is the simulated value at each daily time step. NSE coefficients range from -∞ to 1, with 1 indicating a perfect fit of the model to the observed data, and a value of NSE > 0 indicating the model is a better predictor than the historically observed mean. Typically, a model is deemed satisfactory if the NSE is larger than 0.5 (Moriasi et al., 2007). The logarithmic form of the NSE also ranges from -∞ to 1, but is more sensitive to low flow and still reacts to peak flows (Krause et al., 2005). The volume error provides insight into whether the model overestimates (VE<0) or underestimates (VE>0) total volume, with a value closest to 0 being ideal.

We created an objective function to select the best-performing parameter set and was developed based on work by Seibert and McDonnell (2002) and Inouye (2014):

$$Obj = \frac{1}{3}(NSE_G) + \frac{1}{3}logNSE_G + \frac{1}{3}(NSE_S) - 0.2 * |VE_G| \quad \text{(eq. 6)}$$

where NSE_G is the Nash-Sutcliffe Coefficient of discharge weighted by areal average of the gauges, VE_G is the volume error for the gauges weighted by areal average, and NSE_S is the averaged Nash-Sutcliffe Coefficient for SWE (snow water equivalent) for all SNOTEL sites.

The top 1% best performing parameter sets were run over the eight-year validation period (2001-2008) and the set that performed on average the best in both calibration and validation years was chosen for our model.

Table 2.6: Data sites used for calibration and validation. See Figure 1 for locations of gauges.

Type	Name	Drainage area (km^2)	Length of record	Site #
Gauge	a) Boise River near Twin Springs	2154.9	1911 – present	13185000
	b) SF Boise River near Featherville	1660.2	1945 – present	13186000
	c) Mores Creek above Robie Creek	1028.2	1950 – present	13200000
	d) Boise River at Lucky Peak*	6571	1895 – present	LUC
Type	**Name**	**Elevation (m)**	**Length of record**	**Site #**
SNOTEL	Atlanta Summit	2310	1981 – present	306
	Camas Creek	1740	1992 – present	382
	Dollarhide Summit	2566	1981 – present	450
	Graham Guard Station	1734	1981 – present	496
	Jackson Peak	2155	1981 – present	550
	Mores Creek	1859	1981 – present	637
	Prairie	1463	1987 – present	704
	Trinity	2368	1981 – present	830
	Vienna Mine	2731	1979 – present	845

*not an actual gauge, but a calculated daily average of runoff at this location if dams were not present. Obtained online from the US Bureau of Reclamation.

2.4.4 Center of timing of streamflow

The center of timing (CT) of streamflow, which is the date when half of the annual volume of water during the water year has arrived at a location, is another metric water managers and researchers examine. We calculate the CT for historical data and future simulations with the following equation (Stewart et al, 2005):

$$CT = \sum(t_i Q_i)/\sum Q_i \quad \text{(eq. 7)}$$

where t_i is the time in days from the start of the water year (October 1) and Q_i is the discharge for that date.

2.4.5 Day of allocation

Since 1986, water managers annually declare a day of allocation (DOA) in the Lower Boise River Basin for the purpose of water rights accounting during the irrigation season (April – October). This day is declared on or after the date of maximum reservoir fill and once natural flow is less than irrigation demand (Idaho Department of Water Resources, 2014). The DOA occurs after peak runoff and has been shown historically to typically occur once natural flow of the Boise River at Lucky Peak reaches below 4000 cfs (Garst, *in prep*), or 113.3 m^3/s (Figure 2.10a), which is roughly equivalent to the diversion demand of the river. It is beneficial for farmers if the DOA occurs later in the season because after the DOA is declared water rights begin to be curtailed, starting with the junior-most water rights holders. While the term DOA is unique to three major river basins in Idaho, many western states have similar methods for appropriating water as the irrigation season begins.

To predict how the DOA may change in our modeled scenarios, we assume that diversion rights will continue to be approximately 4000 cfs. We model our DOA date by finding the last day during peak runoff during the irrigation season that flow is greater than 4000 cfs and select the day after. We then manually observe the hydrographs and the DOA selected to ensure we are capturing a date on the downfalling limb of peak runoff and not a later season event. If a later season event was modeled, then we manually select the date on which modeled flow falls below 4000 cfs during the recession limb of spring runoff. We ran the model during the historical period to investigate how well the model reproduces historical DOA using this definition, which provides confidence in our interpretation of DOA changes in modeled future scenarios.

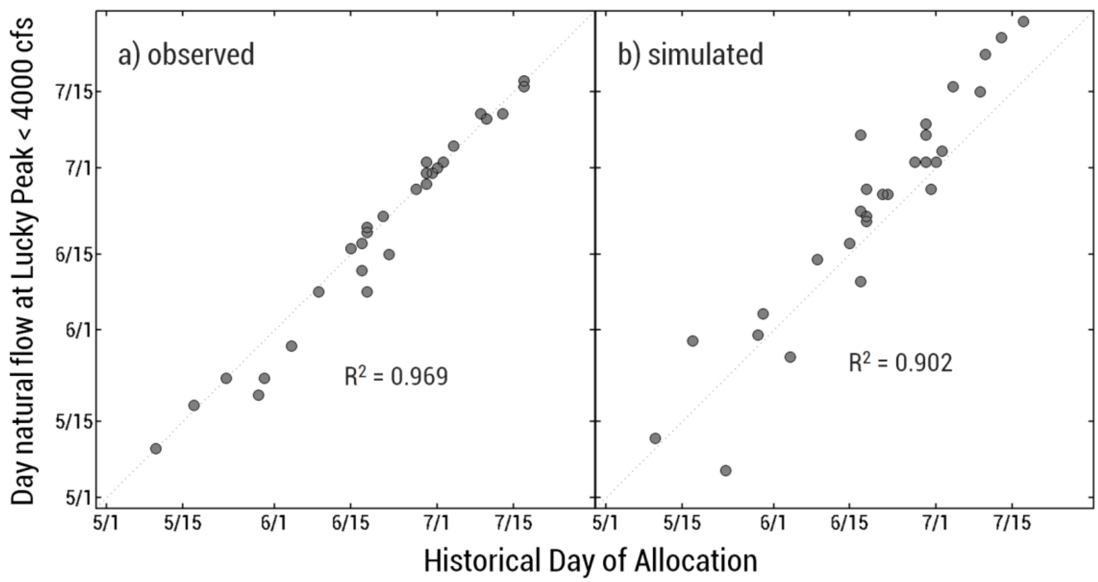

Figure 2.10: (a) Relationship between the day natural flow at Lucky Peak reaches below 4000 cfs and the date the day of allocation is declared, modified from Garst (*in prep*). (b) Our modeled historical day of allocation using the same method as (a). Dashed line is 1:1 in both plots.

2.5 Results

2.5.1 Calibration and validation

We calibrated and validated the model using historical records from three USGS gauges and nine SNOTEL sites. The parameter set that performed best had an objective function score of 0.63 and 0.62 for calibration and validation periods, respectively (Table 2.7). We averaged the NSE for each gauge by its respective drainage area, which resulted in a NSE of 0.71 and 0.70 for calibration and validation, respectively. However, it should be noted that Mores Creek on its own achieved a lesser NSE of 0.58, which is potentially due to this smaller watershed exhibiting some major differences from the other two (notably lower elevation, less precipitation, and less steepness).

Among all gauges, we see relatively good agreement between the model simulations and observed flow for the historic period (Figure 2.11), although the model frequently under predicts the magnitude of peak flows at all gauge sites and over predicts baseflow at Mores Creek. While the unregulated flow for the Boise River at Lucky Peak (Table 2.6) was not used to calibrate the model, we used this as an additional verification dataset to ensure accuracy of the model. With the chosen parameter set, we achieved a NSE at this site of 0.74 and VE of -0.01 averaged over the entire calibration and validation period.

Table 2.7: Calibration and validation results for top 1% of parameter estimation runs. The bolded row is the set that was selected for this study.

Calibration					Validation				
NSE_G	log NSE_G	VE_G	NSE_S	Obj	NSE_G	log NSE_G	VE_G	NSE_S	Obj
0.71	0.64	-0.10	0.64	0.64	0.64	0.61	-0.09	0.56	0.58
0.71	**0.61**	**-0.03**	**0.59**	**0.63**	**0.70**	**0.66**	**-0.06**	**0.52**	**0.62**
0.60	0.46	-0.01	0.52	0.52	0.50	0.50	-0.02	0.40	0.46
0.65	0.33	-0.23	0.63	0.49	0.69	0.52	-0.24	0.52	0.53
0.52	0.44	-0.12	0.55	0.48	0.42	0.54	-0.13	0.43	0.44
0.74	0.40	0.08	0.34	0.48	0.63	0.54	0.06	0.23	0.46
0.57	0.56	0.01	0.28	0.47	0.41	0.54	-0.02	0.13	0.36
0.57	0.51	0.06	0.35	0.46	0.43	0.51	-0.01	0.24	0.39
0.49	0.56	-0.09	0.39	0.46	0.31	0.54	-0.12	0.24	0.34
0.58	0.58	-0.32	0.39	0.45	0.44	0.56	-0.33	0.19	0.33

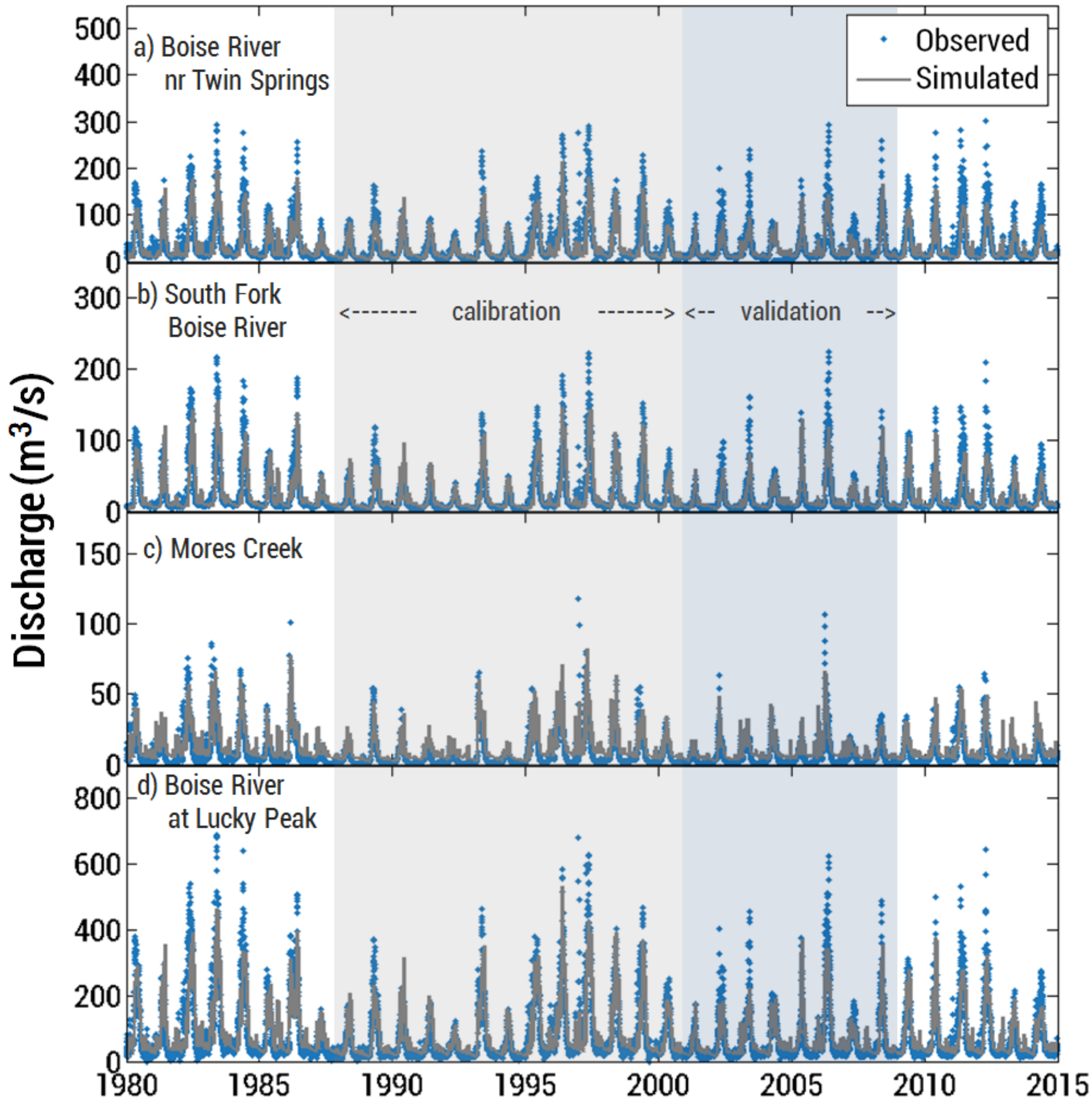

Figure 2.11: Observed and simulated streamflows during the historical period from 1980 to 2014. See Figure 1 for locations of sites. The model does a good job at simulating historical flows, but under estimates magnitude of peak flows and over estimates baseflow at Mores Creek

2.5.2 Streamflow

The following section describes characteristics of future streamflow output. In all cases, unless mentioned otherwise, the outputs are for unregulated discharge on the Boise River occurring at the location of Lucky Peak Dam's outlet.

2.5.2.1 Annual discharge

In all future climate scenarios, we see an increase in the median annual discharge from the Boise River (Figure 2.12). By midcentury (2040-2069), all climate scenarios showed an increase in annual discharge over historical (1950-2009) averages, with an average increase of 13% and ranges of increase from 6-24%. RCP 8.5 climate scenarios showed a greater rate of increase over RCP 4.5 scenarios. Because our hydrologic model did not perform well historically in accurately capturing the magnitude of peak discharges, we do not have adequate confidence to predict future magnitudes.

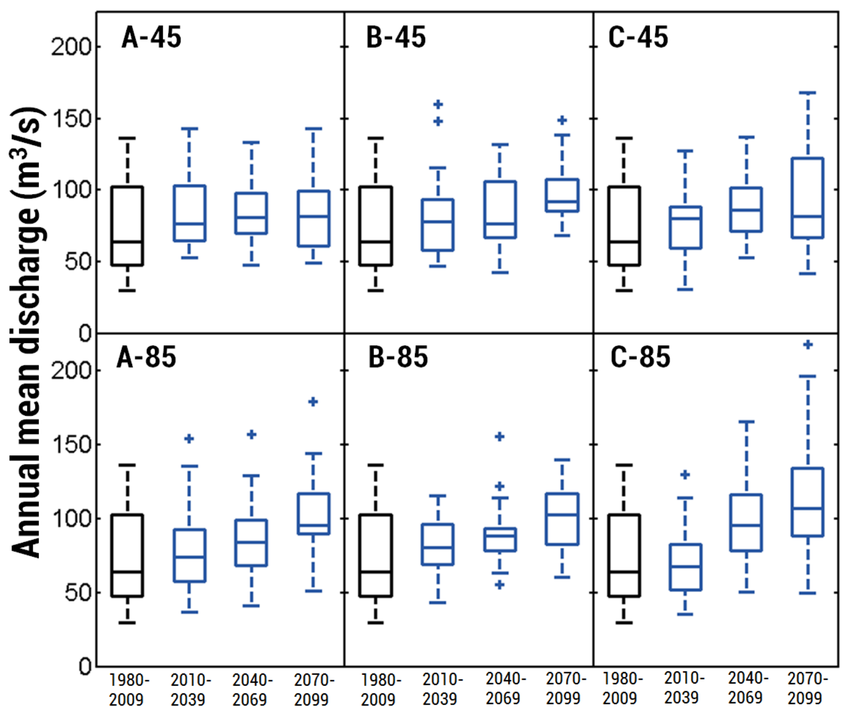

Figure 2.12: Average annual discharge of the UBRB. Values for 1980-2009 are observed. In most scenarios, we see an increase in overall discharge throughout the century. Boxes represent upper and lower quartiles and lines inside are the median.

2.5.2.2 Timing of discharge

While the volume of annual discharge does not change dramatically, discharge is projected to arrive at much different times than the historical past. However, these arrival times vary greatly between different climate models.

In all six future climate scenarios the date of peak discharge occurs earlier in the season, with an increase in early winter flooding events (Figure 2.13). In extreme climate cases (i.e. C-85), the average peak discharge occurs approximately 45 days earlier in the period 2040-2060 relative to 1980-2009. In a conservative climate model (i.e. A-45), peak discharge may only be on average about 5 days earlier by midcentury.

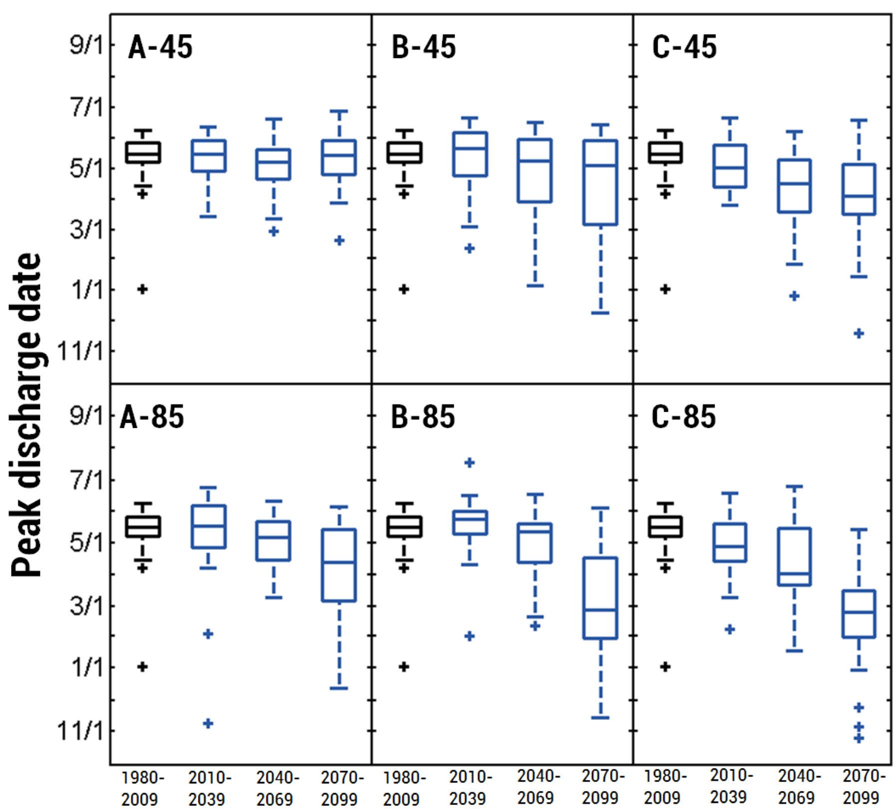

Figure 2.13: Date when peak discharge occurs for the Boise River at Lucky Peak. Values for 1980-2009 are observed. Overall, we see peak discharge date moving substantially earlier in five scenarios.

To get an understanding of the shift in seasonality and variance between climate scenarios, we can look at the multi-decadal averaged hydrographs between two endmember climate models predicting the least and most amount of change (Figure 2.14). With the coolest climate scenario (A-45), there is little discernible deviation from the historical average hydrograph. However, if we look at the warmest climate scenario (C-85), we see obvious differences in the average hydrograph, where by 2050-2070 the average peak of the hydrograph is over a month and half earlier. Additionally, this scenario shows greater peak magnitude of flows moving later throughout the century, and an increase in early season (December) discharge events.

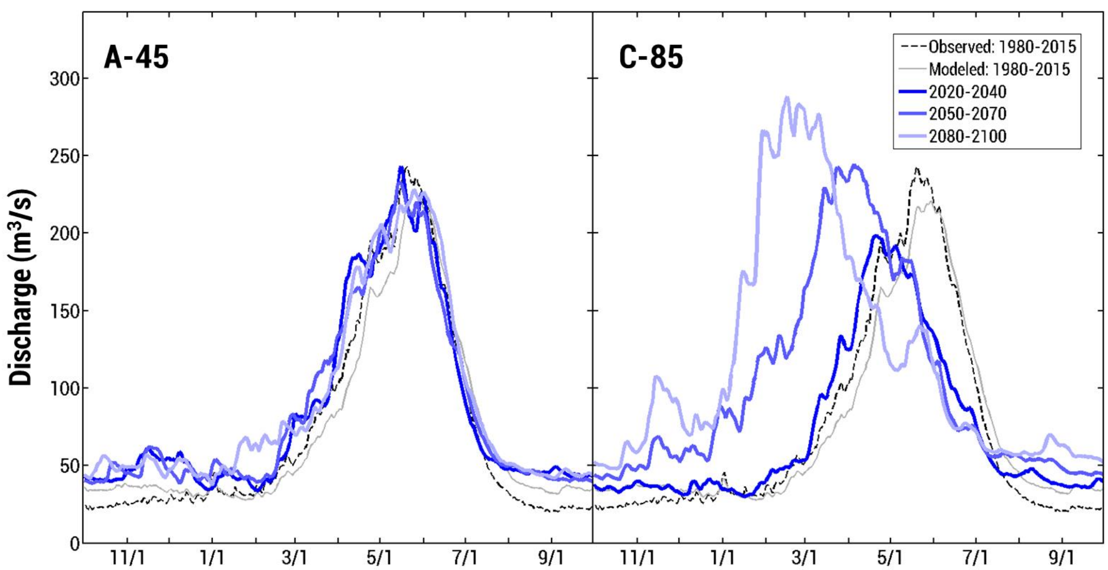

Figure 2.14: Hydrographs averaged over 2-decadal timespans for scenarios predicting the least amount of change (A-45) and the greatest amount of change (C-85) from historical.

2.5.2.3 Center of timing of streamflow

The historical average (1980-2009) center of timing (CT) of streamflow for the UBRB is April 22. In our simulations, we see this date shift earlier in most of our climate scenarios (Figure 2.15). Three scenarios (C-45, B-45, and A-85) experience similar shifts by deviating from the historical range of variability between 2040 and 2050 and experience a CT date between 2070 and 2099 that is 13-17 days earlier on average. Both C-85 and B-85 begin to deviate from historical averages around 2030 and average a CT date 27-30 days earlier than historical average from 2070-2099. A-45 remains relatively similar to historical ranges through the century, however, its CT date shifts a few days earlier, which results in fewer occurrences of exceeding the historical 75th percentile.

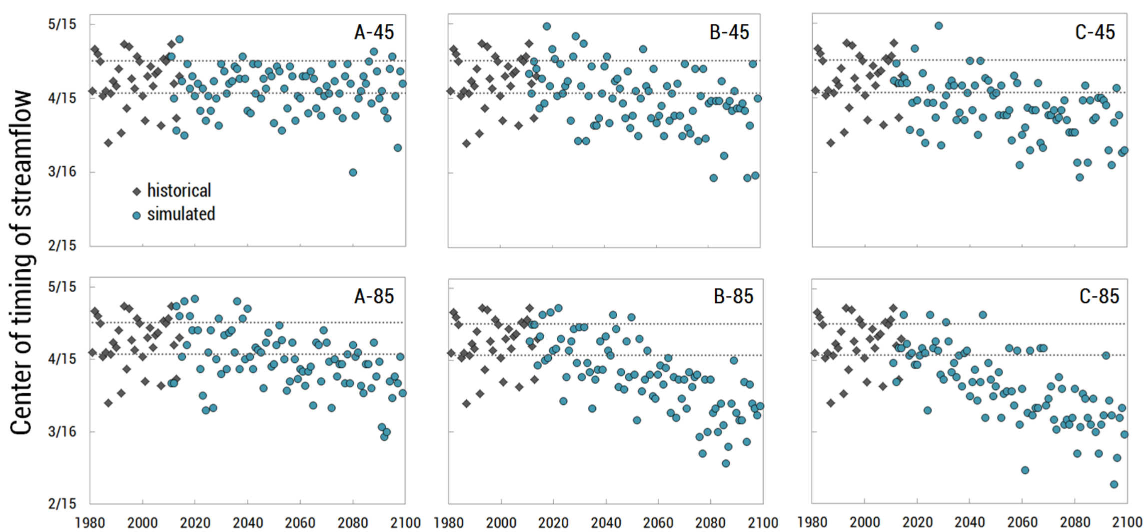

Figure 2.15: Center of timing of streamflow for historic and future simulations. Dashed lines show the upper and lower quartile ranges from 1980-2009.

2.5.3 Snowpack

The following sections describe how metrics of the snowpack will change under modeled scenarios. We show results in terms of averages over three elevation zones: low (1500-2000 m), medium (2000-2500 m), and high (2500+ m) zones. These zones cover 43.4%, 25.8%, and 6.9% of the area of interest, respectively. We do not show results for elevations less than 1500 m as the lowest SNOTEL station to aid in calibration is the Prairie site at 1463 m.

2.5.3.1 April 1 SWE

Historically, water managers have used April 1 SWE as an indicator for water availability throughout the rest of the water year, as it has correlated well with maximum SWE at many SNOTEL sites in the West (Bohr and Aguado, 2001). Our results (Figure 2.16) show a substantial decrease in April 1 SWE in five of the climate scenarios, with lower elevations essentially experiencing no April 1 SWE by midcentury. Higher elevations remain less affected across all RCP 4.5 scenarios, but begin substantially decreasing around 2050 in B-85 and C-85 where they experience virtually no April 1 SWE from 2080-2100. Under A-45 scenario, April 1 SWE experiences variability, but has no discernible downward trend.

2.5.3.2 Dates and amounts of maximum SWE

As shown in the previous section, April 1 SWE is not a good indicator of maximum SWE date moving into the future. Instead, we see the maximum SWE date happening earlier across most scenarios (Figure 2.17). Both C-85 and B-85 show maximum SWE occurring more than two months earlier on average by the end of the century. Three scenarios, A-85, C-45, and B-45 behave similarly with maximum SWE date happening between 38 and 42 days earlier than historically observed averages. A-45 produces little change in timing by the end of the century (7 days earlier on average). Within each scenario, the three elevation zones follow similar trends to each other with respect to how their change in maximum SWE date is changing.

The magnitudes of maximum SWE may change as well (Figure 2.18). Within mid elevation zones (2000-2500 m), we see a drastic decrease in occurrence of annual amounts above the historical 75th percentile in five of our climate scenarios. Furthermore, from 2050 onward, we see that 80% (C-85) and 84% (B-85) of the time the maximum SWE is falling below the historical 25th percentile. As with many of the metrics previously mentioned, A-45 shows very little change from historical trends.

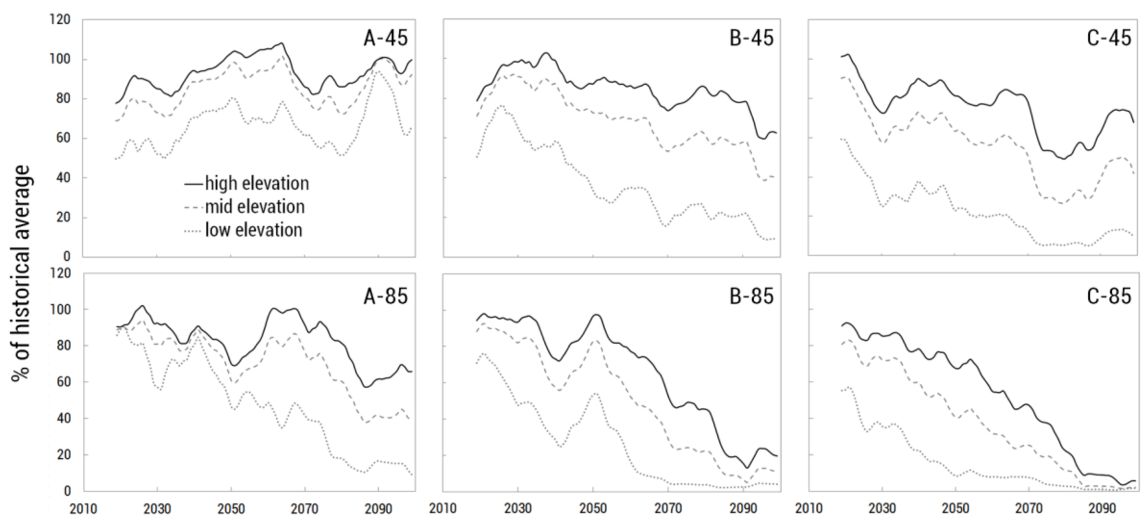

Figure 2.16: 10-year moving average percentage of April 1 SWE from historical simulated averages (1980-2009) for low, medium, and high elevation zones, corresponding to 1500-2000, 2000-2500, and 2500+ m, respectively.

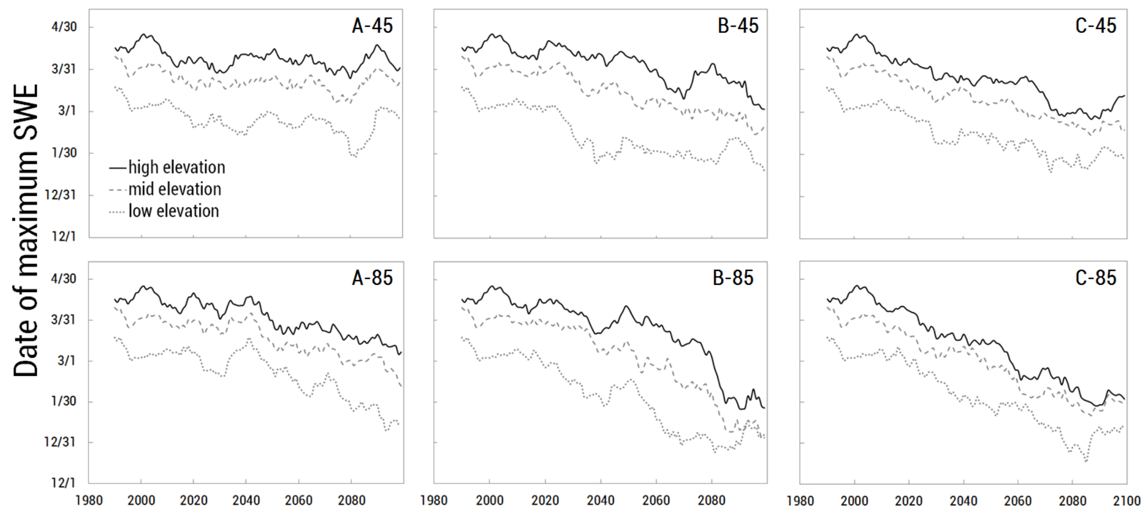

Figure 2.17: 10-year moving average of dates of maximum SWE for three elevation zones. Values for 1980-2009 are simulated with MACA METDATA.

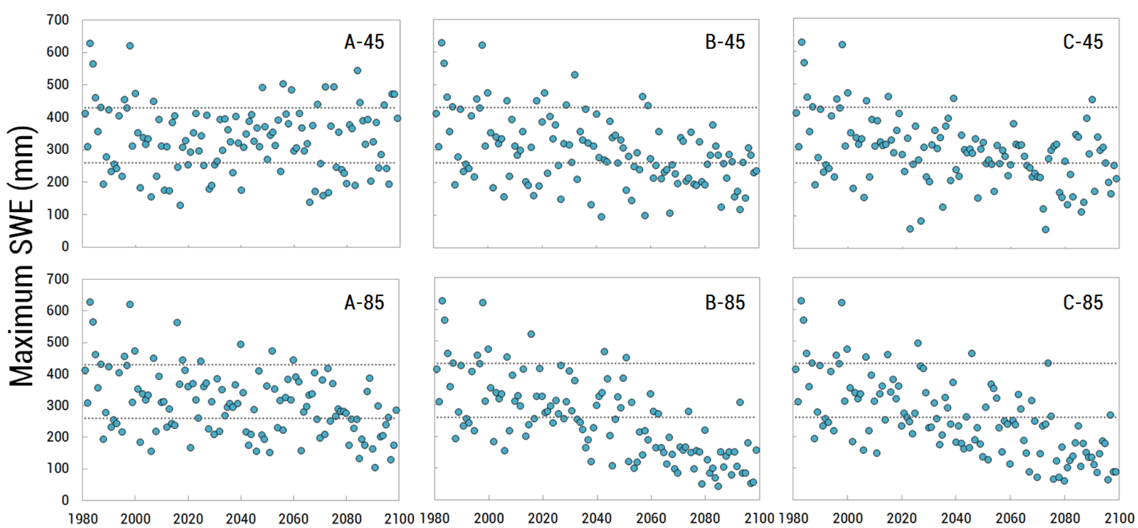

Figure 2.18: Maximum SWE amount (mm) for mid-elevations (2000-2500 m). Values for 1980-2009 are simulated with MACA METDATA. Dashed lines show upper and lower quartile ranges for 1980-2009.

2.5.4 Water management impacts

2.5.4.1 Day of allocation

The developed model reasonably reproduces the DOA in the historical period (R^2=0.90), although it over-predicted the date on average 4.8 days later (Figure 2.10b). Thus, the defined metric for the DOA provides a reasonably robust vehicle to analyze how DOA may shift under different climate scenarios.

Our results show the DOA occurring much earlier under four of our scenarios (Figure 2.19), ranging from 11 to 33 days earlier on average by the end of the century. Scenarios A-45 and B-45 resulted in little to no change in trend of DOA. While the DOA remains variable on an interannual basis, we do not see this variability becoming more or less intense through time (Table 2.8).

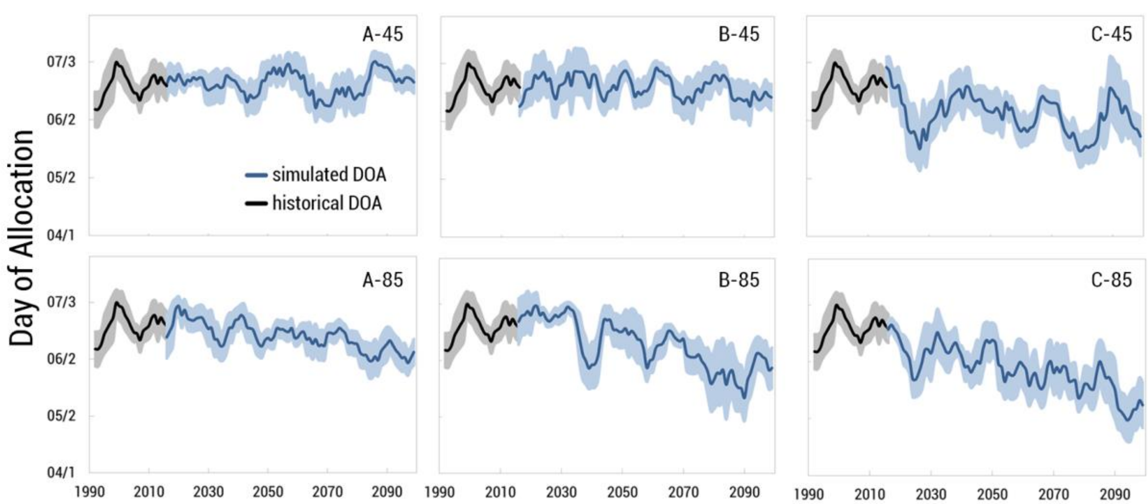

Figure 2.19: Future simulated (2010-2099) and historical (1986-2014) day of allocation with a 7-year moving average. Shaded area is +/– 0.5σ of 7-year moving average values.

Table 2.8: Simulated mean day of allocation (DOA) and standard deviation (italicized, in parentheses) over three future time intervals. Historical (1986-2014) average DOA is 6/19.

Time periods	A-45	B-45	C-45	A-85	B-85	C-85
2010-2039	6/22 *(12.0)*	6/21 *(20.0)*	6/10 *(24.3)*	6/19 *(17.1)*	6/20 *(20.6)*	6/10 *(19.0)*
2040-2069	6/20 *(17.3)*	6/20 *(15.3)*	6/7 *(16.8)*	6/15 *(13.1)*	6/15 *(17.2)*	5/30 *(23.5)*
2070-2099	6/23 *(15.1)*	6/18 *(16.1)*	5/29 *(24.0)*	6/8 *(14.9)*	5/27 *(25.6)*	5/17 *(23.5)*

2.6 Discussion

We calibrated our model using metrics that included historic snowpack levels, daily streamflow, logarithmic transformation of streamflow, and streamflow volume. Choosing multiple metrics to select the best parameter set provides some additional confidence that the model is simulating key attributes of historical hydrologic regimes and, therefore, strengthening confidence in the robustness of our interpretations of the implications of future climate change on hydrologic regime predicted by the model. However, HBV is a semi-conceptual model and represents hydrologic processes in a simplified way. As such, the parameters calibrated using historical climate may not realistically represent how the watershed may respond to future climate scenarios – a challenge that many climate change studies encounter. For example, HBV uses a temperature threshold to partition incoming precipitation as either rain or snow (Seibert, 1997). This temperature-threshold method has worked reasonably well historically for snow modeling, but is nevertheless a simplified proxy for more complicated processes of atmospheric energy and water mass balance. Therefore, calibrating for a temperature value that partitions incoming precipitation into either rain or snow may not be robust for future climate studies, as that proxy may not work well in a warmer climate. Despite the limitations of this type of modeling approach, the model nevertheless simulates historical hydrologic regime metrics reasonably well and provides robust indications of how climate change may impact historical flow regimes in the UBRB.

We have shown that a variety of hydrologic regime characteristics within the UBRB could exhibit significant changes, depending on which climate model and RCP scenario is used. It is impossible to know which climate scenario is more likely to reflect future climate change in the region, and it may be that future climate change in the area presents characteristics of all of the considered models and scenarios. Nevertheless, it is crucial to have improved understanding of the consequences stemming from a range of projected hydrologic regimes in the UBRB, together with continued evaluation of the accuracy of climate scenarios in the intermediate future. This is particularly critical in mountain watersheds that exhibit complex topography and vegetation characteristics where observational data are sparse to begin with.

Curiously, while each of the six scenarios produced different results, there were obvious similarities between them in how hydrologic regimes responded, such that we could classify them into three different groupings. Scenario A-45 remained relatively similar to historical hydrologic trends across all of the results we showed. Scenarios B-45, C-45, and A-85 produced significant changes from historical hydrology, but exhibited similar trends in timing and magnitudes of flows among each other. On the more extreme end, scenarios B-85 and C-85 exhibited the largest change relative to historical hydrologic regimes with regards to snowpack timing and amount, streamflow timing and amount, and day of allocation.

Our modeled scenarios support previous studies (Pederson et al., 2011; Klos et al., 2014) that April 1 SWE is not likely to remain a reliable metric for estimating maximum SWE (and therefore snow water storage) in the future for water resource prediction and management. This work suggests declines in the amount of SWE on April 1 and a maximum SWE date over a month earlier than historically observed in five of the six considered scenarios. Rather than choosing a static date to estimate peak SWE across a large region, managers may need to more closely monitor hydrologic regimes and the timing of peak SWE in their regions, potentially necessitating increased investment in monitoring of snow conditions.

There is little evidence to conclude that we will experience future water shortages from the UBRB in an absolute sense, as most models suggest at least a small increase in annual discharge. However, we will likely experience hydrologic shifts that are outside of our current range of variability. All climate scenarios show peak discharge occurring earlier in the year. This is problematic for reservoir managers who primarily manage dams to provide storage for flood mitigation. Managers might have to release more ‘usable’ water from reservoirs in preparation for these events, which could equate to shortages during the irrigation season. Such outcomes could be viewed as an “operational deficit” that arises because of a mismatch between the release of water from storage for flood mitigation and the timing of water allocation as codified in water rights laws.

At the same time, in this region agricultural land is increasingly transitioning to urban areas (Dahal et al., 2017), which could indicate that future water demand may be substantially different from the past. With warmer climates, farmers might plant earlier in the season, which would change timing of water demand. Recent modeling efforts have shown that current water rights are not always able to support irrigation demand (Han et al., 2017), however, agricultural water use efficiency is likely to increase with technological advances, which could lessen water demand. A more comprehensive examination of how, when, and where water is being used downstream and how that may change in the future will help managers understand to what extent regional water infrastructure is vulnerable.

Our results show that under most climate scenarios, the day of allocation occurs much earlier than it has historically, with two models showing the date moving by over a month earlier. If this projection becomes reality, then there is an earnest need for exploring potential conflicts between water users in the future. It may be necessary, for instance, to incentivize farmers to transition to more efficient irrigation practices (e.g. switching from flood to drip irrigation) and to diversify with crops that require less water. If junior water rights holders are curtailed over a month earlier without any mitigation practices set in place, it may result in substantial repercussions to Idaho's agricultural sector. These effects are compounded if other mountain water supply basins exhibit similar changes to hydrologic regimes.

It is worth noting that this study did not simulate reservoir operations. There are three dams present in the study area that are located close to the outlet of the basin. For purposes of simplicity, the present work focuses on evaluating the ramifications of climate change on natural flows in the UBRB and capturing reservoir operations outside the scope of study. A significant challenge in future work will arise from the need to develop plausible scenarios by which water managers from federal agencies, irrigation districts, environmental groups, and utility companies can create strategies to adapt to potential changes in hydrologic regimes similar to those simulated here. Given the complexities in both biophysical and social responses to climate change, such studies will likely need to be region- and context-specific.

An additional source of uncertainty in this study lies with the land cover data used in the hydrologic model, which was treated as static. Specifically, the land cover dataset used represents a snapshot estimated based on Landsat reflectances from 2011. Vegetation along ecotones is sensitive to changes in climate, and there are likely to be additional large-scale vegetation and land cover changes that occur after wildfire events or through management actions. Future modeling studies should incorporate plausible shifts in vegetation to understand the sensitivity of changes in hydrologic regimes to associated change in land cover as well as climate change. This might be best accomplished using a physically-based model, rather than conceptual, to be able to better capture complex interactions between climate, hydrology, vegetation dynamics, and changing land cover.

2.7 Conclusion

In this study we used a multiagent-based modeling framework, Envision, to simulate future hydrology in a mountainous watershed that supports an urban and agriculturally intensive region below it. We calibrated the hydrologic model to metrics of both streamflow and snowpack, and it performed well under historical conditions. We ran the model to year 2100 under six climate scenarios (three GCMs and two RCP scenarios) to analyze future possible hydrologic regimes.

Our results suggest that overall annual streamflow will increase, and five of six scenarios suggest the timing of arrival will occur substantially earlier. This could lead to operational water shortages later in the season as water managers balance release of water from storage in reservoirs to mitigate flooding hazards with retention of water for supplying irrigation in the warm, dry summers. This could have repercussions to late-season irrigation demand, hydropower operations, recreational flows, and municipal water supply.

Mountainous, snowmelt-dominated watersheds have already begun responding to climate change, which will almost certainly continue in the future. The degree to which the runoff response of these watersheds changes in association with climate change is uncertain, and will depend heavily on the nature of the change in the climatic forcing variables. Increasingly sophisticated comparisons with climate model predictions and observations, as well as regionally focused and contextual modeling of coupled hydrologic and social systems, will improve our ability to constrain how hydrologic regimes will change in the future. This may increase the efficacy of efforts to respond to changes and potential conflicts between potentially competing demands for water.

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3. TESTING THE SENSITIVITY OF HYDROLOGIC VARIABLES TO MODELED LAND COVER CHANGE WITHIN AN AGENT-BASED MODELING FRAMEWORK

3.1 Abstract

Land cover plays a significant role in different hydrologic processes, from altering evapotranspiration rates to changing surface energy fluxes. Improved projections of land cover are needed to understand how hydrologic regimes may change going into the future. However, few land cover projections exist at the scale needed for watershed studies and our hydrologic models may be unable to simulate key interactions occurring between land cover and hydrologic processes. In this chapter, we use an alternative future land cover from the FORE-SCE model as an input to our hydrologic model from Chapter 2 and run it under diverse climate scenarios. Our future land cover produces less evapotranspiration and more runoff, which stems from misclassification of high elevation regions between the FORE-SCE model and our initial land cover dataset, due to changes in the NLCD classification methodology. Even if the classifications were comparable, FORE-SCE does not explicitly model wildfire or vegetation response to climate, both of which will likely be major drivers of change in the western United States. With evapotranspiration being the only hydrologic process changing between land cover types in our model, we do not recommend our method to examine the entirety of the influences of land cover change on hydrology, and future work may find more success using physically-based hydrologic models. There is a need for cohesive land cover projections

in natural ecosystems that are attuned to drivers of change, both natural (e.g., climate, disturbance) and anthropogenic (e.g. management, invasive species) to better predict the sensitivity of future runoff response.

3.2 Introduction

Forested and mountainous watersheds supply water to approximately 4 billion people globally (Vörösmarty et al., 2005). However, the timing and magnitude of water delivery from these watersheds has already and will continue to change as the climate warms (Mote et al., 2005). Additional changes in vegetation and land cover, both human-induced and ecological response to climate change, further affect the runoff response of watersheds (DeFries and Eshleman, 2004). There is a need, therefore, to develop tools that predict the potential rate, magnitude, and uncertainty in future changes to land cover and the associated and coupled changes in hydrologic variables in a changing climate.

Changes in land use and land cover are known to affect various components of the water cycle (Brauman et al., 2007; Sterling et al., 2013). For example, urbanized areas are shown to produce less evapotranspiration (ET) and flashier stream hydrographs (Shuster et al., 2005), attributed to the lack of vegetation and increase in impervious surface area. Forested areas typically sublimate more snow compared to adjacent open areas due to increased interception (Gelfan et al., 2004) and frequently have a higher snowmelt rate (Lundquist et al., 2013). Post-fire, annual streamflows and flooding typically increase due to a decrease in evapotranspiration rates and increased overland flow resulting from hydrophobic soils and faster snowmelt rates (Luce et al., 2012, Gleason et al., 2013). Lastly, owing to the substantially different ET rates associated with different land cover types, some studies have suggested deforestation as a management strategy to temporarily increase local water supply (Ellison et al., 2012). While we can apply broad generalizations to how changing land cover affects hydrologic regimes based on arguments grounded in first principles, the specific response of hydrologic regimes to land cover change vary substantially from region to region.

The majority of western U.S. headwaters lie in forested mountain regions, with 65% of this region's water supply originating from forested lands (Brown et al., 2008). Forests are shown to provide clean, reliable water supplies (National Research Council, 2008), yet their structure and function is frequently altered through actions such as thinning, timber harvest, species migration, and wildfire (Vose et al., 2011). These changes in forested ecosystems influence water as it moves through the landscape by altering ET and interception rates, snowpack duration, and soil flow paths (Ford et al., 2011). Yet, the amount of change forests may experience in the future is uncertain and relies on many unknown variables.

Spatial patterns in vegetation and land cover on the landscape are almost certain to change in a warming world, both as ecosystems respond to altered patterns in climate and as humans seek to manage landscapes to adapt to a changing climate (Ford et al., 2011; Sohl et al., 2014; Shafer et al., 2015). Researchers and managers would benefit from plausible future projections of land cover to be able to forecast how environmental resources will respond. There have been several efforts to project future land cover change, although many of these models disagree on their projections and may not be well suited for specific regions (Sohl et al., 2016b). For example, more land conversion has occurred historically near populated centers resulting in models that tend to focus on conversion trends near those regions and less of land conversion occurring in settings perceived to be natural and/or undeveloped. Regional projections of land cover change developed by researchers with intimate knowledge of human- and natural-caused land conversion in a particular region, therefore, remain a critically important resource and a challenging endeavor.

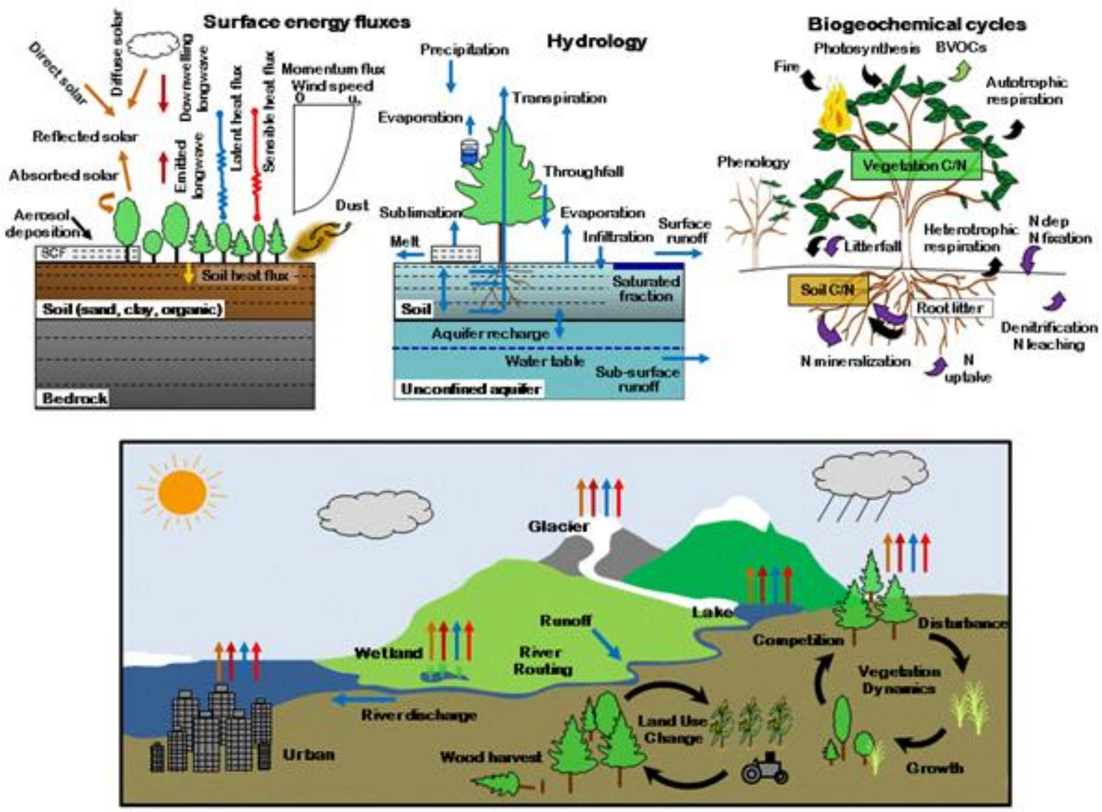

Figure 3.1: Overview schematic of the Community Land Model, obtained from http://www.cesm.ucar.edu/models/clm/

Even with robust land cover projections, there is substantial variation in how our hydrologic models couple land cover with hydrologic processes. For example, in sophisticated land surface models, such as the Community Land Model (Oleson et al., 2010), various fluxes and states are dependent on land cover (Figure 3.1). To name a few, land cover affects surface energy fluxes and net radiation to the landscape, and vegetation affects throughfall, interception, and canopy evaporation. However, most hydrologic models are not nearly as sophisticated, and for good reason, as they require less computing power and are more user friendly. While most common hydrologic models require land cover as an input to the model, changing the land cover type within these models may only affect one to two modeled hydrologic processes (e.g., evapotranspiration). Yet land conversion affects several hydrologic properties that are not correspondingly changed in many of these models when the land cover type is changed. It is therefore important to understand the limitations of both the projections of land cover as well as the limitations of the chosen model to represent the associated feedbacks to hydrology.

The overall objective of this chapter is to assess the sensitivity of hydrologic variables to changes in land cover under diverse climate futures. We approach this task by implementing a ‘future’ modeled land cover in the hydrologic model built in the Envision framework (described in the previous chapter) and subjecting it to the same climate change scenarios previously introduced. We analyze outputs at spatial scales ranging from point to the watershed to understand the sensitivity of our model predictions of hydrologic regime to changes in land cover. Specific objectives are:

1. Determine if there is a significant change in hydrologic variables when modeled with a future land cover projection;
2. Investigate if changes in hydrologic variables due to land cover change vary between contrasting climate scenarios; and
3. Assess the ability of the model and methodology to represent interactions between climate, land cover, and hydrology.

3.3 Study Area

We perform our study in the Upper Boise River Basin, Idaho (UBRB; Figure 3.2). We described important attributes related to hydrologic regime of the UBRB in the prior chapter. Here we would include additional information regarding land cover, focusing specifically on some of the major drivers of land cover change within the study area.

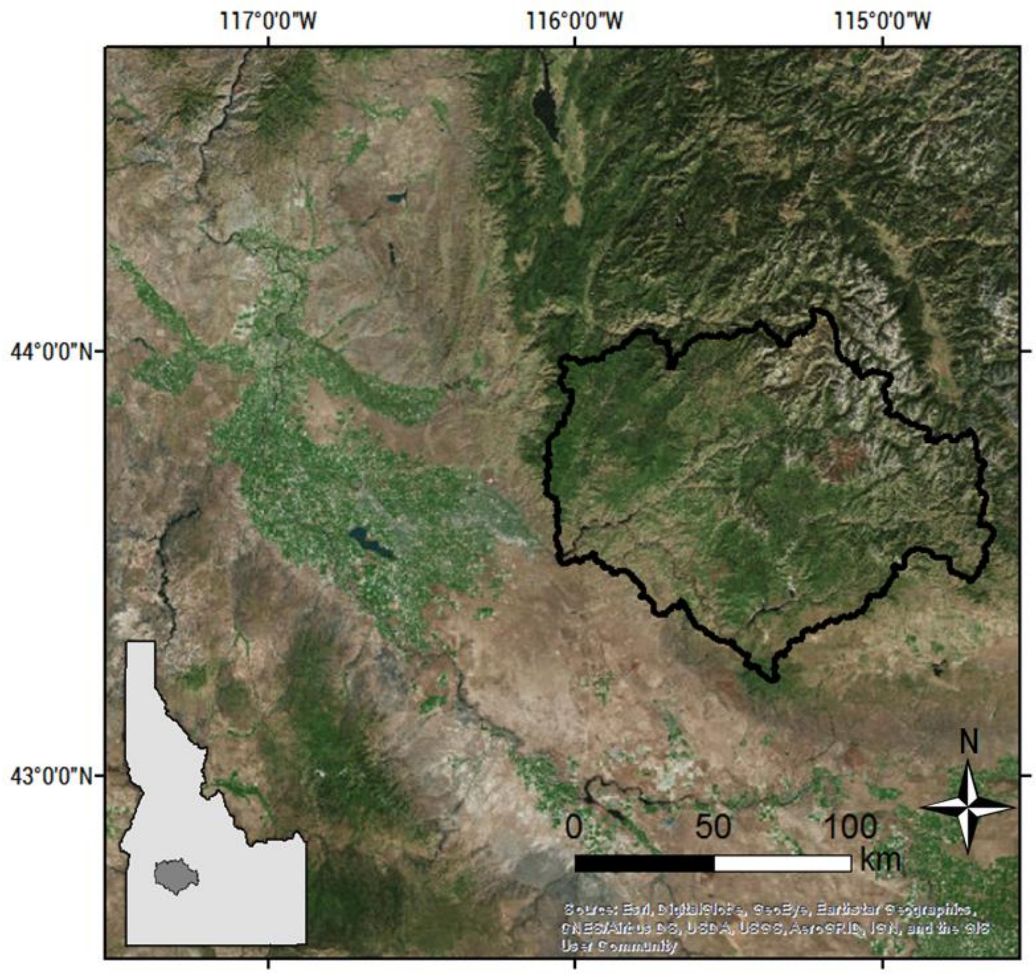

Figure 3.2: Location of study area (outlined in black). Note the large agricultural region to the west, as well as the sharp transition in land cover from shrub/grass to forest in the south.

Table 3.1: Percentage of land managed by different agencies in the UBRB

Managing agency	% of study area
U.S. Forest Service	80.8
Private	11.1
State	4.8
Bureau of Reclamation	1.6
Bureau of Land Management	1.3
Other	0.4

The UBRB is sparsely populated with the largest municipality, Idaho City, containing 485 inhabitants in 2010 (U.S. Census Bureau, 2010). The U.S. Forest Service (USFS) primarily manages the land, with jurisdiction over 81% of the region (Table 3.1). Some land-altering management activities that occur in the UBRB are timber harvest, prescribed burning, grazing, road and trail building, and large-scale wildland firefighting. The UBRB has a small amount of agriculture (0.4-0.5% of total area), mostly concentrated in the southern portion of the basin.

The role of fire affecting vegetative communities has been documented in previous studies (Lenihan et al., 1998; McKenzie et al., 2004; Hart et al., 2005) and likely one of the largest drivers of short- and long-term landscape change in this region comes from its extensive wildfire history. Over 2/3 of the study area has burned over since 1900, with ~56% burning since 1985 (Figure 3.3). There is a strong relationship between fire occurrence and warming temperatures within the study area, which has also been noted across the West by other studies (Westerling et al., 2006; Morgan et al., 2008) and fire areal extent is predicted to increase with further warming (McKenzie and Littell, 2017).

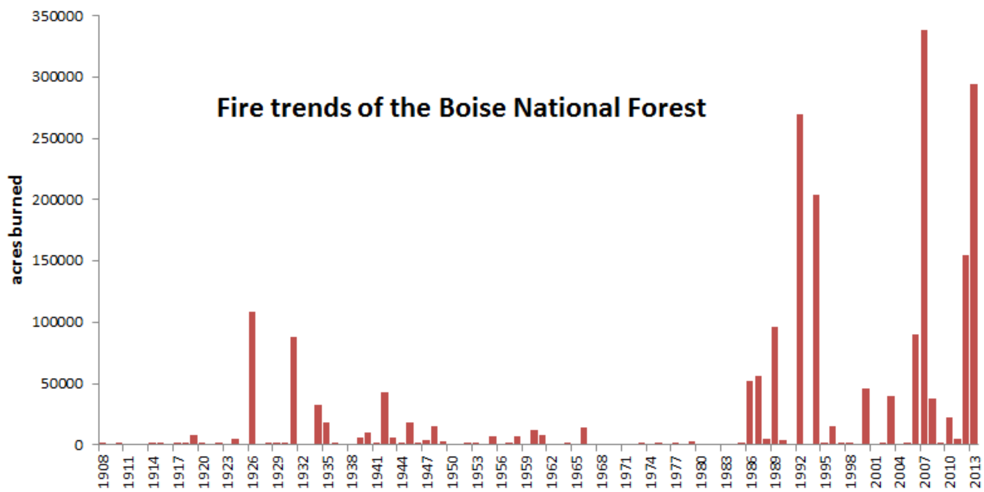

Figure 3.3: Annual fire-burned areal extent of the Boise National Forest, which overlaps over half of the study area but also extends northward outside the study area boundary.

3.4 Methods

3.4.1 General Overview

To test the sensitivity of hydrologic variables in our model to a different land cover, we selected 'future' land cover scenarios from an existing dataset (explained below) and ran the hydrologic model using the six previously described climate scenarios as input. We retained the same methods as the previous chapter with respect to setting up, running, and analyzing model predictions of climatic inputs. We also performed additional spatial post-processing to examine how spatial trends of hydrologic variables change. An overview of our model setup is shown in Figure 3.4 and methods specific to this chapter are discussed in the following sections.

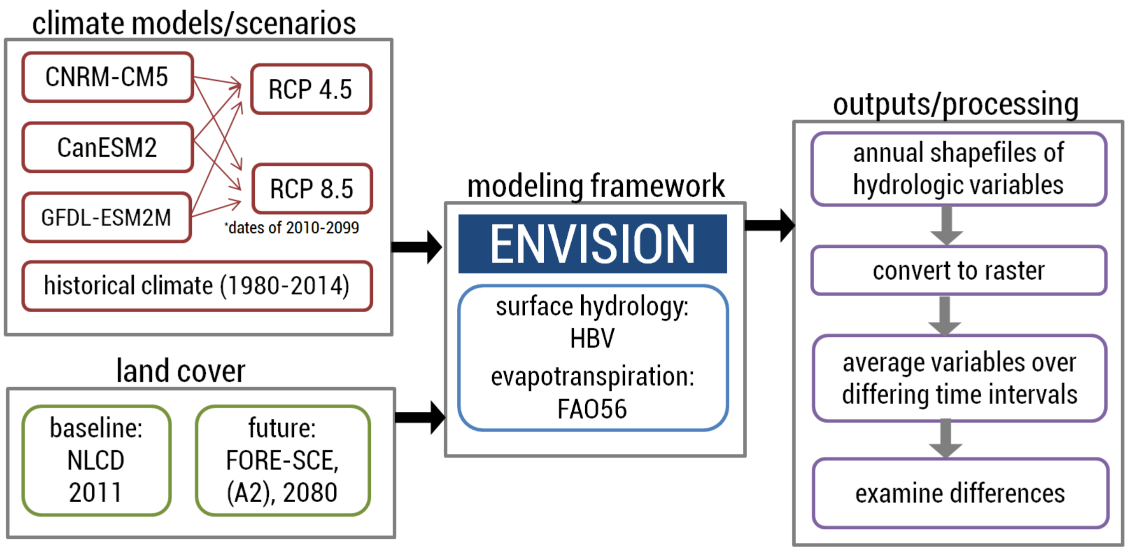

Figure 3.4: Flow chart of the methods employed in this study

3.4.2 Land cover change

To explore the sensitivity of the hydrologic model to changes in land cover, we used model output from the USGS FOREcasting SCEnarios of Land-Cover (FORE-SCE) model, which was developed to provide plausible, spatially explicit projections of annual land cover for the coterminous United States (CONUS). The model was created for applications in biogeochemical cycling, biodiversity, climate variability, and hydrology (Sohl et al., 2014) and has been used in a number of studies examining the role of future land cover on hydrology (Wu et al., 2013; Tao et al., 2014; Byrd et al., 2015; Rajib et al., 2016). Data is available annually from 1992 through 2100 at a spatial resolution of 250 m (Sleeter et al., 2012; Sohl et al., 2012, 2014). The model projects land cover change using a combination of biophysical and socioeconomic drivers (Figure 3.5) and uses land cover from NLCD-1992 as its baseline (i.e., initial condition) for future projections.

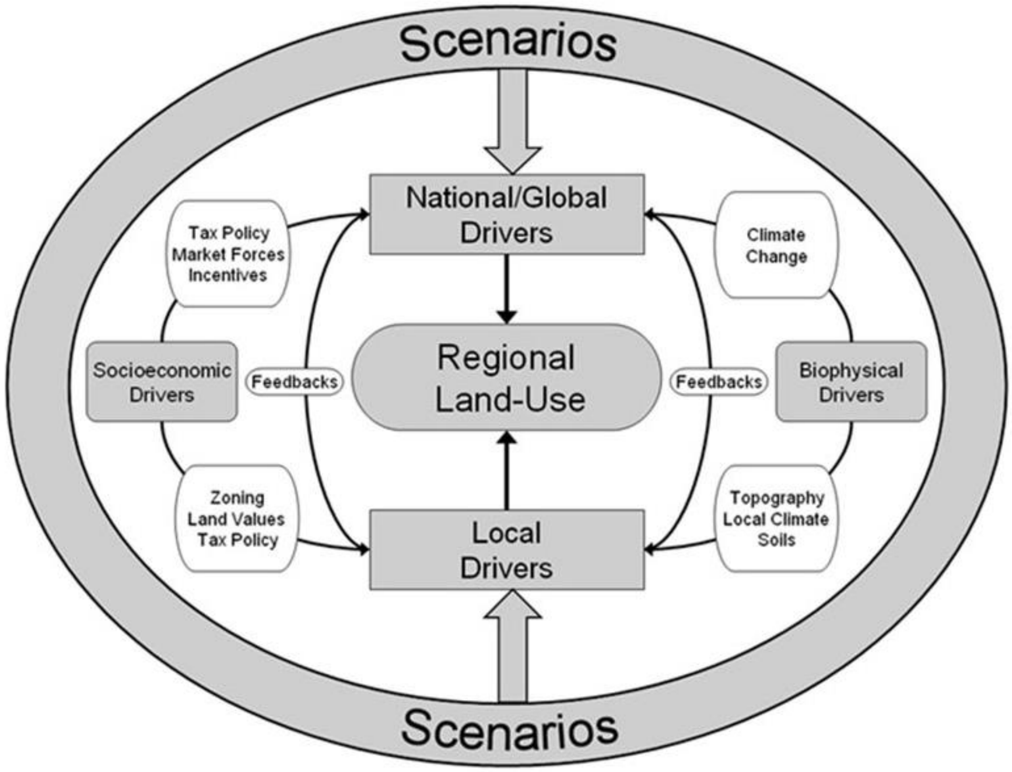

Figure 3.5: Overview schematic of the drivers of land cover change within the FORE-SCE model. Obtained from https://landcover-modeling.cr.usgs.gov

FORE-SCE was developed for four storylines (A1B, A2, B1, B2) from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) emission scenarios (IPCC, 2000), part of the IPCC Third Assessment Report. These SRES scenarios were created with narratives that contained assumptions about population growth, globalization, energy development, and societal values. For example, the A2 scenario describes a varied world, in which the fundamental theme is self-reliance and preservation of local identities. Global population increases and economic development is regionally oriented (IPCC, 2000). The climate science community has since adopted Representative Concentration Pathways (RCPs) to underlie future climate projections. RCPs are a consistent set of projections that are named according to their radiating forcing level at 2100 (e.g. RCP 8.5 = 8.5 W/m^2 net radiative forcing). The range of RCPs span the range of forcings as projected in the scientific literature and do not contain socioeconomic driving forces, narratives, or storylines (van Vuuren et al., 2011). While SRES and RCP scenarios are not the same, there are similarities between scenarios (Table 3.2**)** with respect to CO_2 concentration, radiative forcing, and temperature response (van Vuuren and Carter, 2014).

Table 3.2: Correlation of Relative Concentration Pathway (RCP) and SRES emission scenarios with respect to CO_2 and climate (van Vuuren & Carter, 2013)

RCP	SRES
2.6	- (post-SRES (E1))
4.5	B1
6.0	B2 / A1B
8.5	A2 / A1F1

To examine how different land cover would affect our hydrologic model, we selected to use the A2 scenario (analogous to RCP 8.5) and year 2080 FORE-SCE coverage. We created an additional IDU coverage with the same process described in the methods from the prior chapter. While FORE-SCE is based off NLCD data, its land categorization differs slightly from our classifications from NLCD-2011, but is reminiscent of NLCD-1992 classifications. To combat this, we grouped together FORE-SCE categories that were similar to the categories we used for ET calculations in the previous chapter (Table 3.3). The resulting FORE-SCE land cover IDU coverage was deemed our ‘future’ land cover.

Table 3.3: Mapping of FORE-SCE land classifications to the classification type used for ET calculations (see Table 2.3)

FORE-SCE classification	Classification for ET
Water	Water/ice
Developed	Developed
Mechanically Disturbed National Forests	Forest
Mechanically Disturbed Other Public Lands	Forest
Mechanically Disturbed Private	Forest
Mining	Barren
Barren	Barren
Deciduous Forest	Forest
Evergreen Forest	Forest
Mixed Forest	Forest
Grassland	Grassland
Shrubland	Shrubland
Cropland	Agricultural
Hay/Pasture land	Agricultural
Herbaceous Wetland	Wetlands
Woody Wetland	Wetlands

3.4.3 Spatial post-processing

In the previous chapter, we looked primarily at hydrologic outputs from a single location or averaged over large areas. In this chapter, we also quantify how hydrologic variables vary spatially with different land covers. In Envision, annual shapefiles can be outputted that contain information for each IDU polygon for variables such as runoff and ET. We converted annual shapefiles to rasters with a cell size of 250 m and averaged those rasters over various averaging windows. Using the time-averaged rasters we were able to examine the spatial distribution of differences in hydrologic variables through time under different land covers and climate scenarios.

3.5 Results

3.5.1 Annual outputs of hydrologic variables from watershed

3.5.1.1 Total discharge

In all cases, we see that the future land cover produces overall more annual discharge at the watershed's outlet than the NLCD baseline land cover (Figure 3.6), with an average increase of 3.0% across all climate scenarios. However, the coolest climate model (A-45) produces a smaller increase (2.8%) in annual discharge under the future land cover. We do not see noticeable trends of this percentage difference becoming lesser or greater through time.

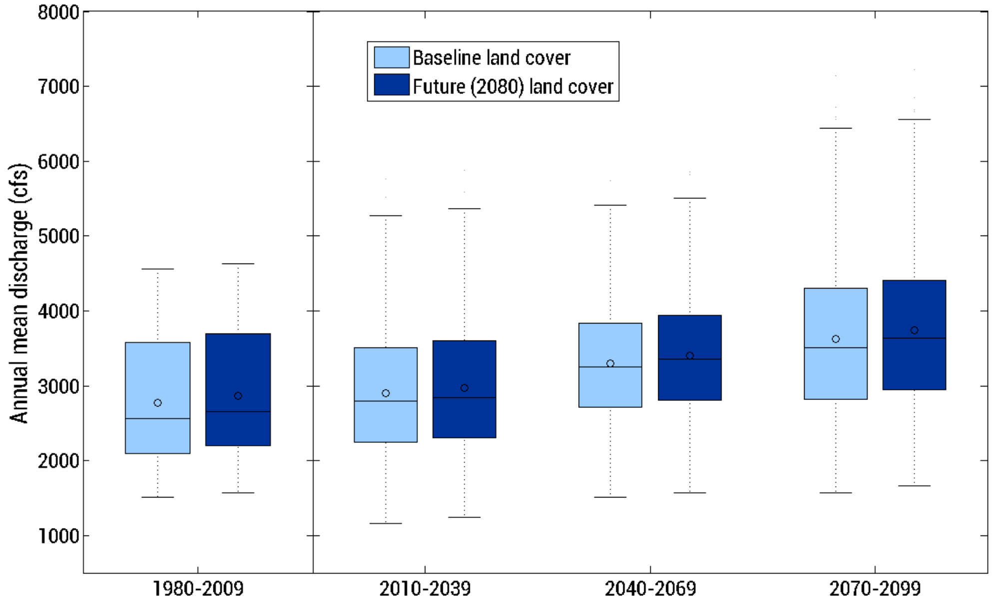

Figure 3.6: Boxplots of annual mean discharge at Lucky Peak averaged across all six climate scenarios for the two land covers. Boxes represent upper and lower quartiles, lines inside are the median, and the circle is the mean.

3.5.1.2 Total evapotranspiration

We see across all climate scenarios that our baseline land cover produces more ET when averaged across the entire watershed than the alternative future land cover (Figure 3.7), resulting in an average of 4.2% more ET across all climate models. This increase in ET associated with the baseline land cover is likely driving the associated decrease in discharge from that same land cover described above.

The changes in ET between two endmember climate scenarios (A-45 [coolest model] and C-85 [hottest model]) reveal the associated end-member behavior in the amount of change associated with changes in land cover. We see that the percentage change in ET between land cover scenarios does not change substantially between baseline and future land cover (Figure 3.8), even though through each 30-year time interval the C-85 scenario produces up to 1/3 more overall ET than the A-45 scenario.

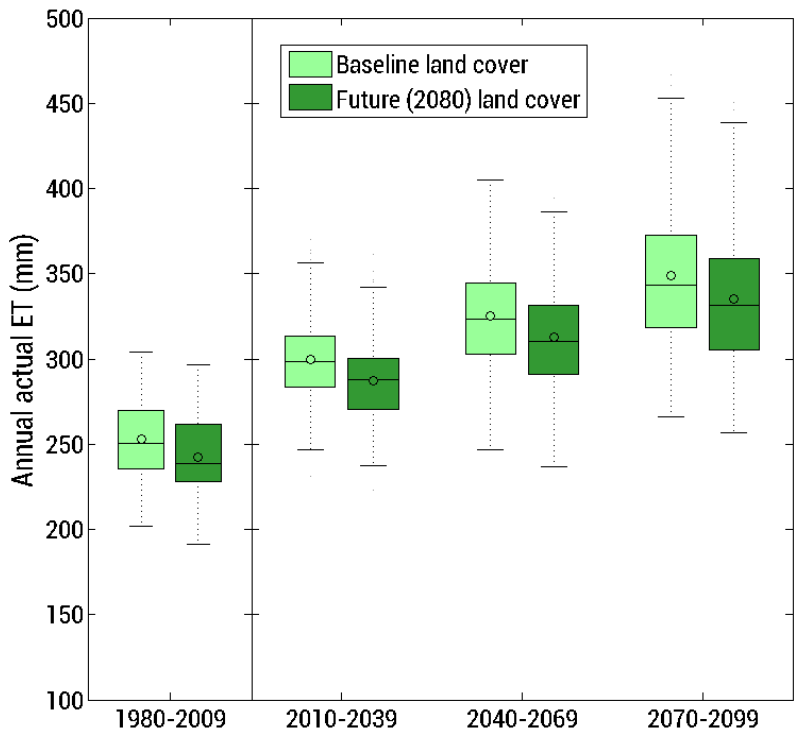

Figure 3.7: Annual evapotranspiration averaged across all climate scenarios for the two land covers used in this study.

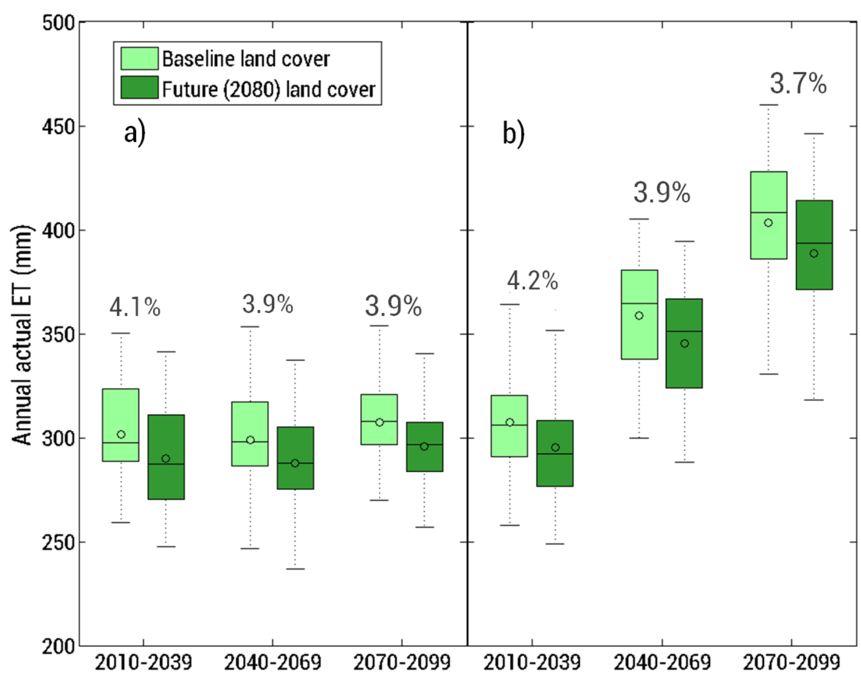

Figure 3.8: Average ET under climate scenarios a) A-45 and b) C-85. We see that under both climate end members, the 'future' land cover produces less ET.

These values, however, are integrated across the basin and associated spatial patterns may reveal important differences in the underlying spatial distributions of ET.

3.5.2 Spatial patterns of hydrologic variables

The previous section showed that spatially averaged ET and discharge vary between land covers. Investigating the underlying differences in modeled spatial patterns between land cover scenarios can provide additional insight into where and by what magnitude these variables vary. Again, this is accomplished by converting Envision shapefile outputs to a 250 m raster and calculating average values over specified integration windows on a per-pixel basis.

3.5.2.1 Runoff

Each IDU polygon stores the annual runoff volume generated by the model. We calculate the ratio of the runoff in the baseline scenario to the runoff in the associated future land cover scenario for each pixel. Since the climate forcings are the same between model runs, this corresponds to computing the ratio of the runoff generated within each pixel. The spatial distribution of this ratio of runoff volumes shows significant variability in the relative magnitude of runoff between the two land covers (Figure 3.9), but there are no real discernible patterns of this distribution.

To understand if runoff generation is affected differently by a change in land cover under contrasting climate scenarios, we examined spatial patterns under the least (A-45) and most extreme (C-85) climate scenarios (Figure 3.9). We see that the mean ratio of annual-average runoff within the basin means remain close to 1.0, but that there is a greater variability in the ratio of annual-averaged runoff between the future and

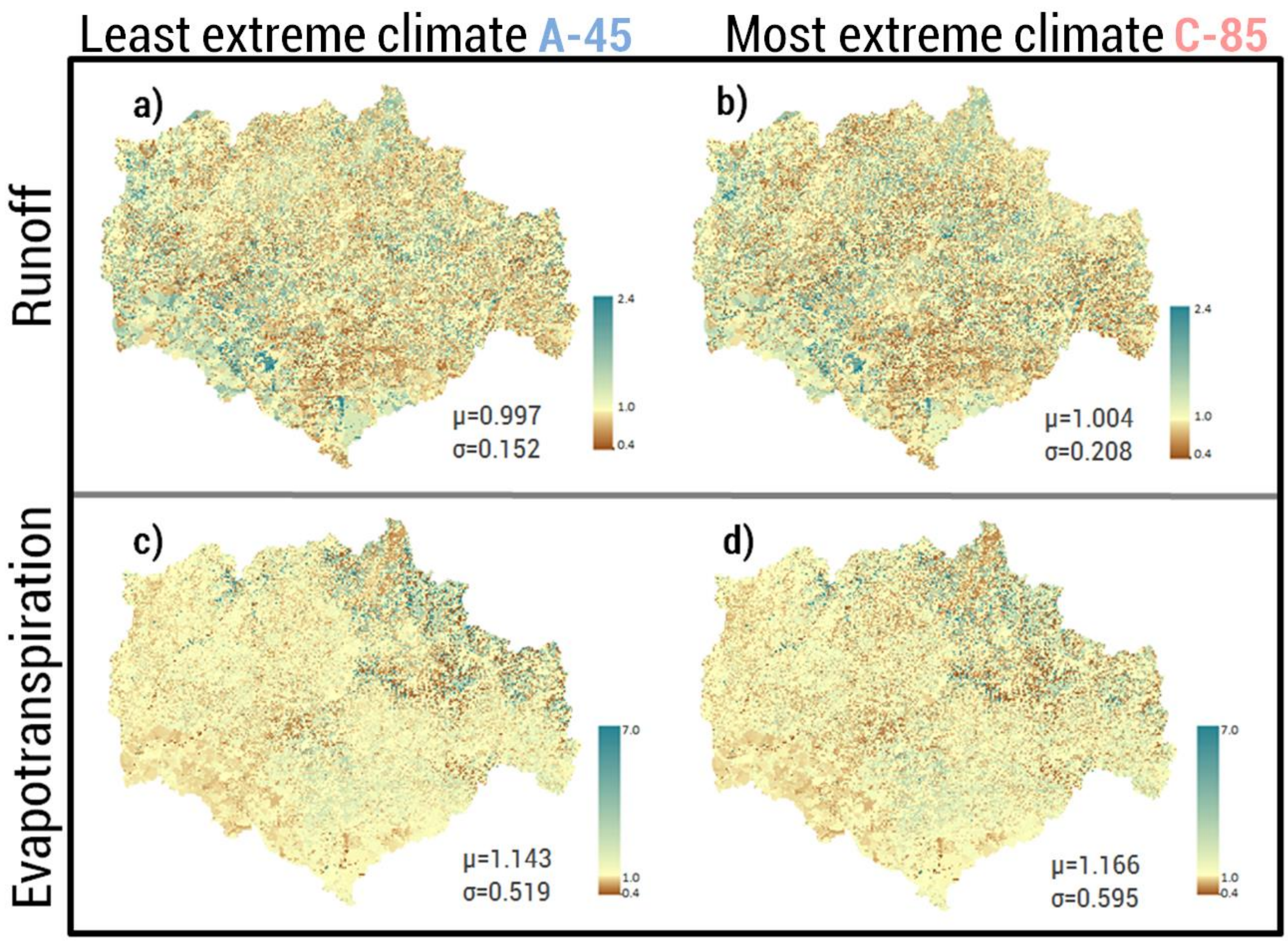

Figure 3.9: **Ratio between baseline and future land covers' spatial distribution of runoff (a,b) and evapotranspiration (c,d) averaged annually between least (a,c) and most extreme (b,d) climate change scnearios for 2010-2100. Values in the maps above 1.0 (blue) indicate greater runoff and evapotranspiration occurs within the baseline land cover.**

baseline land cover scenarios in the simulation with the more extreme climate model inputs (Figure 3.10). Performing a t-test to compare the means of the two distributions and the null hypothesis (i.e., that the mean of the two distributions is equal) can be rejected at the 0.05 confidence level, indicating the distributions are likely different.

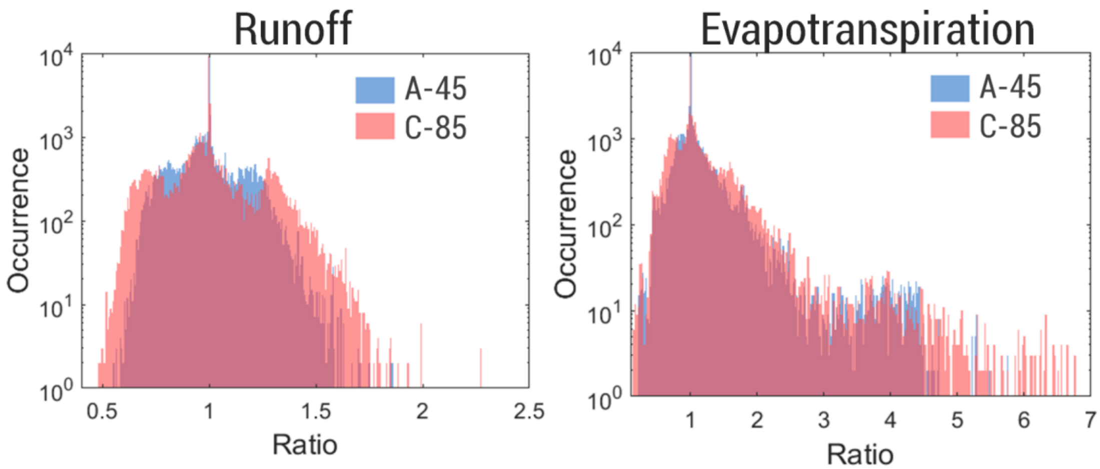

Figure 3.10: Histograms showing the distribution of values from Figure 3.9, with a) corresponding to ratios of runoff between contrasting climate scenarios and b) corresponding to ratios of evapotranspiration between contrasting climate scenarios.

3.5.2.2 Evapotranspiration

When we investigate the spatial distribution of the ratio of time-averaged ET in the baseline landcover to the time-averaged ET in the future land cover (Figure 3.9), we observe different spatial patterns than the associated patterns of the analogous ratio in runoff. Most noticeably, the high elevations in the northeastern portion of the watershed produce substantially higher values of ET in our baseline land cover. Lower elevations did not show as much of a change of ET values between land covers as runoff did. Where there were differences in lower elevations, however, they indicate that higher ET typically occurs in the future land cover.

Examining histograms of these ratios between the contrasting climate scenarios (Figure 3.10), there is less of a noticeable difference than the analogous histograms of ratios in time-averaged runoff. Visual inspection shows an increase in higher ET values occurring in our baseline land cover under the C-85 climate scenario. A t-test on the mean of these distributions of time-averaged ET ratios also rejected the null hypothesis at the 0.05 confidence level, suggesting the ratios are not drawn from the same underlying distribution.

3.6 Discussion

In this chapter, we assess the degree to which changes in land cover, as captured by an extant dataset that captures 'future' land cover, leads to significantly different hydrologic regimes when subjected to the same climate scenarios as the baseline land cover used in the previous chapter. We obtained our future land cover from the FORE-SCE model and we selected the year 2080 under the A2 SRES scenario. Across all time intervals, our future land cover produced less ET (~4% less) and more runoff (~3% more) than our baseline land cover.

Examining spatial patterns, we see that high elevations in the study area produced much less ET in our future scenario. After further investigation, we found that our baseline land cover (NLCD-2011) classifies this high elevation region as grassland, whereas FORE-SCE classifies it as barren (Figure 3.11). As previously mentioned, the FORE-SCE dataset used the 1992 NLCD dataset as an initial condition. Interestingly, this was the only vintage of NLCD data that classified this high elevation region as barren, which could be argued to be a more appropriate classification for this area, which is located high in the Sawtooth Mountains. Because of the differences between the 1992

NLCD and later years, it becomes apparent that comparisons between FORE-SCE and post-1992 NLCD are potentially problematic (Wu et al., 2013; Rajib et al., 2016) because of subsequent changes in the classification of land cover by the originators of the NLCD product.

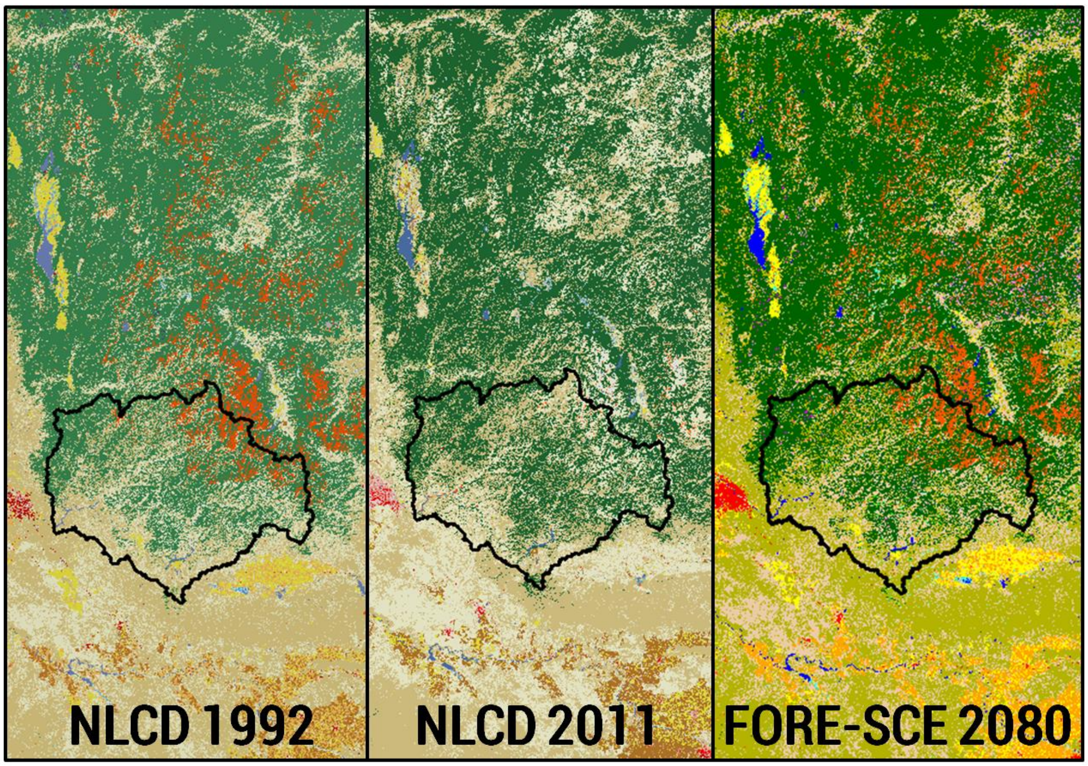

Figure 3.11: Classification maps for the study area and mountainous region surrounding it for NLCD 1992, 2011, and the FORE-SCE model. Dark orange area (seen in NE quadrant of UBRB and beyond) is classified as 'barren', which NLCD-2011 (and all post-1992 NLCD products) classify as 'grassland/herbaceous', creating a mismatch when comparing newer NLCD products with the FORE-SCE model. Ignore the difference in color scheme between NLCD and FORE-SCE products.

While some CONUS-scale land cover projections exist, such as FORE-SCE or ICLUS (Integrated Climate and Land Use Scenarios; Bierwagen et al., 2010), they typically are calibrated better or exclusively towards urban/agricultural areas. Nationally, these land covers have experienced large magnitudes of change in the historical past (Sohl et al., 2016b) and modeling algorithms are more attuned to their trends of change.

Because of the importance of mountain watersheds as the “water towers of the world,” however, researchers also need robust projections of land cover change that occurs in these environments. Some studies have attempted to project where different vegetation types could potentially exist in the future under different climate and fire regimes (Shafer et al., 2015; Sheehan et al., 2015), but these projections most frequently map “potential vegetation types” and do not account for human modification and management. How humans manage landscapes in the presence of longer and more intense wildfire seasons or under scenarios of intensified natural resource extraction can dramatically alter land cover. Additional understanding of the factors and drivers that go into decision making by land managers could aid in future efforts to make predictions of the future distribution of land cover, as is required by a number of regional climate and hydrologic models to assess the interaction between global climate change and associated changes in land cover patterns.

3.6.1 Limitations of the FORE-SCE model

We used the FORE-SCE model as our future land cover scenario. While this dataset has many beneficial qualities (i.e. spatial and temporal coverage, ease of access, built upon NLCD classifications), it may not be particularly well suited for studies such as ours. We discuss some of those limitations here.

- FORE-SCE uses both biophysical and anthropogenic drivers of change in its model algorithm. However, it currently does not have a linked model to explicitly model wildfire (Sohl et al., 2016a). As such, it misses drivers of change specific to this region, such as complex feedbacks between climate, wildfire, and landscape change.

- Additionally, FORE-SCE may be somewhat outdated. It uses SRES emission scenarios, rather than the more contemporary RCP scenarios, which are more commonly used by the climate science community nowadays. While similarities exist between these two scenario types, they do not map directly onto one another, which may hinder consistency of studies that use both.
- FORE-SCE was built off the classification categories and data from NLCD-1992. NLCD altered its classification for all releases post-1992, making direct comparisons for later products (i.e. 2001, 2006, 2011) challenging. Typically, it is beneficial to use the newest release of products, so in order to get a direct comparison to FORE-SCE output, it may be necessary to use an older NLCD product, despite acknowledged uncertainties in that older product.

3.6.2 Limitations of Envision to capture feedback between land cover and hydrology

Envision has the ability to apply different hydrologic models within its Flow extension. However, there are at present very few hydrologic models available to the user. The framework, as we understood and used it, is such that altering hydrologic parameters due to land cover change is not easily accommodated. Here we discuss a few key issues with our current hydrologic setup.

- The only hydrologic property that was directly altered between the two land cover runs was the amount of ET that occurred, which later affects other variables, such as runoff. However, we know that different land cover types can affect other hydrologic processes, such as snow accumulation and ablation, and soil routing. The model would be improved if some of these properties were manipulated between land cover types.

- We used the FAO56 method to calculate evapotranspiration. This method requires discrete values for ET parameters. However, land cover change may occur at a slower transition rate, so you may not be able to capture, for example, thinning a forest through time without parameterizing each tree density level. Additionally, the ET scheme itself is rudimentary because most ‘natural’ land cover types (i.e. evergreen forest) do not have crop coefficient curves built specifically for them. Instead, researchers have altered crop coefficients, stemming mostly from agricultural research, to estimate ET rates for a land cover such as an evergreen forest. While this method, or ones similar, are not terribly uncommon (Inouye, 2014; Rajib et al., 2016), there may be better approaches to parameterize ET for varying land covers (Oleson et al., 2010; Niu et al., 2011; Turner et al., 2017).
- The process of forming the IDU coverage for Envision is time consuming. Therefore, it is more efficient to work with models built within Envision’s framework, instead of using spatial output from another model as input for Envision, as we did in this study. While Envision has capability to explicitly model landscape change, moreover, there is little documentation and some models (i.e. DynamicVeg) are built using data sources that are only available for only the regions where they were initially applied.

3.7 Conclusion

In this chapter, we ran our hydrologic model from Chapter 2 using modeled future land coverage (FORE-SCE) as our input. We examined multiple-scale hydrologic regime variables to see if there were significant changes in hydrology when a future projected land cover was used. While our future land coverage produced less ET and more runoff, this was likely due to discrepancies in land classification from the two coverages (notably, classifying high elevations as either barren or grassland). We did see that under more extreme climate change scenarios, there was a greater divergence of change of hydrologic variables occurring spatially between the two land coverages. However, comparisons between FORE-SCE and post-1992 NLCD datasets are potentially misleading because of changes in the NLCD classification methodologies. More robust modeled projections of land cover change that are calibrated to specific drivers of change in the West (e.g. wildfire, land management) and models that can capture the feedback of land cover change to hydrological processes are needed to better predict the range and sensitivity of future runoff response.

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4. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

4.1 Project Conclusions

- Increasing temperatures and changing precipitation patterns are already altering runoff behavior in the western U.S., and will do so increasingly more as we move into the future. The extent to which hydrologic regimes will change largely depends on the degree of warming and the amount, timing, and phase of precipitation. Continued monitoring of climate variables, especially precipitation, and comparisons between model predictions will help constrain future climate projections.
- Generalizations for the hydrologic results simulated in this study suggest that we will have overall greater volume of water, earlier streamflow, reduced snowpack, a shortened snow season, and an earlier day of allocation. For the most part, the RCP 8.5 modeled scenarios resulted in a more dramatic version of the aforementioned results, which makes sense as the RCP 8.5 scenario represents a larger increase in anthropogenic forcings (+8.5 W/m^2), enhancing radiative forcing. Warmer temperatures can melt the snowpack faster, resulting in earlier streamflow. A warmer climate spurs more evaporation from land and water, and with the atmosphere's water-holding capacity increasing as it warms, this increases precipitation leading to an overall increase in volume of water, as seen in our results.

- Water managers will be increasingly challenged by larger flows arriving earlier than historically observed. As most western dams are managed first and foremost to mitigate floods, more water will need to be passed through these dams at an earlier date, potentially when it is not needed downstream. It will prove to be a difficult task for managers to balance the competing mandates of flood safety and storage for irrigation. Further, our day of allocation results suggest that current methods of water appropriation and the legal infrastructure underlying it may need to be revised as we increasingly experience earlier spring runoff. For example, some of our runs simulated the day of allocation occurring as early as the first week of April. With the irrigation season defined as April 1 to October 31, it will be a challenge to manage water resources if this season is not flexible.
- The majority of water managers rely on statistical models to predict the timing and magnitudes of streamflows, which guides their management decisions. This is problematic as our climate is nonstationary and increasingly no longer resembles the historical range of variability. Some managers use index dates and metrics (e.g. April 1 SWE as a proxy for maximum SWE) to estimate the amount of streamflow for the upcoming runoff season, but with changing hydrologic regimes, those dates and metrics lose credibility. Other managers may use "similar years" to estimate upcoming runoff behavior (i.e. looking at past records for a hydrologically similar year), which becomes increasingly problematic as we experience record years that have no analog in the historical record. These current methods that rely on historical statistical relationships will not be suitable for

predicting runoff behavior moving forward and other methodologies should be explored, such as physically modeling the snowpack.

- The hydrologic model used within the Envision framework has some fundamental limitations that make simulating interactions between land cover and hydrology challenging, and conceptual models in general may not be a good tool to look to examine these interactions. For example, in our model the only parameter altered with changing land cover was evapotranspiration. There exists large amounts of field data showing how different land cover produces changes in hydrologic processes, however, it is difficult to incorporate that data into a conceptual model, whose parameters are calibrated for and immeasurable.
- Comparisons between FORE-SCE and post-1992 NLCD products are potentially problematic as their classification methodologies are not the same. However, the amount of mismatch may vary depending on geographic area of interest and the types of land cover present. Additionally, the FORE-SCE modeled land cover projections are likely not a robust projection for the mountainous, western United States, as there is no explicit wildfire model or species-distribution model, which are likely the largest drivers of future change in managed landscapes in this region.
- There exists a breadth of research in how demographics (e.g. sex, income, education) influence private land management (e.g. agriculture, private timber owners), yet there has been little assessment of the extent to which the conclusions reached by those researchers could be transferrable to public land managers. With the federal land management workforce diversifying in gender,

educational background, and expertise in recent decades, we hypothesize that demographics likely play an increasingly significant role in how land managers manage the land.

4.2 Recommendations for future work

- Chapter 2 simulated future hydrology under six future climate projections. Future work should consider incorporating a greater number of GCMs under different downscaling techniques as inputs to a variety of hydrologic models. Interesting questions could be asked when comparing different types of downscaling methods (e.g. Can we better predict magnitudes of peak flows with dynamically downscaled climate forcings?). As computations become increasingly more efficient, we may begin to explore some of these questions in the future and would allow a better estimate of the range, likelihood, and uncertainty of future runoff response.
- Water managers and users are likely to adapt in some fashion as regional hydrology changes. Future work should focus on how different stakeholders (e.g. dam owners/operators, irrigation districts, farmers, policy makers) would work together to adapt to the types of changing hydrologic regimes we have simulated in this study.
- As a hydrologic model has been developed to simulate water rights in the lower basin, a future project could link the outputs from this study, apply different water management techniques (informed by activities suggested above) to link the upper and lower basins and test different types of adaptation strategies towards future hydrologic regimes.

- Envision is a powerful modeling framework with substantial capability for complex social-ecological systems studies, yet, there is little documentation to aid in implementing many of its models. If selected for future work, it should involve a team of dedicated researchers, including software developers, to be able to use it more effectively.
- While we had previously tried to examine the role of fire on hydrology, we struggled with the structure of Envision to alter hydrologic properties other than adjusting ET parameters. We know there are many feedbacks to the hydrologic system post-fire (e.g. hydrophobic soils, increased snowmelt), and future work should consider incorporating some of those processes into a hydrologic modeling framework, potentially a physically based one.
- As stated in Chapter 3, our conceptual hydrologic models may not be well suited to assess the feedback between land cover and hydrology. Future work should try to design studies such as this one using physically-based models.
- While a few CONUS-scale land cover projections have been developed, they vary in spatial and temporal resolution, as well as the type of land conversion processes they can represent (e.g. emphasis on urban development vs. biophysical processes). Future research should work to develop ecoregional-scale land cover projections that are based on both biophysical and anthropogenic drivers of landscape change.
- A better understanding of the internal and external drivers that affect public land management will help aid in producing land cover projections on western landscapes, which are largely managed publically. Drawing on a breadth of

literature that suggests demographics plays a large role in how private land managers choose to manage their land, this topic should be researched more in-depth for the public land managers.

- Lastly, as we approach problems regarding future water management, which is inherently a complex, interdisciplinary problem; future work should increasingly incorporate researchers and stakeholders from a diverse set of backgrounds to better achieve future water security.

APPENDIX A

How do public land managers decide to manage their land?

A synthesis on current literature and the factors involved in decision-making

LIST OF ABBREVIATIONS

EA	Environmental Assessment
EIS	Environmental Impact Statement
NEPA	National Environmental Policy Act
USDA	United States Department of Agriculture
USFS	United States Forest Service

A.1 Abstract

Scenario and alternative future modeling studies have increasingly become more widely used by scientists and planners alike, and in order to make plausible scenarios, there needs to be an understanding of the driving forces behind a system. In order to project and create scenarios about how land cover in the western U.S. may change as we head into the future, we must examine how our public lands may be affected, as they make up a large areal extent in this region. However, the factors that drive decision-making in land management are not well understood, especially as it relates to individual level decision-making. Here, I propose four major areas of concentration that largely influence public lands decision-making (policy and politics, environmental, local sociocultural dynamics, and employee demographics) and highlight the need for further research to better understand how and why decisions are made across a breadth of scales.

A.2 Introduction

Federally managed public lands make up nearly one-third of all lands in the U.S. and nearly half of all lands in the West alone (Gorte et al., 2012). These lands perform many key ecosystem service,s including climate and water regulation, nutrient cycling, carbon sequestration, timber, food, and cultural and recreational opportunities (Millennium Ecosystem Assessment, 2005). As such, there would be a detrimental consequence associated with degradation of these lands.

The consequences stemming from present and future climate change pose an increased risk to the productivity of public lands in the western U.S. Within this region, numerous impacts of climate change have already been observed on the landscape. Since the 1980s forests have experienced greater large-areal extent fire frequency, longer-burning fires, and increased wildfire seasons (Westerling et al., 2006). Additionally, forests globally have been experiencing effects from climate with forest die-off occurring due to extreme temperatures and increased mobility of insects and pathogens (Anderegg et al., 2012).

One method to better understand and predict how landscapes might change as we move into the future is called scenario modeling, which has been widely used and has had positive reception with stakeholders (Peterson et al., 2003; Tang et al., 2005; Turner et al., 2015). This type of modeling tries to understand the driving forces behind a system and to what extent variations in those forces have an effect on the system. This is accomplished by first researching the system in-depth and then creating potential scenarios that represent plausible trajectories. These scenario analyses do not attempt to predict what the state of the system will be in the future, but allows for planners to understand the scope of potential 'future worlds' that can aid in planning and decision-making in the present.

For studies that examine the resiliency and direction that public lands management might take into the future, scenario modeling can be a useful tool. However, little work has been done to understand how and why land managers make the decisions they do. Here, I propose that there are four overarching categories of factors that may affect public land management decision-making and discuss them within the context of the U.S. Forest Service. The four overarching factors are (1) policy and politics; (2) environmental; (3) local sociocultural dynamics; and (4) employee demographics. It should be noted that there is frequently overlap between categories and the boundaries are fluid. However, for the sake of this paper these categories will mainly be discussed separately and examples will be provided of how these factors influence decision-making.

A.3 Background on the Forest Service

The U.S. Forest Service (USFS) was formed in 1905 and is housed in the U. S Department of Agriculture (USDA). The agency administers 154 national forests and 20 national grasslands in 44 states and territories, which encompass roughly 193 million acres and 30% of all federally owned lands (Dillard et al., 2008). The majority of these lands reside in the western U.S., but their extent spreads all over the country. The agency employs roughly 35,000 scientists, land managers, and administrators, with increasing numbers of seasonal employees in the summer to fight fires and support recreation (USDA, 2015).

The agency's headquarters are located in Washington, D.C. and is overseen by a Chief. The Chief and their staff work to implement the direction of the agency as well as apply broad policy. This staff also works to get annual budgets submitted to Congress and to provide them with accomplishments of the organization. The USFS's budget is passed by Congress on an annual basis, and for 2015 they were budgeted $5.4 billion with 52% of that funding ultimately used for wildland fire management, up from 16% in 1995 (USDA, 2015).

There are nine regions within the USFS and over 600 districts that make up the regions. Each district is managed by a ranger, varies in spatial size, and staffs somewhere between 10-100 people. The rangers are responsible for most of the functions of forest management applicable to their district. Therefore, it has been suggested that they are on the frontlines of decision-making (Kaufman, 1960; Koontz, 2007).

A.4 Types of decisions made by the agency

Before I begin the discussion of factors that influence USFS decision-making, it is crucial to briefly discuss the types of decisions that districts make. I will refer to managers/decision-makers throughout this paper as either rangers or the personnel working beneath them making on-the-ground decisions.

The lands managed by the USFS are guided by the principle of multiple-use management (Bowes and Krutilla, 1985), which mandates that they be managed for a wide variety of purposes and users. This can lead to conflict while trying to balance the needs of diverse users. Here, I will briefly discuss three major areas of management (fire control, resource sales, and recreation use) and give examples of the types of decisions land managers make.

As of 2015, fire control makes up over half of the USFS budget and is presently one of the agencies largest activities (USDA, 2015). With greater fires occurring in the last few decades (Westerling et al., 2006) and more life and property located on the outskirts of forests (Stephens and Ruth, 2005), firefighting has taken a large toll on the agency's time, resources, and money. Decisions related to fire control can be broken into four different stages:

- **Fire prevention**: encouraging and informing the public, as well as enforcing rules that avoid the creation of wildfires (e.g. fire bans, campsite checks, fire level danger signs, Smokey the Bear campaign, outreach with local communities)
- **Fuels management**: decreasing vegetation mass on the landscape in hopes of lowering the likelihood and severity of a burn (e.g. selective thinning, timber harvest, brush pile and prescribed burns)

- **Fire preparedness**: being ready to fight and control a fire if it occurs (e.g. hiring extra personnel, having supplies on hand, be able to mobilize in a moment's notice, training staff)
- **Fire suppression**: the actual act of working to put out or limiting growth of a fire that has already been ignited (e.g. moving fire units around, building and maintaining fire camps, planning and executing methods of attack, working with local communities, assessing hazards and dangers)

Within these four stages, decisions vary drastically between districts. Vast, sparsely populated, mostly roadless forest districts, say in northern Idaho, will make decisions in quite a different manner than districts in populous regions like California or the east coast (Kaufman, 1960). Thus, depending on location, as well as other external and internal factors, the types of decisions relating to fire control vary between districts.

Resource sales and permits is another large management area, with timber sales being a large source of revenue for the agency. Rangers must decide where and how much timber to put up for sale, the methods that will be used for extraction (e.g. selective thinning vs. clear-cutting, replanting vs. natural regeneration), and the aggressiveness in which a district pursues sales. In addition to timber sales, rangers make decisions regarding permitting land for grazing livestock as well as for other resource extraction activities (e.g. mining, drilling).

The last large area where decisions are made is in regards to how the general public interacts with the National Forests. Many recreational opportunities are present on these lands in the form of backpacking, hiking, camping, hunting, fishing, skiing, and swimming. Additionally, communities rely on these areas to provide other key ecosystem services, such as water quality and delivery. USFS personnel make decisions that include the needs of general public users, such as deciding where roads can be built, camping restrictions, recreational facilities, road maintenance, and more.

Within these areas of decision-making, managers must attempt to balance the competing interests between multiple uses, including industry, and public users (Martin et al., 2000). This guiding principle may have led the agency to a point where no single group is content with the agency's performance, which may be hurting their public image (Sedjo, 2000).

A.5 Factors affecting decision-making

As mentioned in the introduction, this paper seeks to explain some of the factors that influence decision-making within the USFS. The next four sections will discuss these overarching factors and provide examples of how they affect decisions (Figure A.1).

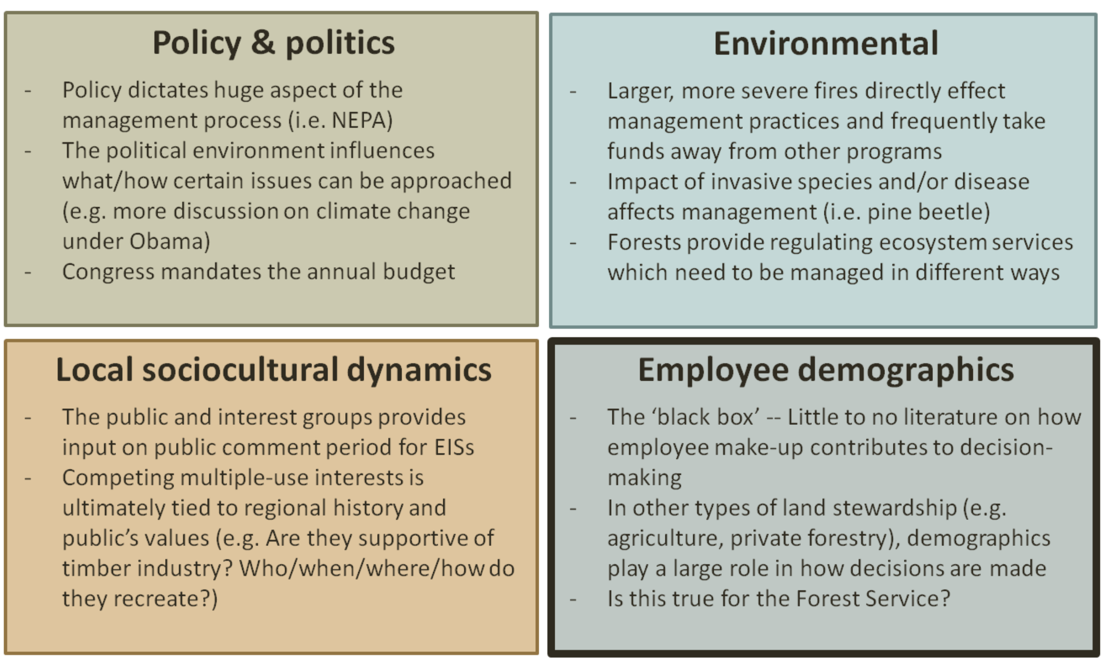

Figure A.1: Overview of the major factors identified in this study to contribute to public land management decision-making

A.5.1 Policy and the political environment

As a governmental agency, the USFS is highly influenced through policy and politics, by having to adhere with policy that is enacted, being led by a leader that is inherently chosen by political forces, and operating with a budget passed annually by Congress. Therefore, it is necessary to discuss how politics and policy combined is a major contributor in USFS decision-making.

Throughout the years, numerous policies have been passed that affect the operation of the USFS, with one of the most significant being the National Environmental Policy Act (NEPA) enacted in 1970. NEPA requires all federal agencies to prepare environmental assessments (EA) and/or environmental impact statements (EIS) for any action that “significantly affects the quality of the human environment” (NEPA, 1970). An EA is first drafted, which highlights positive and negative aspects of a project, as well as proposed alternatives. If it is found that there are no significant consequences to the environment, the project can continue, otherwise a lengthy EIS must be prepared which includes the steps of scoping, project alternatives, analysis of each alternative, draft EIS, responding to public comments, and selection of decision. Rangers can no longer make simple decisions such as what stands of trees to put up for harvest without going through a much more lengthy and resource-consuming process. This has had serious ramifications for management in that NEPA has altered decision-making at all levels throughout the agency, although variations in the NEPA process are apparent across the country (Ackerman, 1990). Additionally, NEPA may have led to the interdisciplinary USFS staff we see today as the policy fosters integrated decision-making where knowledge of multiple resources is mandatory (Ackerman, 1990).

A Chief leads the USFS, who is typically a long-term career employee that has risen up through the ranks. They report and work closely with the Under Secretary of the USDA for Natural Resources and Environment, someone who is a presidential appointee. The Chief provides and implements broad policy for the agency, which can lead to changes in management at lower levels. For example, Gail Kimbell, who was Chief from 2007-2009, shifted the emphasis away from timber during the Bush administration to more resource protection and planning for the future of climate change. As Chief, many discussions were held about climate change which led to the *Forest Service Strategic Framework for Responding to Climate Change* (USFS, 2008), which outlined goals focused on both managing the land and their employees to be more sustainable. This framework set forth the stage for better integration of climate change at the National Forest level and each forest is reviewed annually to monitor their progress. With the ability to apply broad policy, the Chief influences the decisions made among employees within the agency.

One of the most influential ways that politics affect decision-making in the agency is that Congress passes the annual USFS budget, which affects which programs receive funding. For example, Congress has failed to acknowledge and recognize the true cost of wildland firefighting and in nearly every budget year has vastly underfunded fire suppression (Stephens and Ruth, 2005). In order to pay for the large fires occurring, the agency has to shift funds from other programs; including ones that would help to reduce large fires from igniting in the first place (Stephens and Ruth, 2005). It has also been proposed that fuels management projects have been used as pork barrel spending in competitive districts or to reward supporters of Congress members (Anderson et al., 2013). Additionally, budget constraints consistently come up as the main barrier for implementing projects by managers to improve the sustainability of their lands (Archie et al., 2012; Kemp et al., 2015).

A.5.2 Environmental factors

Part of the USFS's mission is to "sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations" (USFS, 2008). This means they must manage the land in a sustainable way and take into account environmental factors as they make decisions. One key environmental factor that is actively discussed by the agency is climate change. As a federal agency, they have taken greater steps towards solutions to combat this issue over other federal land management agencies (Smith and Travis, 2010). However, several studies have shown that on-the-ground management has not yet begun incorporating climate change into their daily decisions (Archie et al., 2012; Kemp et al., 2015). Besides climate change as an overarching environmental issue, there are much smaller environmental factors that affect decision-making, with some that are tightly associated with a changing climate.

Our nation's forests are experiencing longer fire seasons and larger, hotter fires, with a noticeable shift in fire regimes occurring in the 1980s (Westerling et al., 2006). This trend was previously assumed to be the result of a long history of fire suppression and subsequent fuels buildup (Keeley et al., 1999), however, recent work has attributed the change in fire regime to elevated summer temperatures and an earlier spring snowmelt (Westerling et al., 2006). This alteration in the fire regime puts greater responsibility on rangers as they try to combat the problem. Furthermore, more citizens are building on the outskirts of forests in the wilderness-urban interface. As these large fires occur, fire personnel has not only the job of trying to contain the fire, but must also work towards protecting life and property (Stephens and Ruth, 2005).

Environmental factors can affect decision-making in both the short and long term. For example, managing for detrimental invasive species (e.g. pine beetle) or working to improve native and/or endangered species habitat might be done over many years. This kind of planning may involve many specialists and researchers to come up with a solution. Other environmental factors may change decision-making at a much shorter timescale. For example, a heavy rain on an already warm snowpack may lead to flash flooding that wipes out roads or destabilizes riverbanks (Swanson et al., 1998). While we mentioned just a few factors here, there are numerous environmental factors at play that can influence decisions at any point of time.

A.5.3 Local sociocultural dynamics

National forests typically have a strong tie to the communities that lie adjacent to their lands. Not only does the public recreate amongst the forests, but often they are dependent upon forest lands for their livelihood, especially in more rural communities (Hansen et al., 2002). Communication between the public and the USFS used to be one-way (Kauffman, 1960), with the agency mostly informing and educating the public on their projects and the status of the lands. However, communication now flows both ways, which is widely due to the passage of NEPA (Koontz, 2007). Not only does the general public have a stake in operations, but interest groups are also involved.

The interests and lifestyles of local citizens plays a significant role in USFS operations, with studies even suggesting that the USFS prioritizes the needs of local public citizens over the directives from Washington, D.C. (Sabatier et al.,1995). For projects that require an EIS, there exists an open comment period composed of local hearings and written statements. The USFS then must reply to all comments in their final EIS. While individuals all over the country can comment on any one EIS, localized persons typically weigh in more heavily on an EIS (Ackerman, 1990). Thus, local interests may influence local decision-making. However, to what extent is not necessarily known and one study showed managers being split about the extent public input actually effects on-the-ground decision-making (Archie et al., 2012).

With the increased contributions of both the public and interest groups, the USFS must balance their needs along with the preferences of industry, which are often at odds and can lead to conflict (Martin et al., 2000). While the USFS has historically had a close relationship with the timber and commodity industry (Kaufman 1960), more focus has recently been given to non-commodity interests, such as environmental and conservation groups (Koontz, 2007), potentially reflecting a shift in the values of local communities (Mohai et al., 1994).

A.5.4 Employee demographics and values

There is a breadth of literature regarding how demographics (e.g. race, gender, religion, political affiliation, income level) affect land management decisions, but this work has primarily focused on agriculture (Meares, 1997; Lambert et al., 2007; Burton, 2014) and private timber owners (Lidestav and Ekström, 2000; Sampson and DeCoster, 2000; Joshi and Arano, 2009). Few studies have explored how demographics and personal values influence day-to-day decisions in a federal land agency. Personal values, defined as someone's internal guiding principles and enduring deeply-held beliefs of what is morally right or wrong (Kempton et al., 1996), have been widely shown to play a large role in how someone views and responds to environmental issues (Corner et al., 2014).

It is acknowledged that private and public land managers differ vastly in their management styles and overall objectives, and as such direct comparisons are difficult to make. However, there is no prescriptive management rulebook in the USFS, and so on-the-ground federal managers actually possess wide autonomy in daily decisions. As such, it is hypothesized that the sociocultural backgrounds and demographics of managers and the values they possess contribute to decision-making within the agency (Trusty and Cerveny, 2012).

Anderson et al. (2013) performed a study where they looked at a database of fuels management treatments and they found that political, ecological, and public factors weighed nearly even in how treatments were chosen. However, this study did not take into account how demographics within the agency personnel could affect decision-making. Kaufman (1960) argued that decisions among rangers remained relatively unbiased due to the fact that the agency had homogeneity with a workforce primarily composed of white male individuals who had received forestry training at similar institutions. Additionally, the USFS encouraged then, and still to this day, rotations between districts in order to move up in the system. If individuals were unable to 'conform' to the agency's standards and precedents, then they would have a lower chance of moving up within the system (Kaufman, 1960). However, the diversity and makeup of USFS managers has drastically changed since Kaufman's landmark piece.

Two major transformations are apparent today compared to the employee makeup of Kaufman's study. These changes have likely brought employees who possess different sets of values. First, the USFS has diversified in respect to race and gender (Thomas and Mohai, 1995). It was not until 1979 that the USFS employed their first female ranger (Carroll et al., 1996) and currently women make up a little over a third of the agency's workforce. With respect to race, the rangers in Kaufman's study were virtually 100% white, and the agency has slowly diversified, with 88% of contemporary rangers identifying as white (Koontz, 2007). While the agency has made small strides with respect to diversity, there still exists a large underrepresentation for both females and people of color in roles that directly lead to leadership positions (Thomas and Mohai, 1995).

Another major transformation that has occurred within the agency is the educational background of its employees. The majority (~90%) of the agency's workforce in the 1960s had a background in forestry, in which the training and educational background put heavy focus on timber and its associated industry (Koontz, 2007). However, nowadays, the USFS is composed of individuals stemming from a wide variety of backgrounds: ecology, hydrology, civil engineering, biology, policy studies, and social sciences, to name a few, with foresters making up only a third of ranger positions. A diversity of educational backgrounds is likely to lead to different value systems and perspectives of employees, in which they might manage different ecosystem services in varying ways.

The agency is built upon the aggregation of decisions made by managers and field workers on a daily basis. Kaufman (1960) noted this and said "the agency program is shaped by what the men in the woods do from day to day. … the Rangers in effect modify and even make policy – sometimes without knowing it" (65). However, he argues in the end that the rangers behave homogeneously and are predictable based upon a shared set of values, beliefs, and attitudes. But has this changed along with a diversification of the workforce?

In a survey amongst USFS resource professionals, more than three-quarters of the respondents agreed that an individual's values were able to influence professional judgment (Trusty and Cerveny, 2012). Furthermore, they were split about whether or not it was appropriate and healthy for values to play a role in decision-making (Trusty and Cerveny, 2012). Although this study's sample size was not large (n=27), there likely exist parallels to the agency as a whole.

Other research has shown that there exists a relationship between USFS employee demographics and their attitude about certain external interest groups. Gender, race, and career level may contribute towards employee beliefs regarding interest groups, such as environmentalists, commodity industries, citizen activists, and recreationists (Halvorsen, 2001). While this study suggests a relationship between employee diversity and beliefs about interest groups, it does not go further into trying to understand how these perceived attitudes might influence their roles as land managers. However, we hypothesize that an individual's values and socio-demographics can be thought to contribute a significant amount to the types of decisions that they make within the USFS.

A.6 Discussion

If there exists a certain amount of discretion in decision-making at low levels, as shown by several studies, then the diversification of the USFS, which has brought employees with different sets of values, has likely contributed to some of the observed direction of the USFS over the years. Yet, a study that attempts to quantify the amount of discretion held by employees or how the role of socio-demographics affects decision-making within the agency has yet to be found.

More research is needed to understand how and to what extent a manager's value system and socio-demographics contributes to the decisions they make on our public lands. Furthermore, the agency currently has a program called Cultural Transformation that aims to increase diversity by recruiting from an even great variety of backgrounds (Tidwell, 2011). With an ever-increasing amount of diversity, it is more pertinent to understand the links between personal values, demographics, and decision-making to try to understand future directions of the agency.

With a greater knowledge set of the types of decisions made and how different factors influence them, we can begin simulating how differing types of land management might respond to future scenarios of change. It would be beneficial for future research to examine the extent these factors presented in this appendix influence decision-making. Additionally, there seems to be a gap in the literature that could be filled with looking at how socio-demographics (e.g. geography, religion, political affiliation, education) of agency personnel affect their decision-making in the field. With other types of land managers showing a strong relationship with values and management techniques, it would be well worth it to explore this area further.

A.7 Conclusion

A federal land management agency, the U.S. Forest Service, was analyzed to understand what types of decisions they make and what factors influence those decisions. There were four large areas that were thought to contribute significantly to decision-making. First, politics and policy provide wide direction to the agency, legislation is passed that affects the decision-making process in the agency (e.g. NEPA), and the agency must work with a budget passed annually by Congress. Secondly, environmental factors (e.g. wildfire, storm events, climate change) affect decision-making on both short- and long-term timescales. Thirdly, local sociocultural dynamics influence decisions through both contributions of interest groups and the participation of the public on the NEPA process. Lastly, we suggest that forest managers exhibit a degree of autonomy in their decision-making authority, and that the increased diversity of USFS employees has likely affected decisions being made. Although there is literature that discusses some of these specific factors, we would like to see greater research that quantifies specifically how and why decisions are made. Not only would this information be pertinent from a policy and sociologic standpoint, but it could aid in modeling studies that are interested in how future states of our public lands might affect key ecosystem services.

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APPENDIX B

Locations of model setup, source code, processing scripts, and model outputs

B.1 Introduction

In order to aid in future studies, I have archived aspects of this project. The majority of files, scripts, and data are housed on a server (Payette) in the Department of Geosciences, on Scholarworks in the Albertson's Library, and on a Github repository for the Lab for Ecohydrology and Alternative Futuring (LEAF). Their locations and selected additional metadata for them are the following:

Preprocessing

Climate

- https://github.com/LEAF-BoiseState/student-theses/2017-Steimke-MS
    - Scripts to process MACA data into a format readable by Envision

Inputs

Climate

- Payette\...\Steimke_2017\MACAclimate
    - Downscaled climate data (MACAv1-METDATA) that has been formatted for Envision
    - Domain covers both upper and lower Boise River Basins, but historical and future datasets have slightly different domain coverage
    - Unprocessed data can be found at: http://maca.northwestknowledge.net/

Hydrologic Data

- Payette\...\Steimke_2017\BRBgauges&SNOTEL

  - Gauges and SNOTEL data used for calibration and validation
  - See Table 6 for site names / period of record

Spatial Inputs

- Payette\...\Steimke_2017\ EnvisionRuns\upperBRB_NLCD2011\idu.shp
- Payette\...\Steimke_2017\ EnvisionRuns\upperBRB_NLCD2011\streams.shp

<u>Envision run files</u>

Source Code

- Payette\...\Steimke_2017\EnvisionSourceCode_v6.197

Run Files

- https://github.com/LEAF-BoiseState/student-theses/2017-Steimke-MS

<u>Model Output</u>

Selected future daily and annual hydrologic metrics

- doi.org/10.18122/B2LEAFD002

<u>Postprocessing</u>

Day of Allocation

- https://github.com/LEAF-BoiseState/student-theses/2017-Steimke-MS

Geospatial postprocessing (Chapter 3)

- https://github.com/LEAF-BoiseState/student-theses/2017-Steimke-MS