

PROPAGATING CLIMATE AND VEGETATION CHANGE THROUGH THE
HYDROLOGIC CYCLE IN A MOUNTAIN HEADWATERS CATCHMENT

by

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ABSTRACT

Prediction of hydrologic response to global climate change is paramount for regions that rely upon snowpack for their dominant water supply. Temperature increases are anticipated to be greater at higher elevations perturbing headwaters systems that provide water to millions of downstream users. In this study, the relationships between climatic change and associated vegetation succession with the corresponding response in hydrologic processes of mountainous terrain are studied in the East River headwaters catchment near Crested Butte, CO. This catchment is emblematic of other headwater systems within the upper Colorado River basin. Therefore, perturbations seen at this study site are likely to occur across the region, altering the water quantity and quality of the Colorado River. Here, we study the effect of climate-induced changes on the hydrologic response of three different characteristic components of the catchment: a steep high-energy mountain system, a medium-grade lower-energy system and a low-grade low-energy meandering floodplain. To capture the surface and subsurface heterogeneity of this headwaters system the basin has been modeled at a 10-meter resolution using ParFlow, a parallel, integrated hydrologic model. This model assesses hydrologic scenarios based on worst-case Intergovernmental Panel on Climate Change (IPCC) climate projections and an estimated worst-case scenario vegetation change observed in a warming experiment conducted in the watershed. Changes in ground evaporation, evapotranspiration (ET) snow water equivalent (SWE), and discharge are analyzed as these catchment characteristics provide useful insight into hydrologic

response. It was found that each component responded differently depending on its inherent orographic location and geologic features. It was also found that the inclusion of vegetation change enhanced the hydrologic changes from the vegetation or warming scenarios alone. Overall, the results show decreases in discharge, shifts in the timing of peak runoff, and prolonged periods of soil moisture declines, all of which can have negative implications for water quality, quantity and vegetative productivity.

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CHAPTER 1

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) is predicting a global increase in temperature ranging between 1°C to 4°C to occur by the year 2100 (Collins et al., 2013). This temperature change is projected to diminish ice and snowpack, and increase the variability and persistence of extreme weather events, such as, droughts, floods and heat waves (Christensen et al., 2007). These impacts are expected to be most prominent over high-elevation, mountainous regions, posing a threat to millions of people who rely on snowmelt as their primary water supply (Fyfe and Flato, 1999; Rangwala et al., 2013). Mountains cover roughly 25% of the global land surface and provide water to over 50% of the world's population (Beniston et al., 1997). In the Rocky Mountains, many of these systems act as reservoirs, storing water in the form of snow and ice during the fall, winter and early spring seasons. In the warmer spring and summer seasons, these reservoirs release their storage and provide water to mountain headwaters systems. Headwaters streams provide water to many major river systems. Globally, mountain headwater catchments provide water to roughly 50% of the world's major river systems (Christensen et al, 2007). Therefore, the prediction of water quality and quantity changes as a result of climate change is particularly important for headwaters systems.

Mountains are comprised of diverse ecosystems as their steep slopes experience vertical shifts in climate. These ecosystems are threatened by climate change as small perturbations can cause serious implications in mountain biodiversity. Climate change

has already begun to effect mountain systems in the past few decades altering snowpack and snowmelt. As a result, the Rocky Mountains have experienced depletion in snowpack, causing an earlier snowmelt season (Stewart, 2009). These changes are attributed to increased temperatures causing transitions in precipitation from snowfall to rainfall. This results in a delay of snowpack accumulation in the fall and throughout the remainder of the snow season. Decreased snowpack results in a decreased albedo, increasing the surface absorption of solar radiation. As more shortwave and longwave radiation is able to absorb into the surface, soil temperature increases and soil moisture decreases (Fyfe and Flato, 1999; Rangwala et al., 2013; Stewart et al., 2004; Stewart, 2009).

Changes in air and soil temperature as well as an increased soil moisture deficit may also contribute to tree mortality and woody plant encroachment. Tree mortality has been noted in many regions across the globe (Allen et al., 2010; Edburg et al., 2012; Kurz, 2008; van Mantgem et al., 2009; Williams et al., 2013;). These studies conclude that some areas of die-off are likely attributable to increased temperature and soil moisture deficit, as well as contributions from bark-beetle infestation, which can be further enhanced in a warming climate. Understanding how a catchment will respond to vegetation change is important as it can alter hydrologic systems by modifying flow path contribution to streams, altering snowpack accumulation and depletion, as well as altering subsurface nutrient and biogeochemical cycling (Bearup et al., 2014; Hubbard et al., 2013; Mikkleson et al, 2012).

Field studies and model projections are the two main ways to predict the future response of mountain ecosystems to climate change. Global Climate Models (GCMs)

are used to predict climate change in association to increased greenhouse gas emission. A variety of scenarios are tested, as future emission inputs to the climate are unknown. While these model runs provide useful information on climate response, the large grids they require for both reasonable timely and costly assessment, cannot be used to assess hydrologic changes at the catchment scale. Therefore, hydrologic models composed of smaller grids can use downscaled GCM climate outputs or pseudo-warming scenarios derived from GCM projections in order to make predictions on catchment response.

The Sustainable Systems Science Focus Area (SFA) 2.0, funded by the Biological and Environmental Research (BER) program of the Department of Energy, is a large team-effort project focusing on understanding multi-scale ecosystem interactions and their response to a future climate. The phase 2 portion of this project is focused in the East River headwaters catchment, near Gothic, CO (Figure 1.1) as it provides an ideal test bed for the understanding of system functionality in a complex, natural environment. To optimally predict future changes within this system the development of a multi-scale, integrated watershed model capable of capturing climate, hydrologic, phenologic, metabolic, and biogeochemical interactions and behaviors is the overarching goal. Hydrology is the main driver of subsurface microbial, geochemical and nutrient cycling processes, therefore an understanding of onsite hydrology is the starting point to understanding catchment functionality.



Figure 1.1 The East River headwaters catchment is located near Gothic, CO, which is within the Upper Colorado River Basin and is signified by the black star. When zooming into the state of Colorado, the white start signifies it's location in respect to Crested Butte, CO. Figure revised from: Reserve on the East River (2014) and Central Basin Municipal Water District (2014).

The hydrologic model presented here was developed for the SFA 2.0. While this site is unperturbed and ideal for understanding natural system interactions, available data at the catchment-scale is limited. Fortunately, several studies have been done in the past within the East River catchment in order to gain insight into ecosystem response to a future climate. A variety of plot scale field studies were conducted at the Rocky Mountain Biological Laboratory (RMBL), located within the East River catchment, near Gothic, CO. Harte et al., (1995) looked at changes to montane meadow soil moisture across a slope exhibiting zones of moist soils and dry soils. They looked at the soil microclimate response to increased infrared radiation as a prediction for an atmosphere

with doubled CO₂. They found that dry soil zones experienced increased soil temperature and decreased soil moisture. Soil moisture increased with depth; therefore a loss of soil moisture was attributable to increased soil evaporation as vegetation was sparse. The moist, densely vegetated soil zones experienced slightly cooler soil temperatures as a result of vegetative shading. The soil moisture did not change much in the shallow soil zones, but decreases were seen in the deeper zone where root uptake is likely.

Harte and Shaw (1995) used the same plots mentioned above to assess vegetative shifts in relation to climate change. They found a transition from shallow rooted forbs to a more drought resistant shrub. This transition occurred only in the dry zone, making this transition mostly attributable to moisture limitations. Past pollen records and sagebrush phenology support this finding. Saleska et al., (1999) used the same field site, but this time to assess changes in CO₂ fluxes. They found that decreased soil moisture caused a significant decrease in photosynthetic inputs, causing a net loss of carbon from the ecosystem. Therefore, the loss was not coming from enhanced soil respiration as a result of increased temperature, as many previously predicted, but from transpiration losses due to decreased soil moisture. This result was again, most prominent in the dry zone and was associated with the reduction of forbs and increase in less productive shrubs. This finding is important as the loss of CO₂ from the subsurface alters nutrient and biogeochemical cycling, creates a positive feedback to the atmosphere and can affect water quality in the surrounding system.

Battaglin et al., (2011) used the Precip-Runoff Modeling System (PRMS) forced with three different GCM scenarios to predict hydrologic changes within the entire East River

basin, located in Almont, CO. Through their assessment they predicted a delayed catchment response to climate as increased temperature didn't take effect until the year 2040. As a result, precipitation shifted from snow to rain by spring and average daily snowpack fell below baseline conditions by year 2050. They also noticed by year 2060 that peak snowmelt shifted from June to May. With a decrease in snowpack, they saw decreases in streamflow, not sure which specific change to attribute it to. Their predictions agree with other mountain region predictions of earlier snowmelt and decreased snowpack.

Each of these studies provides important information on ecosystem response allowing further insight into hydrologic changes at the catchment scale, as well as soil and vegetative changes at the plot scale. However, these studies are limited in their capabilities due to either variable constraints or scaling response, both a pitfall of system heterogeneity. Ideally, studies should be done at scales representative of system variability to allow for an understanding of a site's complexity, something that is often disregarded in modeling studies and is hard to achieve in field-scale studies. While field studies provide good conceptual models and are important in determining how a particular system may respond to climate change, definitive predictions cannot be applied across the whole watershed. Therefore, applying field study findings to model predictions will both enhance field findings and allow for better model predictions. The East River basin, as described above, has seen hydrologic model predictions in association to climate change as well as separate field studies for the prediction of ecosystem response. However, no studies have attempted to put these two together.

In this study, a high-resolution approach is used to best capture catchment heterogeneity and response in a high relief, hydrologically varying domain. Capturing this hydrologic variability, such as the high-energy mountain stream down to the low-energy meandering floodplain will allow for a more in-depth understanding of their relative importance in water quality and quantity inputs. The purpose is to predict hydrologic changes as a result of large-scale climatic change and vegetative shifts. A representative water-year (WY) of current climatological conditions is used to establish contemporary conditions, noted as the baseline scenario throughout the remainder of the paper. This baseline scenario was perturbed with three future climate scenarios in relation to worst-case IPCC predictions and worst-case vegetative change in association with the shrub succession observations noted by Harte and Shaw (1995). Worst-case scenario predictions were chosen in order to understand the importance of each scenario through the determination of the magnitude at which they perturbed the hydrologic system. This allows for future focus on hydrologically important parameters within climate and vegetation change. Results will include the comparison of three different future scenarios for three different hillslope transects within the model domain, noted as the large model throughout the remainder of the paper. Comparisons and analyses will be made by hydrologic responses in SWE, discharge, evaporation and evapotranspiration and lastly, soil moisture.

CHAPTER 2

STUDY SITE

The East River headwaters catchment is located in Gothic, Colorado, just northeast of Crested Butte (Figure 1.1). RMBL is located in the headwater catchment, providing a vast database of both past and present studies related to the catchments diverse ecosystem, a majority of which are focused on phenology, entomology and ecology. This catchment is representative of many other systems within the Upper Colorado River Basin, making it an ideal area to study. The East River is one of two major tributaries that form the Gunnison River and is accountable for approximately one-quarter of its discharge. The Gunnison River is important as it in turn, attributes just under half of the Colorado River's discharge at the Colorado/Utah boarder (Battaglin et al., 2012). The Colorado River is part of a continental scale watershed that supplies water to tens of millions of users throughout the southwest. The vast area to which this watershed provides highlights its importance for prediction. Therefore, the assessment of the East River in response to climate change will provide valuable information for water managers, as the alterations seen in the East River study site will likely resemble changes seen across the Colorado Rockies, creating a ripple effect down the Colorado River Basin.

The East River study site is comprised of three different life zones: montane, subalpine and alpine. The catchment receives about 0.8-m of precipitation each year, a majority of which is snow. The headwaters catchment covers an area of about 275-km², has a maximum elevation of 4122-m, an average elevation of 3266-m and a

topographic relief of 1420-m. This relief, as well as the site's complexity, drives the varying stream characteristics seen throughout the catchment. The headwaters reach contains a steep high-energy mountain stream that migrates into a low-energy meandering floodplain in the lower elevations of the catchment. The site also contains a wide variety of heterogeneity within its geologic and vegetative structures. The heterogeneity within the site allows for the examination of the varying effects of climate-induced changes on the hydrologic response of different locations within the catchment.

CHAPTER 3

METHODS

In this study, ParFlow is used to simulate hydrologic response to climate and vegetative changes. The following section describes the model used and its setup.

3.1 ParFlow Code

ParFlow is a parallel, integrated, hydrologic model capable of capturing surface and subsurface interactions. To capture these interactions the three-dimensional Richards equation is used with a free-surface overland flow boundary condition (Jones and Woodard, 2001; Kollet and Maxwell, 2006). The parallel aspect of ParFlow allows for efficient solving of high-resolution, large-scale, heterogeneous domains (Ashby and Falgout, 1996; Kollet et al 2010; Maxwell, 2013; Osei-Kaffuor et al., 2014). ParFlow is also coupled to the Common Land Model (CLM), which simulates a number of land-surface processes including, energy balance, snow dynamics and moisture exchange (Maxwell and Miller, 2005; Kollet and Maxwell, 2008). While it cannot model vegetative change with time, it is able to model vegetative phenology and its exchanges to a given environment. CLM is driven by observed meteorological parameters allowing for the orographic alterations in weather patterns associated with mountainous regions.

3.2 Model Inputs

To create the model domain, datasets have been prepared, analyzed and input into ParFlow. Public access datasets include: Digital Elevation Models (DEMs) from National Map Viewer at 10-meter resolution, land cover from National Land Cover Database (NLCD) at 30-meter resolution (Figure 3.1) and soil data from STATSGO2 at 1-km resolution bias corrected with land cover and surface geology to represent exposed rock

(Figure 3.2) (USGS, 2014; Jin et al., 2013; NRCS, 2014a). The surface geology dataset was constructed from US Geological Survey (USGS) geological maps (Figure 3.3) and labeled with corresponding lithologic permeability values from Gleeson et al., 2011 (USGS and AASG, 2014). Initially, subsurface hydraulic conductivity was estimated using the e-folding technique from Fan et al., (2007). This technique is based on slope, depth and underlying rock type, and applies an exponential decay in hydraulic conductivity with depth. However, the e-folding technique was not able to capture typical mountain subsurface flow patterns as the large contrasts in surface geology generated large, unrealistic contrasts in the subsurface resulting in compartmentalized flow patterns. Therefore, a hydrologic conductivity (K) value of 0.002-m/h, typical of fractured bedrock in steep mountainous terrain was used uniformly across the subsurface (Welch and Allen, 2014). Surface roughness values (mannings-n) were inferred from the 30-m land cover dataset and ranged between 0.03 and 0.1-s/m^{1/3}. On site land cover types include: Grasslands (33%), Evergreen Needleleaf (24%), Deciduous Broadleaf (17%), Barren (17%), Permanent Wetlands (6%), Open Shrublands (1%), Cropland (<1%), Mixed Forests (<1%), Water Bodies (<1%) and Urban (<1%). CLM requires meteorological forcing for 8 different parameters (downward shortwave radiation, downward longwave radiation, precipitation, air temperature, northerly and westerly wind speed components, surface air pressure and air specific humidity) and is typically forced with atmospheric datasets from National Land Data Assimilation Systems (NLDAS). However, due to the large topographic relief and relatively small area of this site, NLDAS datasets were not realistic and were not applied. However, there is a Clean Air Status Trends Network (CASTNET) station located in the center of the domain near

the confluence of Copper Creek and the East River that provides all 8 required parameters (EPA, 2015). This station was also used in the meadow warming experiments previously mentioned in the introduction. Therefore, the CASTNET station was used to develop the East River headwater catchment's hydrologic system. Observed discharge measurements were taken throughout the East River domain between WYs 2005 and 2009. These WYs were compared against National Oceanic and Atmospheric Administration (NOAA), National Climatic Data Center, 1981-2010 averaged climate data for Crested Butte, CO in order to determine the most climatologically representative year (NOAA, 2015). For location consistency the CASTNET station was not used for this comparison, as it is located in Gothic, CO, not Crested Butte, CO, and would otherwise skew the comparison. Therefore, the NOAA climate data was compared to yearly averaged maximum temperature, minimum temperature and total precipitation values from Crested Butte, CO, U.S climate data for each WY (USCD, 2015). From these comparisons it was determined that WY 2006 (1-October-2005 to 30-September-2006) was the most climatologically representative as it had the overall smallest differences from the NOAA climate data. Differences were as follows: yearly averaged maximum temperature was 0.4°C less than the climate average of 9.9°C , yearly averaged minimum temperature was 0.3°C greater than the climate average of -7.9°C , and lastly, yearly total precipitation was 0.08-m greater than the climate total of 0.6-m. This WY also received peak discharge in mid-to-late May, typical timing within the East River Basin.

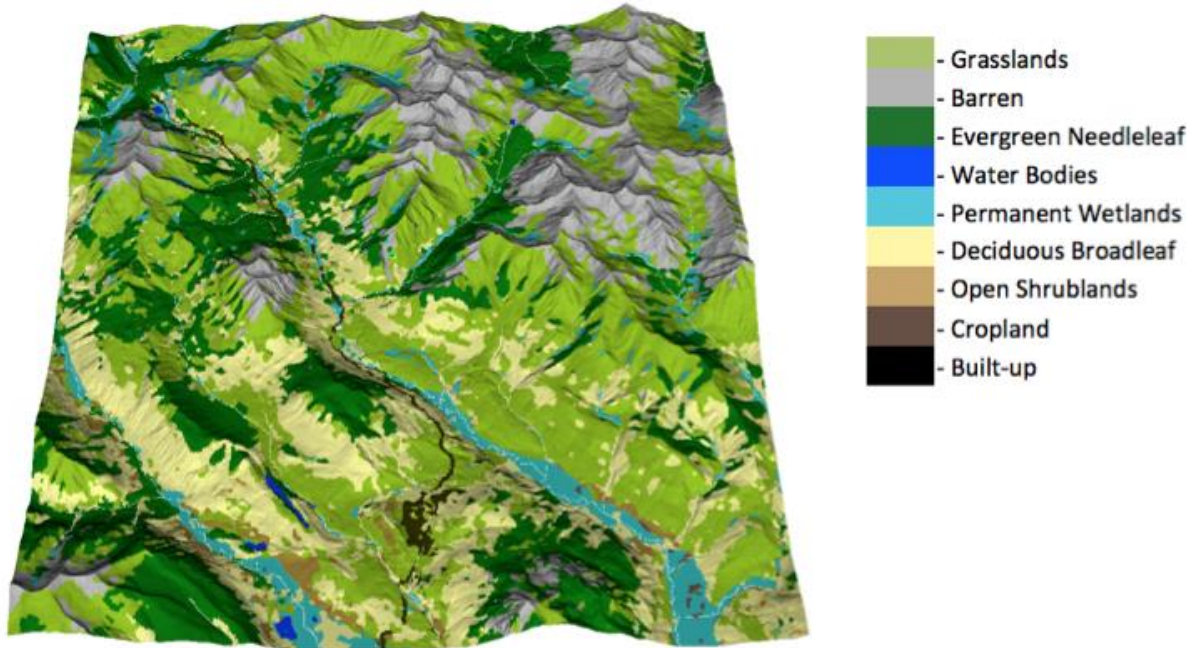


Figure 3.1 Land cover data, 30-m resolution, from the National Land Cover Database.

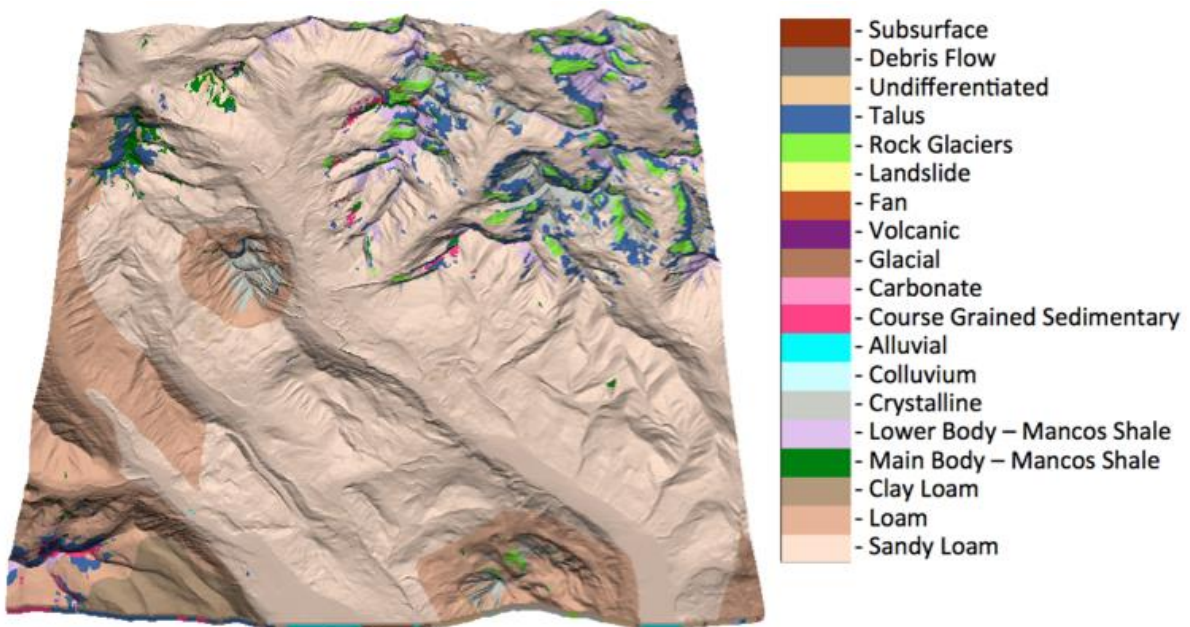


Figure 3.2 Soil Dataset, 1-km to 10-m resolution, from STATSGO2 and 4 different hand digitized geologic maps from the USGS.

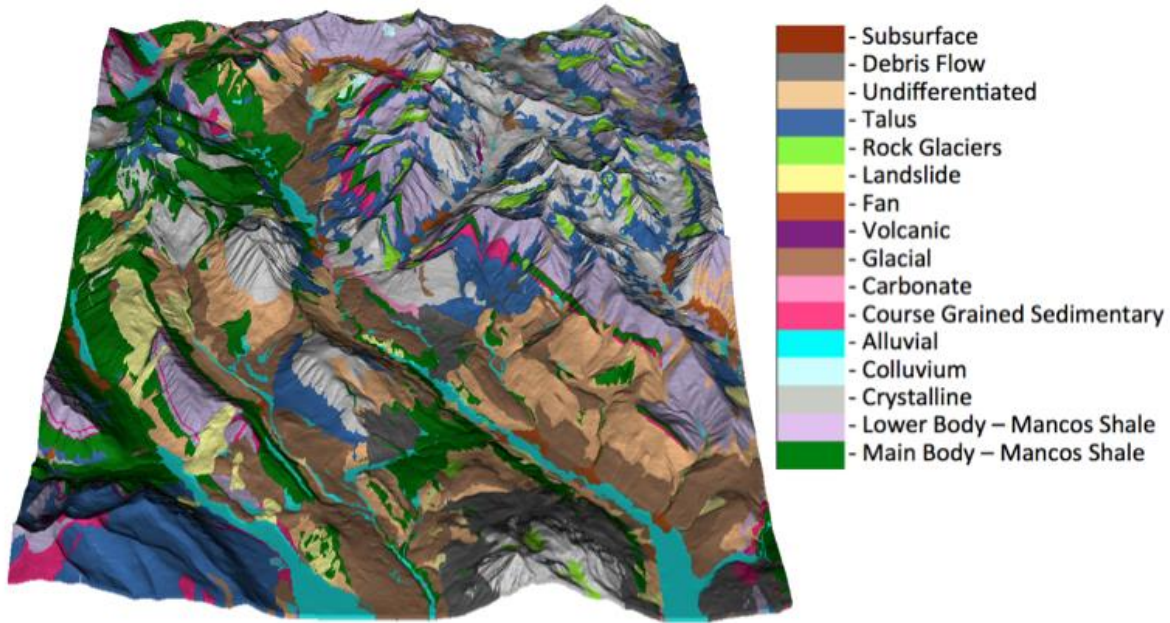


Figure 3.3: Geologic Dataset, 10-m resolution, from 4 different hand digitized geologic maps from the USGS.

3.3 Domain Setup

To best represent the heterogeneous system and to allow for the future assessment of subsurface nutrient and biogeochemical cycling as per the SFA 2.0, the domain was modeled at a 10-m lateral resolution and a varying (0.1-m to 21-m) vertical resolution. The three-dimensional model grid (Figure 3.4) consists of 1581 cells by 1743 cells at the surface and has 5 layers with depth, giving the model at total of nearly 14 million grid cells. The top three model layers consist of the bias corrected soil data and are at the following thicknesses, in meters, 0.1, 0.3 and 0.4, respectively and complete to a total depth of 1-m. The fourth layer consists of surface geology and is modeled at an 8.0-m thickness and is completed to a total depth of 9-m. The depth of the geology layer was determined from available data from one on-site borehole log stating that the valley and had an alluvial thickness of 9-m. Layer five consists of a uniform subsurface that is 21-m thick and is completed to a depth of 30-m.

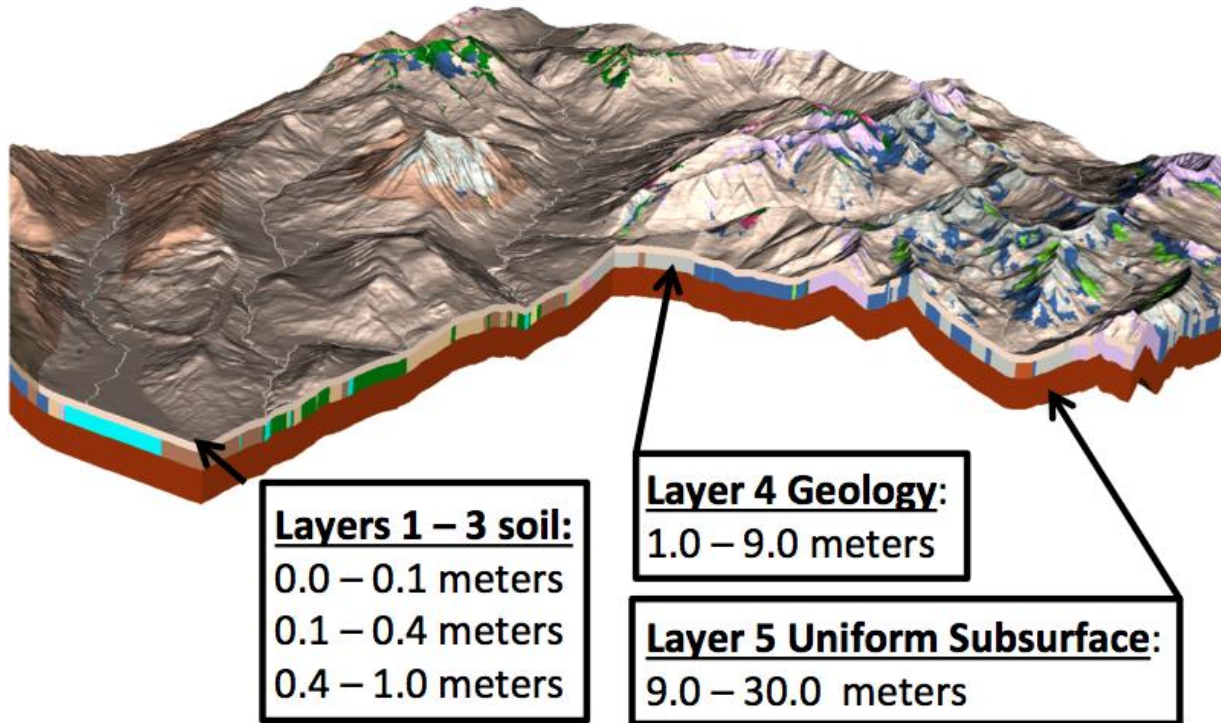


Figure 3.4 Cutout of the 3D model domain. Layers 1 through 3 consist of the bias correct soil dataset. Layer 4 consists of the hand-digitized geologic maps. Layer 5 consists of a uniform subsurface.

3.4 Approach

This model is used to assess the question of how the East River headwaters hydrologic system will change as a result of climate and vegetative change. To do this, three different future climate scenarios are applied. Scenario 1 consists of a stark vegetation change from grasslands to open Shrublands and is only applied where grasslands are present in the current landscape. When applied across the entire domain this equates to a shift from 33% grasslands to a total of 34% open Shrublands (Figure 3.5). Grasslands within the basin are spread fairly evenly between high-elevation slopes and low-elevation valleys, while the open Shrublands, which only cover 1% of the current system, are located in the low-elevation meandering floodplain. Shrublands have a deeper rooting system and have a 3-times larger leaf area index

than grasslands providing both a larger canopy for interception and transpiration, as well as vegetative shading. Scenario 2 consists of the IPCC worst-case scenario temperature projection, where a uniform 4°C increase is applied across all times in the forcing data (hourly data). Scenario 3 consists of a combination of scenario's 1 and 2 where temperature is increased by 4°C and all present grasslands are converted to open Shrublands. Running each of these scenarios individually will allow for the analysis of each effect (temperature vs. vegetation) and their enhancement or diminishment of one another.

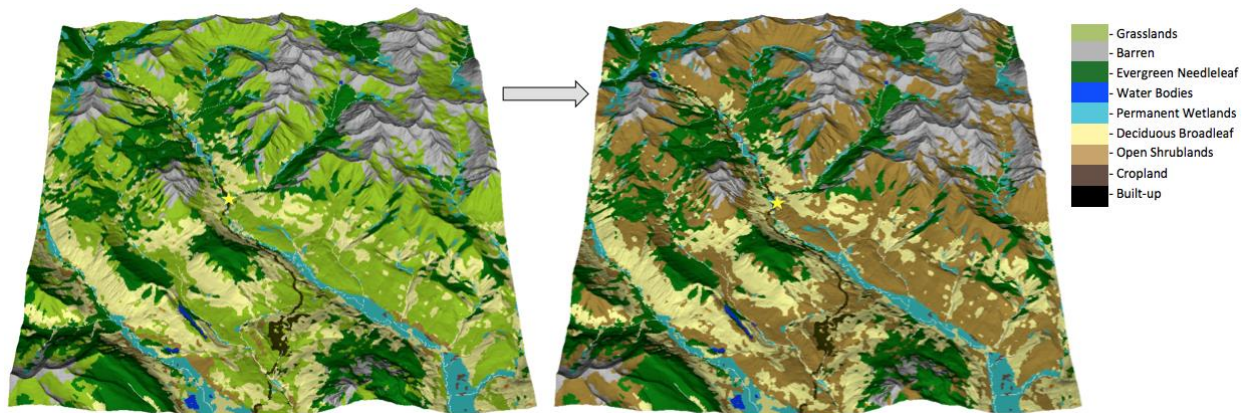


Figure 3.5 Scenario 1 vegetation transition from grasslands to open Shrublands for the entire model domain. Grasslands cover 33% of the current system.

Each scenario is applied to three different hillslope transects within the model domain (Figure 3.6). Each transect is in a location that best represents the East River's complexity and heterogeneity. While the large model was initialized with forcing from the CASTNET station, two SNOw TELemetry (SNOTEL) sites are located in the vicinity of the northern and southern most transects (Transects 1 and 3), therefore, their temperature and precipitation data were used in the transect hillslope studies to best represent the actual precipitation and temperature associated with each transects

orographic location (NRCS, 2014b). Transect surface, subsurface and climatological parameters are described below.

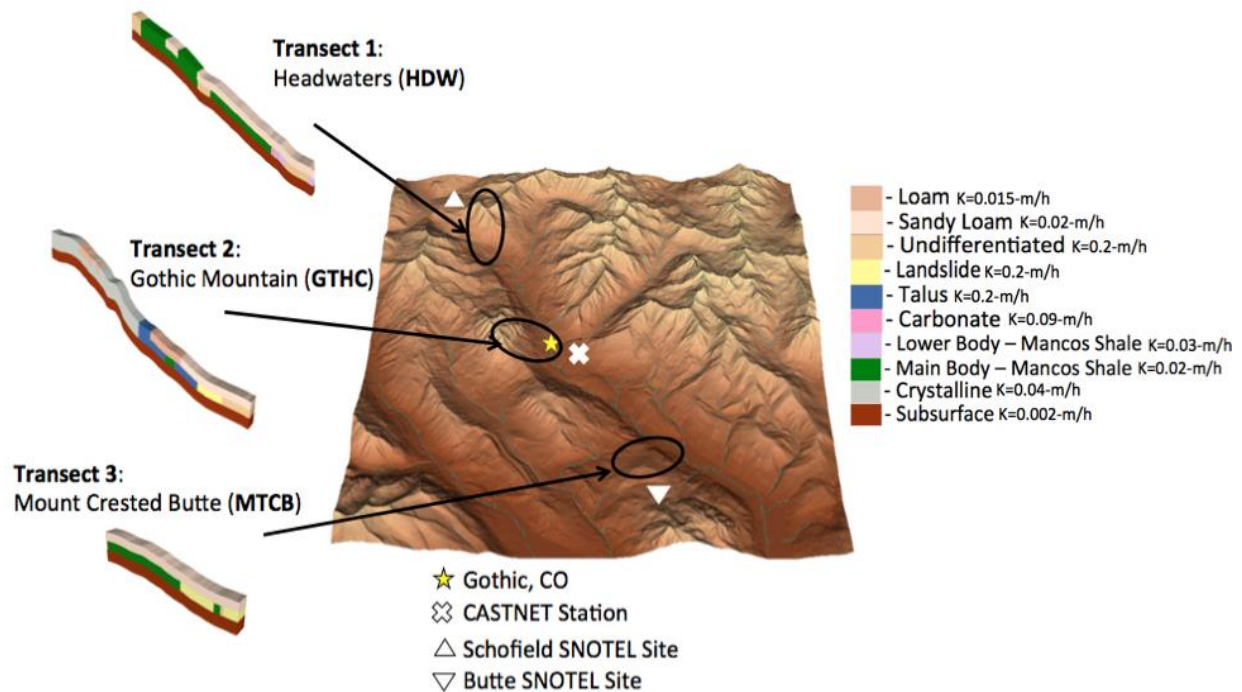


Figure 3.6 Model domain and locations of the three hillslope transects. Each transect is heterogeneous as they all have different land cover, soil and geologic properties.

Transect 1 (HDW) is located in the headwaters section of the domain and contributes water to the steep, high-energy headwaters system and is forced with the meteorological parameters from the CASTNET station, with the exception of temperature and precipitation which are from the Schofield SNOTEL site located at an elevation of 3261-m and is found just to the West of the transect. This transect is 1.65-km long, has a 0.48 average slope and runs North-South from the top of the watershed boundary to the East River, however, due to the use of radiation from the CASTNET station, and the temperature from the Schofield SNOTEL site, the hillslope is artificially

given a westerly aspect. This site has temperatures ranging from -28°C in the winter to 23°C in the summer and receives the largest amount of precipitation, about 1.27-m a year, about 68% falling as snow, providing an average maximum depth of 0.68-m^3 SWE. Snow accumulation begins in late October, snowmelt begins in early April and snow depletion occurs in late July. Stream discharge reaches baseflow in early April and begins to rise in early June before it peaks in early July (Figure 3.7a). Refer to table 3.1 for a description of land cover, geology and corresponding K values.

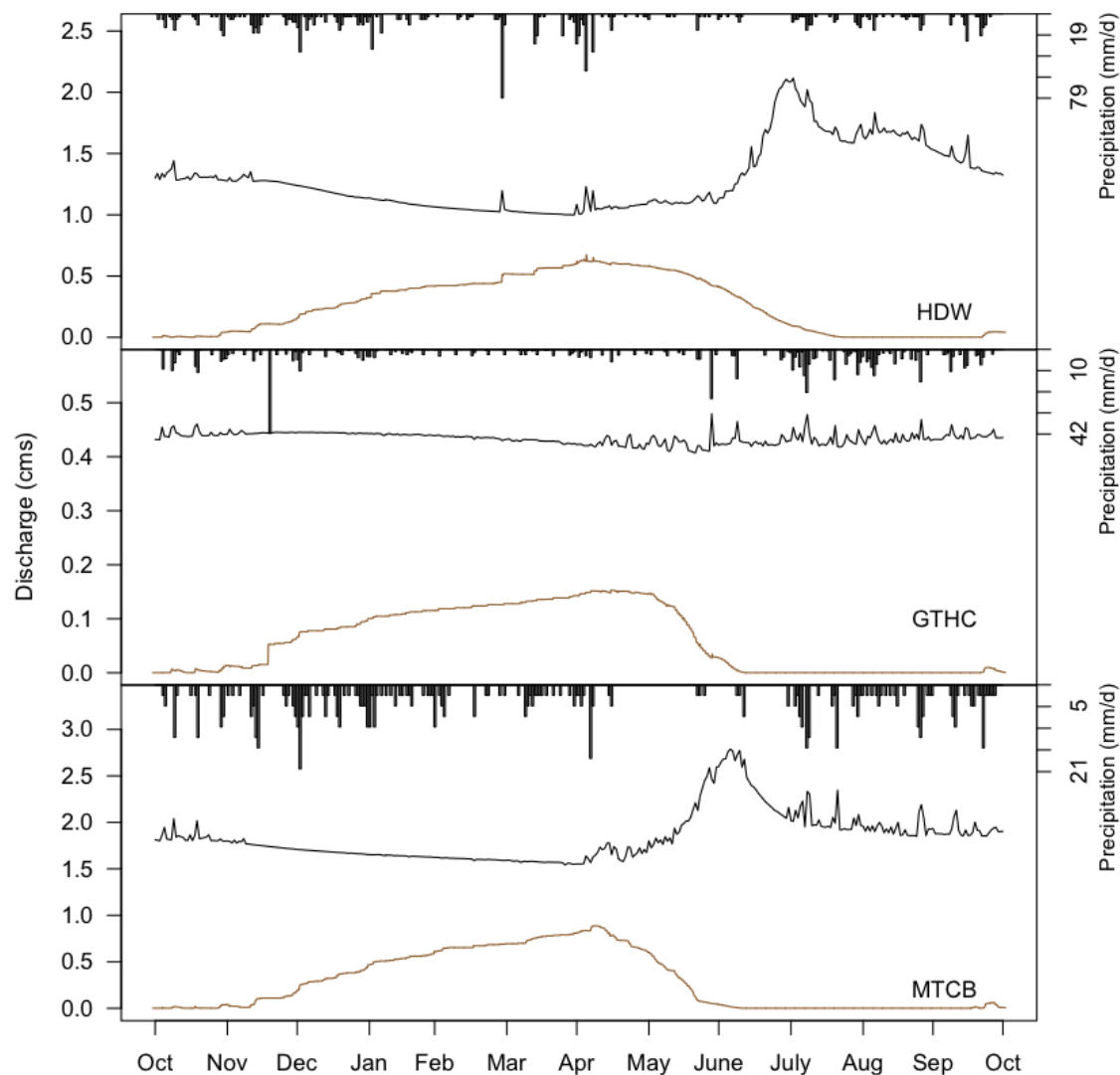


Figure 3.7 Modeled current system (baseline scenario) hydrographs for each transect. The bottom of each plot is relative SWE.

Table 3.1 Transect 1 (HDW) hillslope parameters.

HDW			
Dataset	Percent	Parameter	K [m/h]
Land cover	49	Grasslands	-
	32	Barren	-
	7	Deciduous Broadleaf	-
Soil	69	Sandy Loam	0.02
	26	Mancos Shale	0.02
	5	Undifferentiated	0.2
Geology	66	Mancos Shale	0.02
	24	Undifferentiated	0.2
	6	Lower Body Mancos Shale	0.03
	3	Carbonate	0.09
	1	Crystalline	0.04

Transect 2 (GTHC) is located in the middle of the domain and contributes flow to the medium-grade, medium-energy river system and is forced with the meteorological parameters from the CASTNET station site located at an elevation of 2915-m and is just to the East of the transect. This transect is 1.68-km long, has an average slope of 0.63 and runs West-East from the western edge of the watershed boundary to the East River, however, due to the use of radiation from the CASTNET station the hillslope is artificially given a westerly aspect. This site has temperatures ranging from -28°C in the winter to 24°C in the summer and receives the least amount of precipitation, about 0.64-m a year, about 38% falling as snow, providing an average maximum depth of 0.17-m³ SWE. Snow accumulation begins in late October, snowmelt begins in mid-April and snow depletion occurs in early June. Due to this site's orographic location, a majority of precipitation falls as rain during the late spring, summer and early fall months. Discharge changes minimally throughout the year, indicating the prevalence of groundwater contributions from this transect. However, during the late fall and winter

months discharge slowly declines and reaches baseflow around late May. Throughout the late spring and summer months, discharge is relatively flashy in response to precipitation events (Figure 3.7b). This means that a large percentage of rainfall is running into the stream as overland flow and as shallow subsurface throughflow. These flow paths are a likely result of the large contrast between low and high hydraulic conductivities present in this transect. The top of the transect is composed of crystalline rock ($K=0.04\text{-m/h}$) and the bottom is composed mostly of unconsolidated materials ($K=0.2\text{-m/h}$). Therefore, as precipitation falls, it is likely to runoff the crystalline rock and into the high K layers below, before exiting into the East River, generating a flashy response. Refer to table 3.2 for a description of land cover, geology and corresponding K values.

Table 3.2 Transect 2 (GTHC) hillslope parameters.

GTHC			
Dataset	Percent	Parameter	K [m/h]
Land cover	41	Barren	-
	30	Deciduous Broadleaf	-
	20	Grasslands	-
	9	Evergreen Needleleaf	-
Soil	38	Crystalline	0.04
	32	Sandy Loam	0.02
	24	Loam	0.15
	6	Talus	0.2
Geology	47	Crystalline	0.04
	25	Talus	0.2
	13	Undifferentiated	0.2
	11	Landslide	0.2
	4	Mancos Shale	0.02

Transect 3 (MTCB) is located in the bottom half of the domain and contributes flow to the low-grade, low-energy meandering floodplain. This transect is forced with the meteorological parameters from the CASTNET station, with the exception of temperature and precipitation which are from the Butte SNOTEL site located at an elevation of 3097-m and is just to the South of the transect. This transect is 0.98-km long, has an average slope of 0.23 and runs West-East from the top of the western edge of the watershed boundary to the East River, however, due to the use of radiation from the CASTNET station, and the temperature from the Schofield SNOTEL site, the hillslope is artificially given a Westerly aspect. This site has temperatures ranging from -24 degrees Celsius in the winter to 27 degrees Celsius in the summer and receives about 0.72-m of precipitation a year, about 64% falling as snow, providing an average maximum depth of 0.30-m³ SWE. Snow accumulation begins in late October, snowmelt begins in early-April and snow depletion occurs in early June (Figure 3.7c). Refer to table 3.3 for a description of land cover, geology and corresponding K values.

Table 3.3 Transect 3 (MTCB) hillslope parameters.

MTCB			
Dataset	Percent	Parameter	K [m/h]
Land cover	52	Deciduous Broadleaf	-
	34	Evergreen Needleleaf	-
	9	Grassland	-
	5	Permanent Wetlands	-
Soil	100	Sandy Loam	0.02
Geology	64	Mancos Shale	0.02
	33	Landslide	0.2
	3	Undifferentiated	0.2

CHAPTER 4

RESULTS

Normalized discharge allows for the comparison and understanding of hydrologic behavior within the system. Modeled discharge from each transects baseline scenario has been normalized from the MTCB transect peak discharge and are compared in figure 3.7. The HDW and MTCB transects have similar behavior with predominately baseflow in the fall and winter months and peak discharge in the late-spring and summer months, a result of snowmelt and the late-summer monsoon. The GTHC transect behaves very differently as described above due to it's geologic structures aiding in runoff and throughflow processes.

Before the model can be used for predictions it should be tested for its representation of the natural system. To determine model validity, modeled normalized discharge for the baseline scenarios of the HDW and GTHC transects were compared against corresponding measured normalized discharge data from WY 2006 (Figure 4.1) (written communication with Brad, September, 2014). The MTCB transect did not have corresponding measured discharge data, so it could not be directly compared. The modeled transect data was normalized with its own respective peak discharges, however, the observed discharge was normalized from a much larger peak discharge further downstream, outside of the modeled catchment. Therefore, the normalized discharge of the measured data falsely appears to be at a much lower magnitude than that of the modeled data. Figure 4.1 shows the modeled HDW transect has a similar baseflow and peak discharge behavior to that of the observed HDW discharge.

However, there is a noticeable difference in peak timing, likely a result of the models inability to capture the correct hillslope aspect, as the modeled transect was artificially given a westerly aspect as described above. In the natural system this hillslope has a southerly aspect, which would cause earlier melt and result in earlier peak in runoff, similar to the observed discharge. The GTHC transect also shows similar behavior to the measured discharge data with a majority of the flow comprised of baseflow with flashy peaks throughout the summer and fall months. Even though there isn't a direct comparison for the MTCB transect, its similar discharge behavior and orographic properties in comparison to the HDW transect provide evidence that the model is capable of capturing natural system behavior. It is important to note that the transects are not modeled catchments, therefore, the comparison with the measured discharge is to determine if the model is capturing system behavior similarly, not quantitatively. Given, the similar responses, the results show that the model is capable of capturing system behavior within this catchment.

To analyze model results, hourly outputs were spatially averaged across each transect and plotted temporally to determine changes in time. To determine how much each parameter changed, as well as compare model results for each transect, spatially averaged results were calculated as percent differences from each transects baseline scenario. This allows for direct comparison of each hillslope transect and the relative importance of each change. Table 4.1 provides a side-by-side comparison from each parameter's percent difference from the baseline scenario for each transect.

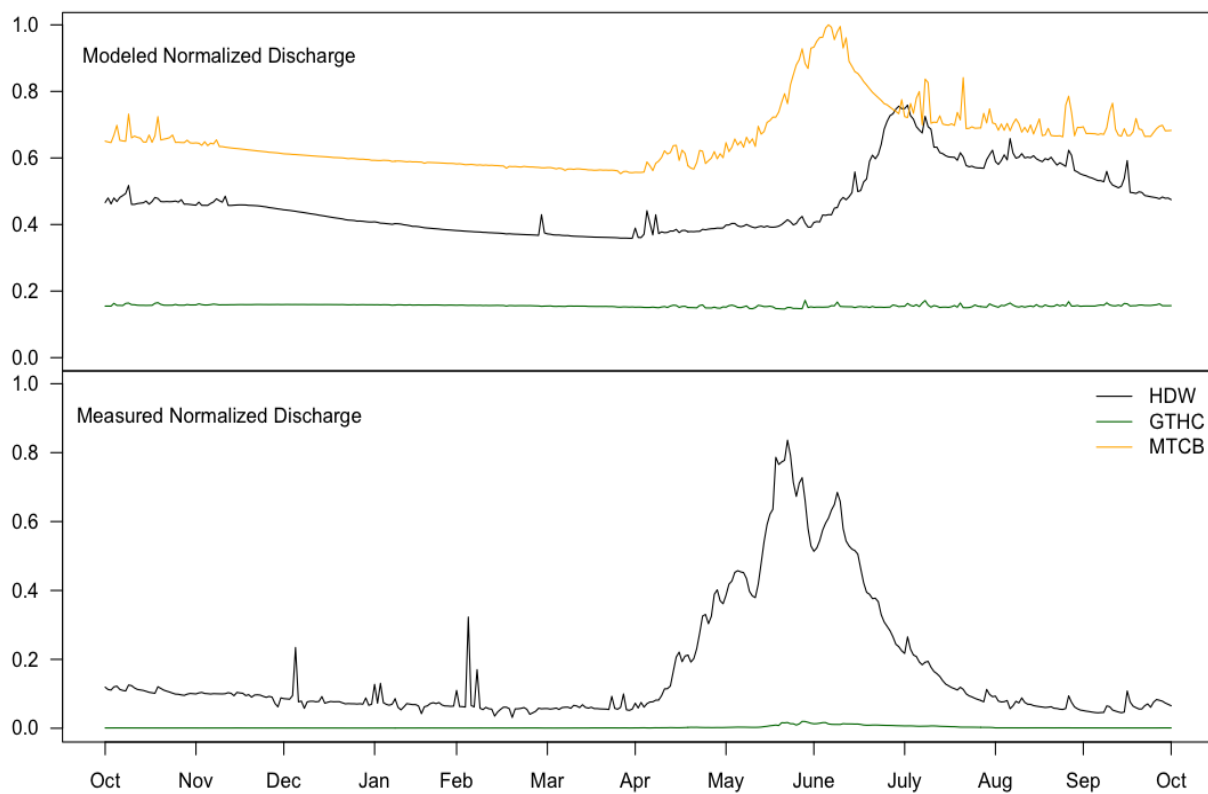


Figure 4.1 Normalized discharge for modeled transects: HDW, GTHC, MTCB versus normalized measured discharge for HDW and GTHC.

Table 4.1 Comparison of percent difference from each transects baseline scenario for each future climate scenario. 1 represents the vegetation scenario (scenario 1), 2 represents the warming scenario (scenario 2), 3 represents the combination scenario (scenario 3).

Parameter	HDW			GTHC			MTCB		
	1	2	3	1	2	3	1	2	3
Vegetation Shift	49	-	49	20	-	20	9	-	9
Precipitation as snow	-	-25	-25	-	-11	-11	-	-26	-26
Days below melting	-	-21	-21	-	-18	-18	-	-9	-9
Discharge	-6.2	-6.4	-16.8	-8.6	-26.2	-41.3	-3.6	-21.7	-33.4
SWE	-0.4	-43.4	-65.5	-0.9	-77.1	-77.9	-1.1	-59.9	-62
Storage	-0.3	-0.4	-0.6	-0.5	-1.5	-2.5	-1.1	-2.5	-4.1
Ground Evaporation	-31.8	29.5	17.4	0.2	30.7	31.7	-0.7	23.2	23.2
Interception	32.8	32	54.1	11.3	17.1	26.1	4.9	4.2	9.6
Transpiration	36.4	28.5	55.7	13.6	18	29.4	6.5	3.6	11.2
Total evaporation	25.2	33.4	50.3	8.9	21.3	27.9	3.2	11.5	14.7

4.1 Temporal and Seasonal Changes

The HDW transect had large variations in temporal and seasonal shifts between all scenarios. Changes in discharge timing and SWE development can be seen in Figure 4.2, while changes in total evaporation and soil moisture can be seen in Figure 4.3. The vegetation scenario created a lag in the snowmelt peak and monsoonal discharges. This change is in correlation to increased SWE in the summer months, while the overall decrease in discharge is in correlation to the increased total evaporation seen throughout the year. The warming and combination scenarios had earlier peak snowmelt and monsoonal discharges due to the earlier snow-rain transition and decreases in snowpack and snow longevity. Snowpack generation began 1 month after that of the baseline, while snow depletion occurred 1 month earlier. These scenarios also created small peaks in winter discharge, as some temperatures were able to generate melt, where it didn't otherwise occur. All these changes equated to a large enough reduction in the snowmelt peak discharge that the largest discharges were in association with the start of the monsoon season. Increases in evaporation can be seen in all scenarios, with the largest prolonged increases occurring over the spring and summer months. However, the results show larger prolonged increases associated with the combination scenario, which is due to both increased growing season from increased temperatures, as well as increased ET as a result of the vegetation change. These changes also correspond to the largest declines in soil saturation and discharge.

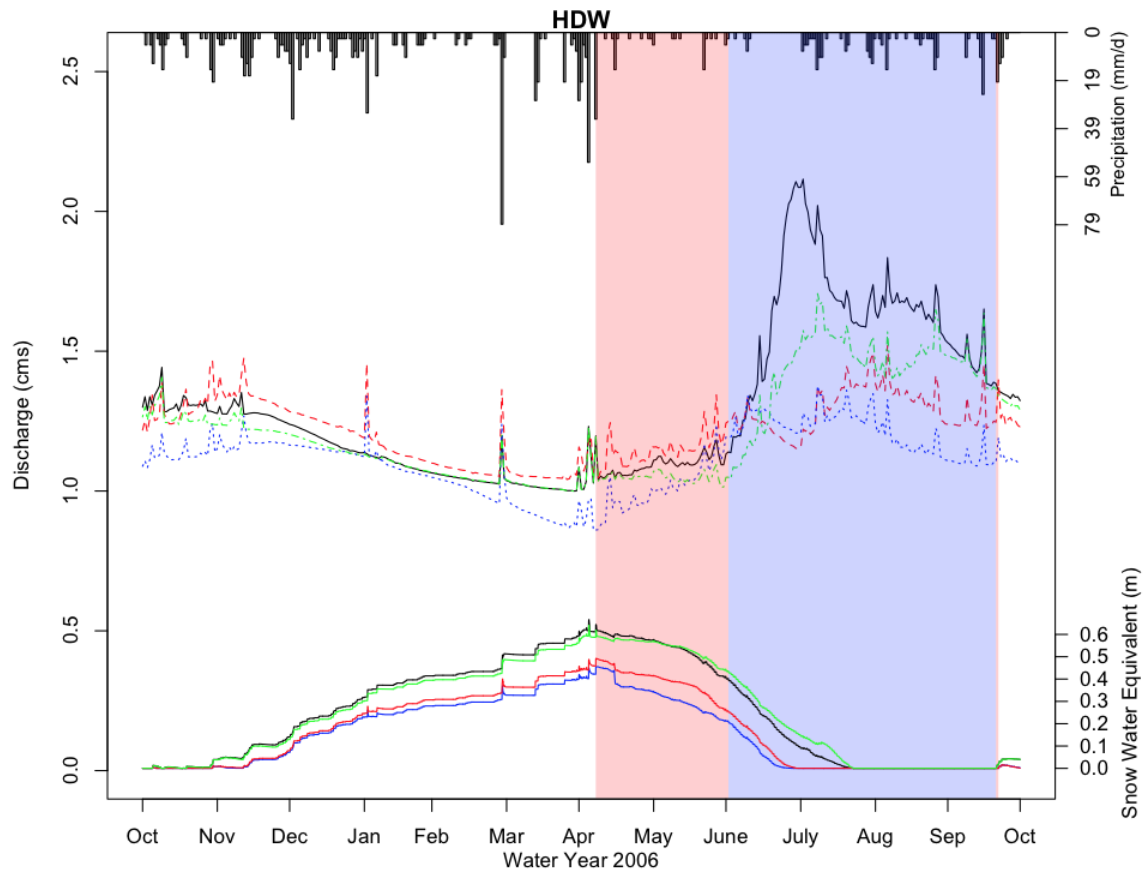


Figure 4.2 Hydrograph for the HDW transect. Precipitation is plotted on the top, discharge is plotted in the middle and SWE is plotted on the bottom. Black discharge and SWE lines represent the current system (baseline). Green lines represent scenario 1 (vegetation). Red lines represent scenario 2 (warming). Blue lines represent scenario 3 (combination). The blue shading represents the baseline fraction of precipitation falling as rain. The red shading represents the warming scenario extension of the fraction of precipitation falling as rain.

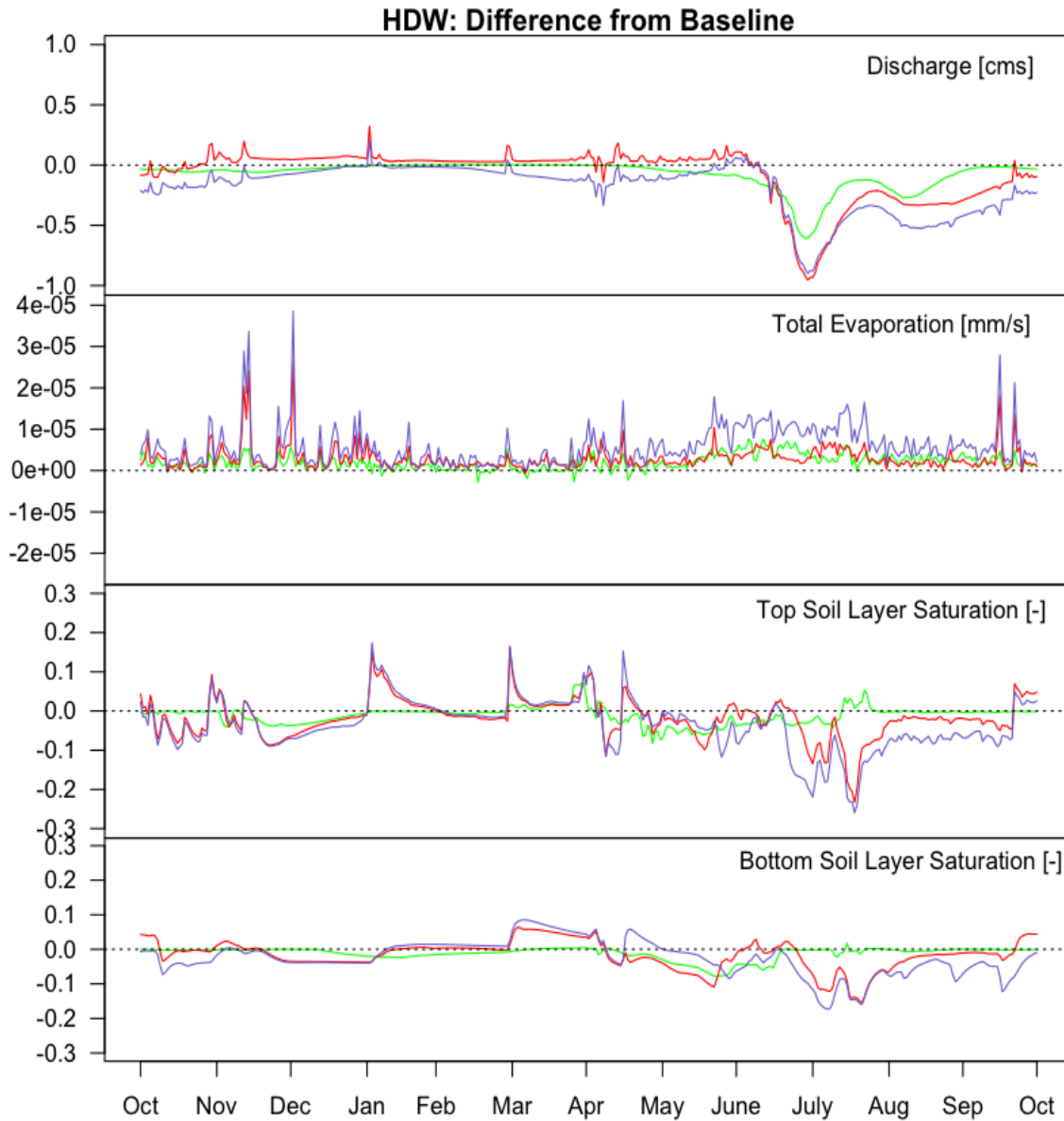


Figure 4.3 Temporal comparison between scenarios. Plotted differences are in relation to the baseline scenario for the HDW transect.

The GTHC transect had small variations in temporal and seasonal changes with discharge, but had large changes associated with SWE, similar to those of the HDW transect (Figure 4.4). The vegetation scenario generated a lag in snowpack throughout the winter, while in the summer it surpassed that of the baseline scenario. However, timing of snowpack generation and depletion did not change. The warming and combination scenarios had large declines in SWE, with snowpack generation beginning in mid November, about 1 month after the baseline, and snowpack depletion occurring in mid May, about one month earlier than the baseline. Snowmelt also occurred about one month earlier, generating a discharge peak a few weeks earlier than the baseline. However, overall increases in baseflow occurred in mid June, about 1 month after the baseline. Discharge for these scenarios were also increased during rain events in the fall. These changes correspond to shifts in the snow-rain transition, as well as increases in total evaporation. The vegetation scenario had the largest increases in total evaporation between May and August, when the shrubs were most productive (Figure 4.5). However, the warming and combination scenarios had large shifts in total evaporation, with a prolonged increase in evaporation beginning in April, when peak SWE and melt occurred. Evaporation stayed above the baseline until early June, when soil moisture declined in both the top and bottom soil layers. Soil moisture declines also occur for prolonged periods, amounting to a 1.5 month increase in declined soil moisture. However, once the monsoon season begins, soil moisture rebounds back to the baseline, but only in the top soil layer.

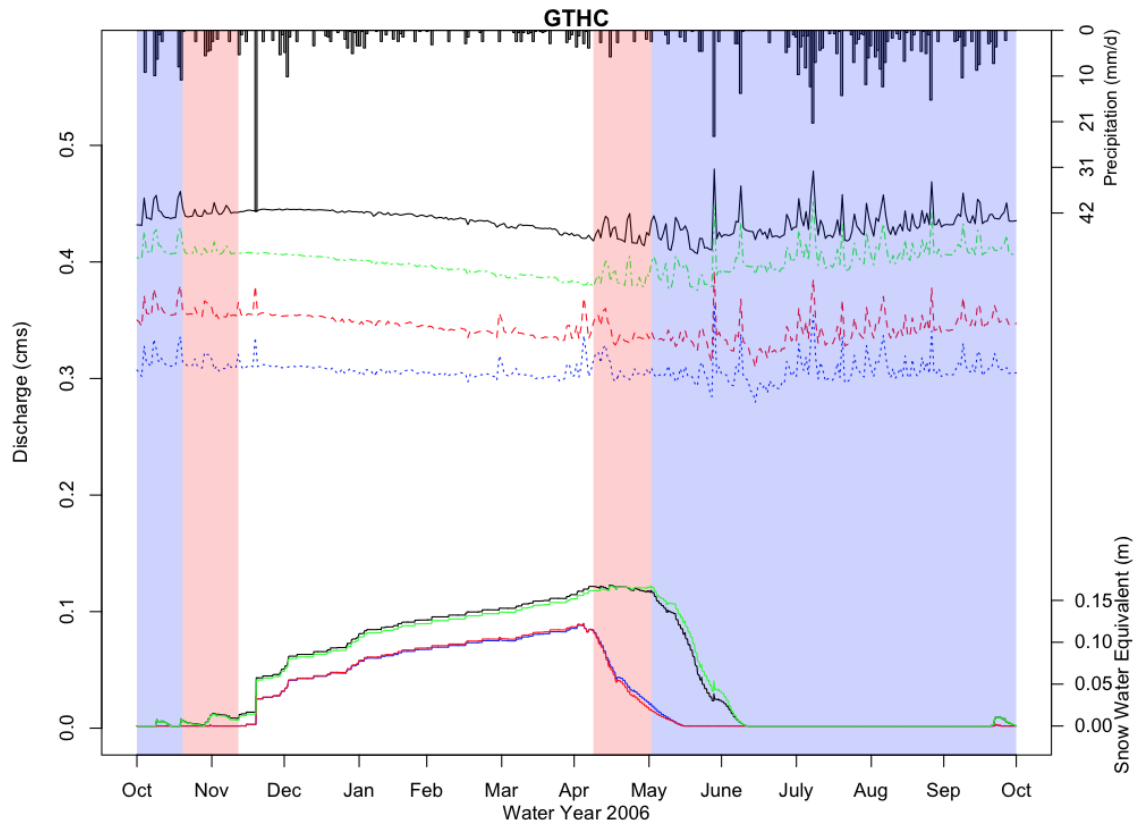


Figure 4.4 Hydrograph for the GTHC transect. Precipitation is plotted on the top, discharge is plotted in the middle and SWE is plotted on the bottom. Black discharge and SWE lines represent the current system (baseline). Green lines represent scenario 1 (vegetation). Red lines represent scenario 2 (warming). Blue lines represent scenario 3 (combination). The blue shading represents the baseline fraction of precipitation falling as rain. The red shading represents the warming scenario extension of the fraction of precipitation falling as rain.

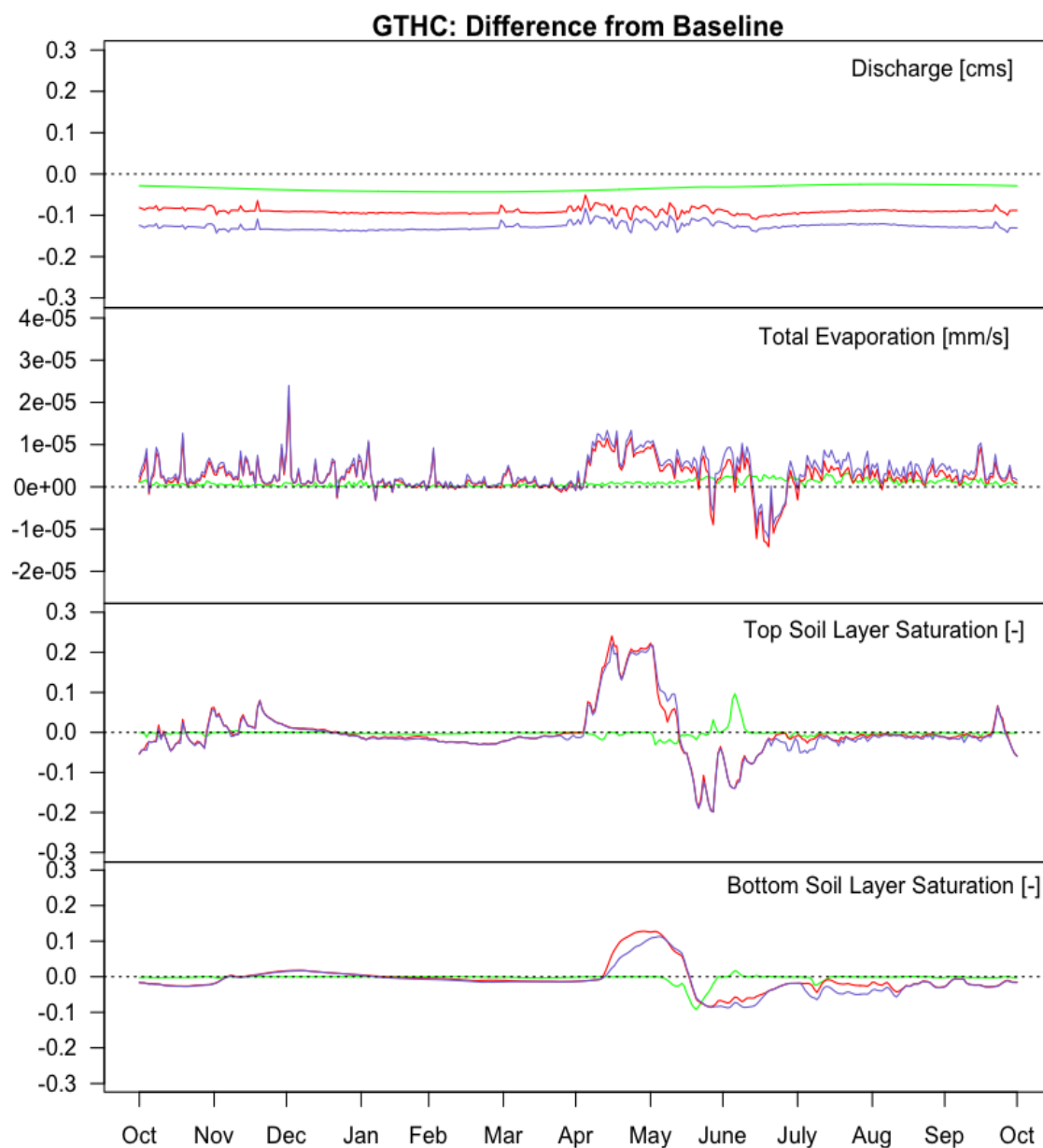


Figure 4.5 Temporal comparison of scenario differences in relation to the baseline scenario for the GTHC transect.

The MTCB transect had similar temporal and seasonal changes in SWE as other transects, but only had similar changes in discharge to that of the HDW transect and similar changes in total evaporation and soil moisture to the GTHC transect. Due to the minimal (9%) amount of vegetative change on this transect the vegetation scenario did not cause many temporal shifts (Figure 4.6). However, there is a slight increase in total evaporation in the summer months. The warming and combination scenarios generated large shifts in SWE and discharge. Snowpack generation began about 1 month after the baseline and snowpack depletion occurred about 1 month before the baseline, however, there wasn't a shift in the spring snow-rain transition so the initiation of snowmelt did not change. However, the warmer temperatures did allow the snow to melt faster resulting in earlier peak discharge, about a few weeks earlier than the baseline. Timing of the discharge peaks in the monsoonal season did not change as a result of the semi-flashy nature of this transect. In the fall months, small peaks in stream discharge occurred as a result of the prolonged period where precipitation was falling as rain. These scenarios also generated large changes in total evaporation and soil saturation, both with scenarios responding with very similar magnitudes (Figure 4.7). Peak evaporation occurred during peak snowmelt and declined as a result of declining soil saturation. Evaporation fell below the baseline when soil saturation in the top soil layer reached residual saturation. The period of declined soil moisture in the top soil layer was extended by 1 month, a result of the earlier snowmelt and increased evaporation, while soil

moisture in the bottom soil layer only exceeded that of the baseline during the short snowmelt period.

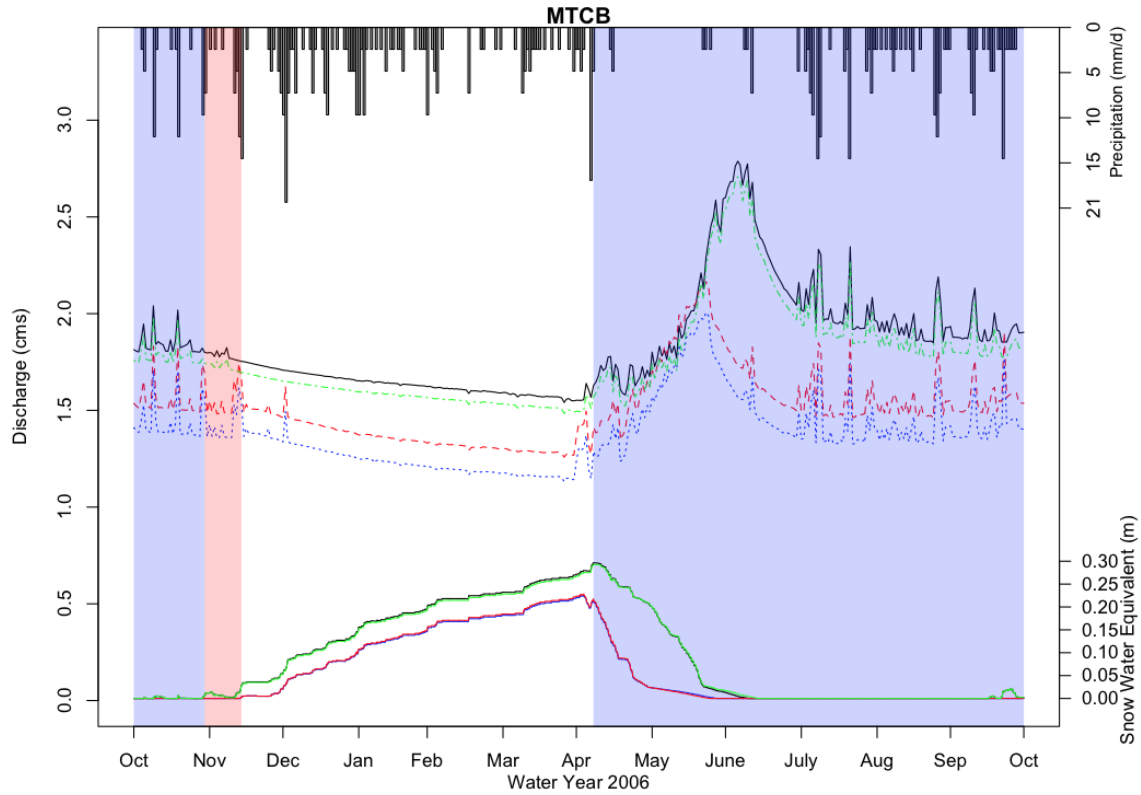


Figure 4.6 Hydrograph for the MTCB transect. Precipitation is plotted on the top, discharge is plotted in the middle and SWE is plotted on the bottom. Black discharge and SWE lines represent the current system (baseline). Green lines represent scenario 1 (vegetation). Red lines represent scenario 2 (warming). Blue lines represent scenario 3 (combination). The blue shading represents the baseline fraction of precipitation falling as rain. The red shading represents the warming scenario extension of the fraction of precipitation falling as rain.

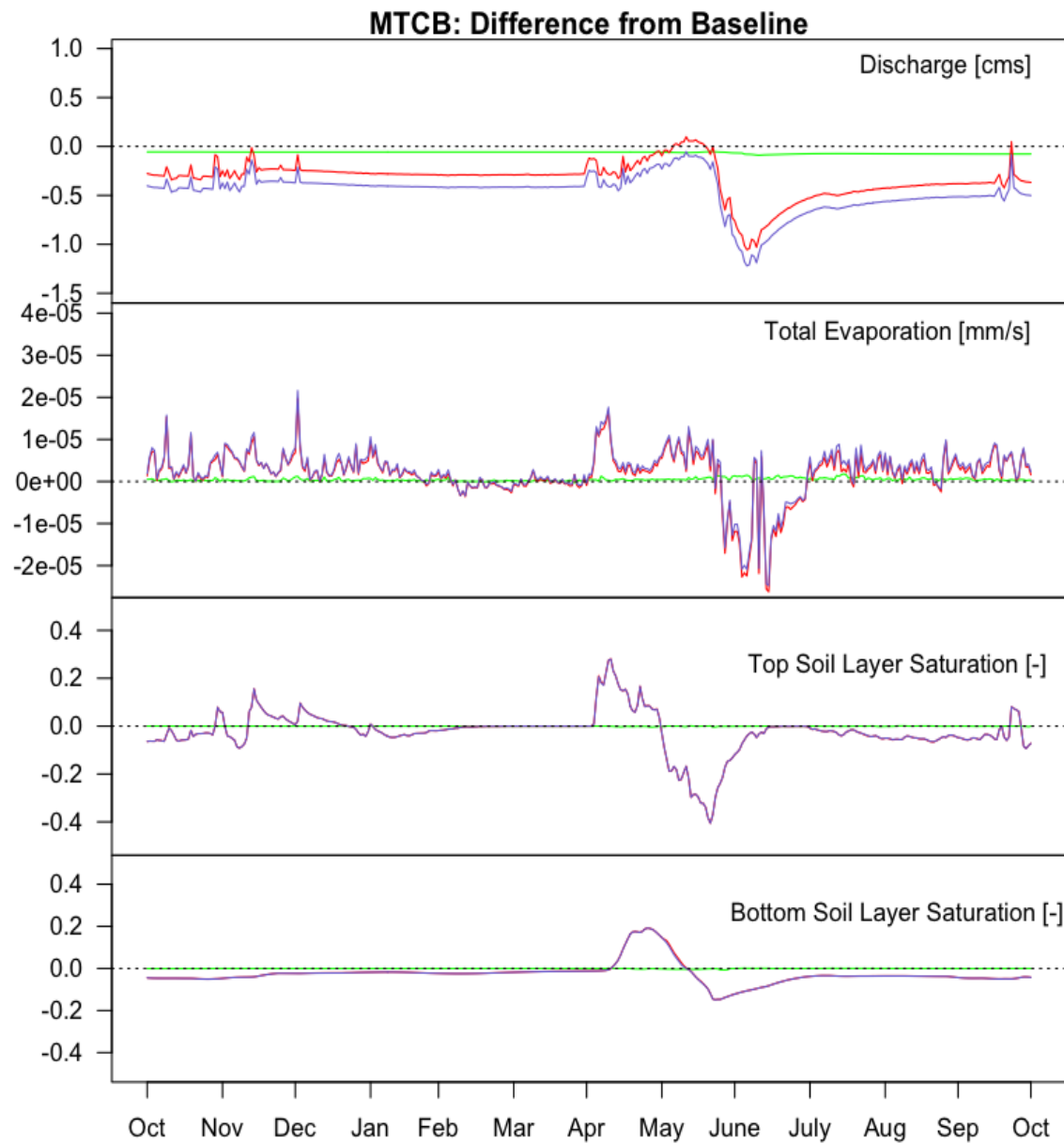


Figure 4.7 Temporal comparison of scenario differences in relation to the baseline scenario for the MTCB transect.

4.2 Percent Differences

The results above indicate that each transect has varying responses to each scenario. To gain a better understating of how much each parameter is changing as well as how greatly each transect is effected, percent differences

were generated. To help differentiate between losses of evaporation due to vegetative demand and atmospheric demand Figures 4.8-4.10 show percent differences for ground evaporation, transpiration, interception, total evaporation, SWE and discharge.

When comparing the vegetation scenarios, results indicate that the percent change in evaporative parameters strongly correlates to the amount of vegetation changed on each transect. The largest changes occur with the HDW transect (49% vegetation change) and the smallest changes occur on the MTCB transect (9% vegetation change). However, the discharge differences do not respond the same way. The largest change is seen in association with the GTHC transect.

The warming scenario had the largest evaporative increases in association with the HDW transect and least changes in association with the MTCB transect. However, the largest decreases in SWE and discharge were found on the GTHC and MTCB transects, with the GTHC transect having a slightly larger decrease in discharge.

The combination scenario had the largest changes in comparison to the vegetation or warming scenarios. The exception is the HDW ground evaporation value, which declined in relation to the warming scenario, a result of the vegetation adding a slight decrease in ground evaporation. Once again, the GTHC transect had the largest declines in SWE and discharge and the HDW transect had the smallest declines.

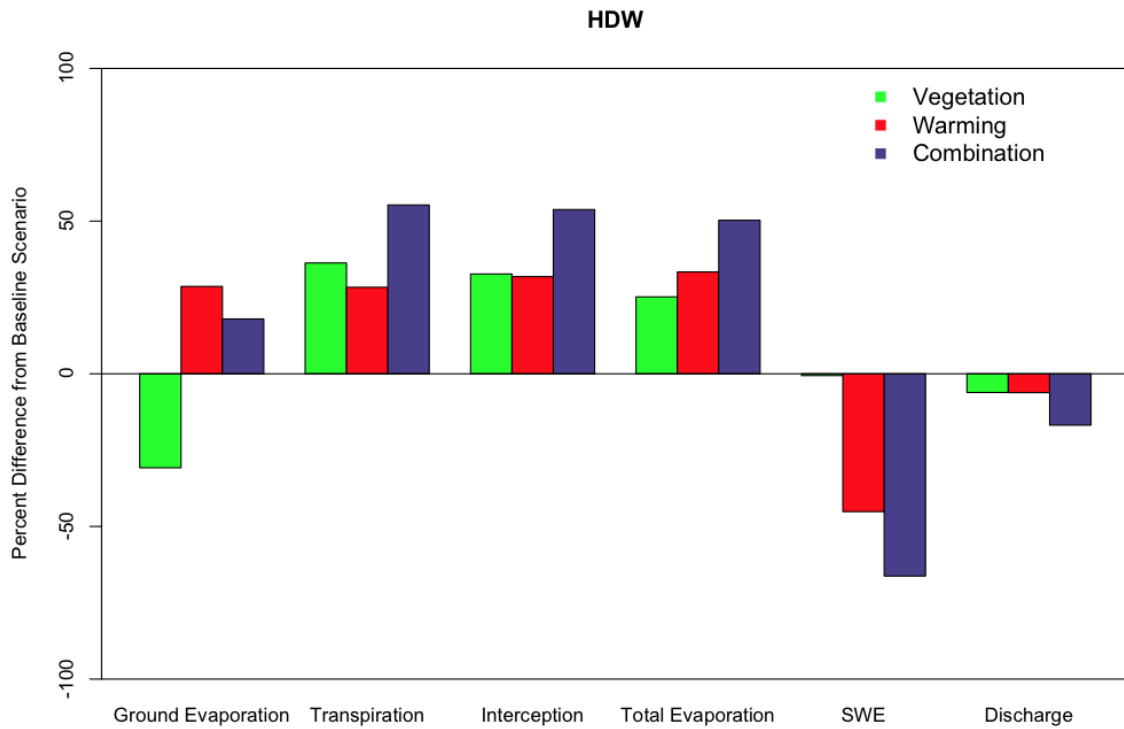


Figure 4.8 Percent difference from the baseline scenario for the HDW transect.

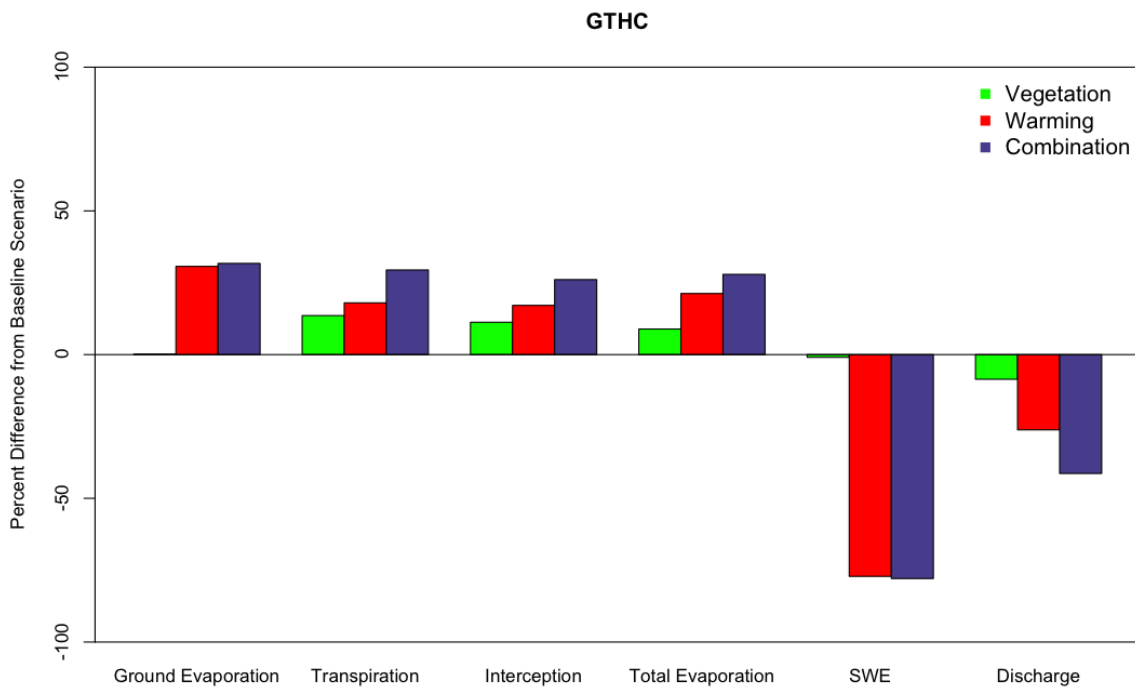


Figure 4.9 Percent difference from the baseline scenario for the GTHC transect.

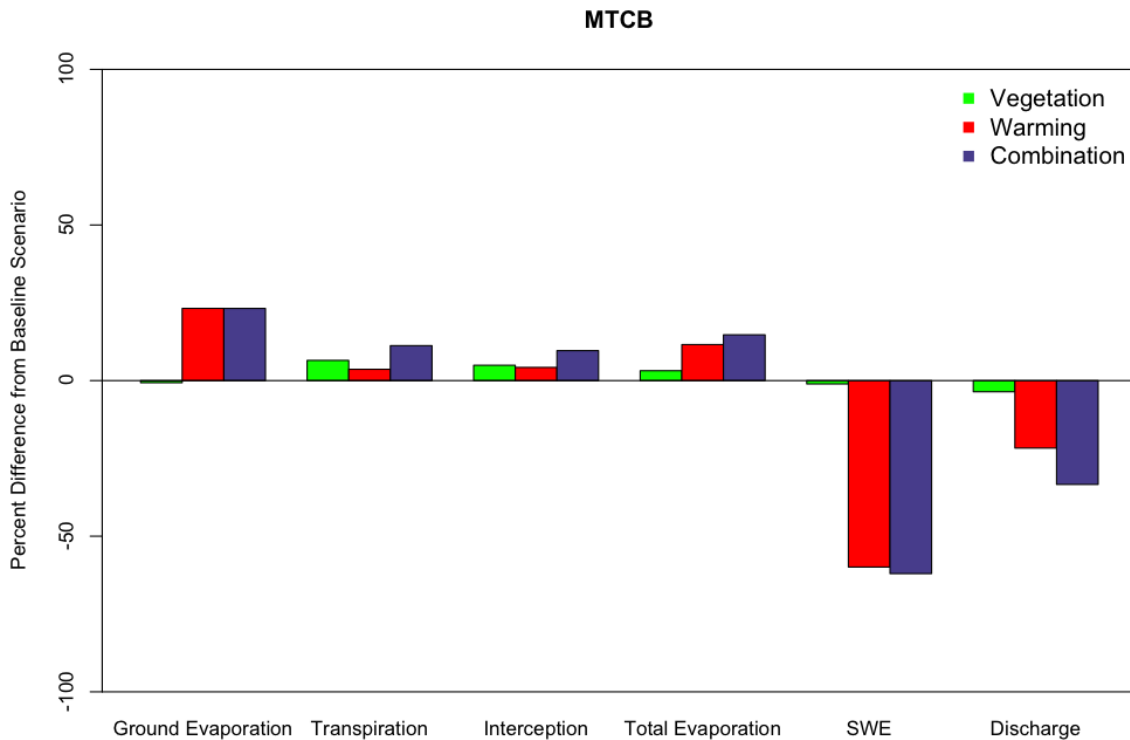


Figure 4.10 Percent difference from the baseline scenario for the MTCB transect.

4.3 Transect Comparison

The results above indicate warming plays a larger role than vegetation change, but the combination of the two amplifies the hydrologic response. In addition, model results suggest each hillslope transect responds differently depending on its orographic location, land cover, soil and geologic properties. The discharge patterns for each transect can be tracked in their respective soil moisture patterns. Soil moisture is also an indicator of how much water is available for vegetative and atmospheric uptake. Therefore a heavy focus for the transect comparison will be on soil moisture changes.

The vegetation scenario, regardless of the amount of vegetation change, increased interception, transpiration and total evaporation for each transect.

However, soil moisture only decreased in the HDW and GTHC transects, both of which contained the greatest vegetation changes, 49% and 20% respectively. These soil moisture decreases correlated with the rise in total evaporation, which was a result of spring and summer plant productivity. However, after the monsoonal rains began, the soil moisture replenished back to baseline conditions. These changes were a result of increased water demand and interception from the open Shrublands as they have a larger canopy and deeper rooting depths. Increased canopy allows for an increase in interception of precipitation and an increase in transpiration. Increased canopy cover also provides vegetative shading and snowpack found in between and below the shrubs. In the winter, the increased canopy causes a lag in snowpack development due to increased interception and evaporation, while the lower snowpack levels allow for an increase in sublimation. The deeper rooting depth of the shrubs allow access to water from the deeper soil layers, maintaining evapotranspiration for a longer period of time in relation to the previously present shallow rooted grasslands. While all these changes were present in each transect, the magnitude of these changes did not respond the same. The effect from vegetation depended on the differences in amount of open Shrublands present, as well as hillslope forcing temperature and precipitation ranges. The largest vegetation and ET changes were seen in the HDW transect, however, the largest discharge change was seen in the GTHC transect. GTHC had an 8.6% decrease in discharge, which is 2% larger than HDW and 5% larger than MTCB. This outcome is likely because GTHC receives the least precipitation and the

least amount of precipitation that falls as snow. This transect also has the lowest overall soil saturation values and has the flashiest system response, with a majority of discharge contributions coming from baseflow. These forcing, flow and saturation differences make GTHC a moisture-limited system and therefore generate an increased response in discharge. The MTCB transect was the least impacted which is likely a result of the minimal vegetative change.

The warming caused an increase in ET, total evaporation and ground evaporation. The warming also generated an earlier snow-rain stemming from an increase in the atmospheric moisture deficit as well as depleted snowpack, a result of the delayed snowfall, increased sublimation and increased snow-rain transition. This scenario caused a large amount All of these changes amounted to a larger system response in discharge and storage depletions than the vegetation scenario. In the HDW transect, spikes in soil moisture can be found in the winter as some days were able to breach temperatures large enough to initiate snowmelt. In the summer months, saturation had and overall decline, but spiked during precipitation events. The GTHC transect has large changes in soil moisture during and just after completion of snowmelt. In May, an extended period of soil moisture decline arises until July, when the monsoonal event arrives. MTCB also, see a prolonged dry period after snowmelt and before the monsoonal event begins. Again, GTHC had the greatest change in discharge, which is likely the result of its moisture limitations. Overall, GTHC had a 26% decrease in discharge, which is 20% larger than HDW and 5% larger than MTCB.

The combination scenario caused the largest depletions in discharge and storage as the increased ET, and snowpack lag from the vegetation scenario combined with the increased atmospheric moisture demand and precipitation and snowmelt day transitions from the warming scenario to create an enhanced system response. These enhanced changes occurred within each transect, showing again, that these changes develop regardless of orographic location. However, the orographic location does play a strong role in the magnitude of response. The GTHC and MTCB transects saw similar declines and prolonged dry periods in soil moisture to the warming scenario, while the HDW transect saw large declines only in the summer months, a result of increased vegetative demand and the increased growing season. Again, the more moisture limited transects (GTHC and MTCB) saw the greatest decreases in discharge and soil moisture. GTHC had a 41% decrease in discharge which is 8% greater than MTCB and 25% greater than HDW.

CHAPTER 5

DISCUSSION

The results indicate that the response of each of these systems is dependent both on its orographic location and its inherent properties as each transect experienced different temporal and percent differences. It is also evident, as discussed above, that vegetation change further enhances the changes generated from the warming scenario alone and as natural vegetation change is unlikely to occur without increased warming, the focus for the rest of the discussion will be on the warming and combination scenarios only. Understanding each transects contribution to the East River catchment is important for determining the magnitude at which these changes will alter the catchment water quality and quantity.

The HDW transect had the least changes in discharge (6%-17%) but had the largest temporal variations in discharge timing. As the HDW transect is located in the headwaters reach of the East River catchment, its contributions to the system are important as it receives the largest amount of precipitation and therefore provides the largest amount of water to the catchment. Therefore the future scenarios bring important implications to the catchments water quality and quantity. During the warming scenario and combination scenarios, peak discharge from both snowmelt and the monsoon were significantly reduced. The snowmelt peak occurred about 1 month earlier than the baseline, while the monsoonal peak ranged from 0.5 to 1 month earlier. Both scenarios also contributed to peaks in discharge during warmer weather winter events. Also, magnitude of the snowmelt peak discharges decreased below that the

monsoonal peaks. Regardless of the exact timing differences between these scenarios they will likely result in changes in nutrient loading timing and concentrations as well as contribute to other geochemical and microbial changes within the system as sustained decreases in discharge will likely result in increased soil and water temperatures.

The GTHC transect had the largest declines in stream discharge, while temporal changes were minimal. Discharge declines ranged from 26% to 41% however, this transect receives the least amount of precipitation and supplies the least amount of water to the catchment. Therefore, these large declines in discharge may not amount to much change within the entire catchment. Its minimal changes in discharge timing mean that its contributions to altering water quality within the catchment will also be minimal. However, as mentioned earlier, the orographic location of this transect as well as its inherent geology, make it moisture limited. Therefore, with the warming and combination scenarios, this transect experienced a 1.5 month increase in depleted soil moisture in comparison to the baseline. While this change may not amount to large changes in catchment water quantity or quality, it can amount to large alterations in the present vegetation on this transect.

The MTCB transect experienced intermediate changes in stream discharge with declines ranging between 22% and 33%. It also had shifts in peak discharge, with water entering the stream 1 month earlier in comparison to the baseline. This transect, like the HDW transect, supplies a large amount of water to the catchment. Therefore, these changes bring similar implications for the catchments water quality and quantity. Due to the warmer temperatures of this transects orographic location, as well as its inherent structure, it experienced large depletions in soil moisture, similar to that of the GTHC

transect, with dry periods extending out an additional month, however, the moisture in the bottom soil layer experienced sustained decreases overall, with the exception of snowmelt. Again, this can lead to negative implications for vegetation growth and productivity. As this catchment provides a large amount of water to the catchment changes in vegetation may also add additional changes in nutrient loading to the catchment.

All of these results show that this model is capable of not only capturing the natural system complexity and heterogeneity between each transect by modeling system behavior, but it's also capable of capturing the variation in hydrologic response to future changes. The high-resolution aspect of this model has allowed for the understanding of how Shrublands and increased warming will alter the system and at what magnitudes given different locations within the domain. This has allowed for pinpointing locations within the domain that are likely to have the largest changes and produce the largest water quantity and quality implications. This model also compares extremely well to the RMBL meadow warming experiments as the warming and combination scenarios for the GTHC and MTCB transects experienced losses of soil moisture, with prolonged decreases in the bottom soil layer. This shows that CLM is capable of modeling the vegetative response of deep-rooted shrubs. It also shows that warming causes additional stress on these environments. Not only, do the model results correspond to the field observations of the meadow warming experiments, but the warming scenario results also correspond to the PRMS model study of Battaglin et al., (2011), where they found peak snowmelt shifted by 1 month, earlier snow-rain transitions occurred in the spring, snowpack decreased and discharge decreased. However, since this model was

done at a much lower resolution, PRMS was not able to determine what the decreases in streamflow were attributable to. The benefit of the model developed in this study is that it is a high enough resolution that it can determine not only why these changes are occurring, but it can also determine where these changes are occurring.

CHAPTER 6

CONCLUSIONS

In this study, a high-resolution, integrated hydrologic model of the East River headwaters catchment was developed using ParFlow. This model was used to study the impact of hydrologic response under different worst-case future climate scenarios, including increased warming, vegetation change and the combination of the two. Modeled streamflow from each transect captured the observed natural variability in the real system (Figure 4.1). Vegetation change, increased temperature and their combination resulted in earlier peak streamflow timing, and decreases in discharge and storage across transects. The addition of vegetation change to increased warming projections led to enhanced predictions as the combination of both scenarios intensified evaporative losses. Overall, discharge and storage losses equated to 4%-41% and 1%-4%, respectively.

The hydrologic responses perturbed from temperature increases shown here (e.g. snow depletions, earlier melt time, precipitation transitions and decreased discharge) are similar to prior studies (Battaglin et al, 2011; Fyfe and Flato, 1999; Rangwala et al., 2013; Stewart et al., 2004; Stewart, 2009). These results also correspond with those seen in the meadow warming experiments, such as the tie between decreased soil moisture and increased ET (Harte et al., 1995).

The use of field study results such as those from the meadow warming experiments (Harte et al., 1995; Harte and Shaw, 1995; Saleska et al., 1999) further enhanced model predictions of a future climate as the inclusion of vegetation change

with warming predictions caused additional decreases in discharge by 10-15%. Many hydrologic models do not include vegetation change when considering hydrologic response to climate change. This study shows the importance it can have in moisture limited systems, like those of the Colorado River Basin. The 10-m resolution also enhances site prediction as individual hillslope response is captured, allowing for the indication of which locations within the catchment will experience the largest changes.

The model results shown here also provide further insight into what may happen with both nutrient cycling and future vegetation change. Subsurface carbon losses in the meadow warming experiment of Saleska et al, (1999) were associated with moisture declines, a result modeled here. Therefore, this catchment may see carbon losses within the subsurface, resulting in alterations of nutrient and biogeochemical cycling. The studies of Allen et al., (2010), Edburg et al., (2012), van Mantgem et al., (2009), and Williams et al., (2013) found tree mortality a likely result of increased temperature and extended periods of decreased soil moisture, again, changes modeled here. Therefore, the East River headwaters catchment may experience losses in vegetation productivity and possibly experience tree mortality. These nutrient cycling and vegetation changes can have further negative implications on water quantity and quality when extended to the entire Colorado River Basin, especially if decreases in discharge range from 6%-41%, as predicted in this study (warming and combination scenario only). To further understand these predictions and the response of the larger system, the combination scenario should be applied to the large model domain. If discharge response is similar to that of the transects shown here, the model area should be extended out to include other portions the Upper Colorado River Basin.

To aid in refining hydrologic conceptualization and model parameterization, on-going data collection has been put in place for the East River headwaters catchment. Over the last year the site has seen the installation of 10 pressure transducers for the collection of stream discharge, weekly and daily stream isotope and nutrient sampling data collection, soil data collection, peak snowpack collection and hyporheic sampling. Within the next year, high-resolution geophysical data and the installation of monitoring wells will have been completed. In the mean time this model can be used to drive field efforts by locating areas of hydrologic importance. In the near term, when this data becomes available, the coupling of this model with microbial, geochemical and nutrient cycling processes will aid in the understanding of ecosystem response and its effect on water quality, improving the understanding of the current and future systems of the East River headwaters catchment.

REFERENCES CITED

- Allen, C.D., A.K. Mcalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H. Hogg, P. Conzalex, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J. Lim, G. Allard, S.W. Running, A. Semerci, N. Cobb (2010), A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, 259(4), 660-684, doi: 10.1016/j.foreco.2009.09.001
- Ashby, S.F., and R. D. Falgout (1996), A parallel multigrid preconditioned conjugate gradient algorithm for groundwater flow simulations. *Nuclear Science and Engineering*, 124(1), 145-159.
- Battaglin, W.A., L.E. Hay, S.L. Markstrom (2011), Simulating the potential effects of climate change in two Colorado basins and at two Colorado ski areas. *Earth Interactions*, 15(22), 1-23, doi: 10.1175/2011EI373.1
- Battaglin, W.A., L.E. Hay, S.L. Markstrom (2012), Watershed Scale Response to Climate Change-East River Basin, Colorado. U.S. Geological Survey Fact Sheet 2011-3126
- Beniston, M., H.F. Diaz, R.S. Bradley (1997), Climatic change at high elevation sites: an overview. *Climatic Change*, 36(3-4) 233-251, doi: 10.1023/A:1005380714349
- Brad Taylor, personal communication, September 2014.
- Central Basin Municipal Water District (2014), Available from:
<http://www.centralbasin.org/blog/2014/02/14/stretching-the-colorado-river/>
- Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, P. Whetton, (2007), 2007 Regional Climate Projections. *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, M. Wehner, (2013), Long-term Climate Change: Projections, Commitments and Irreversibility. *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Edburg S.L., J.A. Hick, P.D. Brooks, E.G. Pendall, B.E. Ewers, U. Norton, D.J. Gochis, E.D. Gutmann, A.J. Meddens (2012): Cascading impacts of bark beetle-caused tree mortality on coupled biogeophysical and biogeochemical processes. *Frontiers in Ecology and the Environment* 10, 416-424, doi: 10.1890/110173

EPA (2014), Environmental Protection Agency, Clean Air Status and Trends Network, Available from: http://java.epa.gov/castnet/epa_jsp/prepackageddata.jsp

Fan, Y., G. Miguez-Macho, C.P. Weaver, R. Walko, A. Robock (2007), Incorporating water table dynamics in climate modeling: 1. Water table observations and equilibrium water table simulations. *J. of Geophysical Research*, 112(D10), 1-17, doi: 10.1029/2006JD008111

Fayfe, J.C., G.M. Flato (1999), Enhanced climate change and its detection over the rocky mountains. *Journal of Climate*, 12(1), 230-243, doi: 10.1175/1520-0442-12.1.230

Gleeson, T., L. Smith, N. Moosdorf, J. Hartmann, H.H. Durr, A.H. Manning, L.P.H van Beek, A.M. Jellinek (2011), Mapping permeability over the surface of the earth. *Geophysical Research Letters*, 38, 1-6, doi: 0094-8276/11/2010GL045565

Harte, J., R. Shaw (1995), Shifting dominance within a montane vegetation community: results of a climate-warming experiment. *Science*, 267(5199), 876-880, doi: 10.1126/science.267.5199.876

Harte, J., S.T. Margaret, C. Fang-Ru, B. Feifarek, A.P. Kinzig, R. Shaw, K. Shen (1995), Global warming and soil microclimate: results from a meadow-warming experiment. *Ecological Applications*, 5(1), 132-150, doi: 10.2307/1942058

- Hubbard R.M., C.C. Rhoades, K. Elder, J. Negron (2013). Changes in transpiration and foliage growth in lodgepole pine trees following mountain pine beetle attack and mechanical girdling. *Forest Ecology and Management*, 289, 312-317, doi: 10.1016/j.foreco.2012.09.028
- Jiang, X., S.A. Rauscher, T.D. Ringler, D.M. Lawrence, A.P. Williams, C.D. Allen, A.L. Steiner, D.M. Cai, N.G. McDowell (2013), Projected future changes in vegetation in Western North America in the twenty-first century. *Journal of Climate*, 26(11) 3671-3687, doi: 10.1175/JCLI-D-12-00430.1
- Jones J.E. and C.S. Woodward (2001). Newton-krylov-multigrid solvers for large-scale, highly heterogeneous, variably saturated flow problems. *Advances in Water Resources*, 24:763-774.
- Kollet, S.J., and R. M. Maxwell (2006), Integrated surface-groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model. *Advances in Water Resources*, 29(7), 945-958
- Kollet, S.J. and R.M., Maxwell (2008), Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model. *Water Resources Research*, 44, W02402
- Kollet, S.J., R.M., Maxwell, C.S., Woodward, S.G., Smith, J., Vanderborght, H., Vereecken, and C., Simmer, (2010), Proof-of-concept of regional scale hydrologic resolution utilizing massively parallel computer resources. *Water Resources Research*, 46, W04201, doi:10.1029/2009WR008730
- Kurz, W.A., C.C. Dymond, G. Stinson, G.J. Rampley, E.T. Neilson, A.L. Carroll, T. Ebata, L. Safranyik (2008) Mountain pine beetle and forest carbon feedback to climate change. *Nature*, 452, 987-990, doi: 10.1038/nature06777
- Maxwell, R.M. and N.L. Miller (2005) Development of a coupled land surface and groundwater model. *Journal of Hydrometeorology*, 6(3), 233-247
- Maxwell, R.M. (2013), A terrain-following grid transform and preconditioner for parallel, large-scale, integrated hydrologic modeling. *Advances in Water Resources*, 53:109-117, doi:10.1016/j.advwatres.2012.10.001

- NOAA (2015), National Oceanic and Atmospheric Administration, National Climatic Data Center, Available from: <http://www.ncdc.noaa.gov/cdo-web/datatools/normals>
- NRCS (2014a), Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, Web Soil Survey, Available from <http://websoilsurvey.nrcs.usda.gov/>
- NRCS (2014b), U.S. Department of Agriculture, Natural Resource Conservation Service, Snow Telemetry and Snow Course Data Products, Available from: <http://www.wcc.nrcs.usda.gov/snow/index.htm>
- Osei-Kuffuor, D., R.M., Maxwell, C.S., Woodward (2014), Improved numerical solvers for implicit coupling of subsurface and overland flow. *Advances in Water Resources*, 74, 185-195, doi:10.1016/j.advwatres.2014.09.006
- Rangwala, I., E. Sinsky, J.R. Miller (2013), Amplified warming projections for high altitude regions of the northern hemisphere mid-latitudes from CMIP5 models. *Environmental Research Letters*, 8(2), 024040, doi: 10.1088/1748-9326/8/2/024040
- Reserve on the East River (2014), Available from: <http://www.reserveontheeastriver.com/location/>
- Saleska, S.R., J. Harte, M.S. Torn (1999), The effect of experimental ecosystem warming on CO₂ fluxes in a montane meadow. *Global Change Biology*, 5(2), 125-141, doi: 10.1046/j.1365-2486.1999.00216.x
- Stewart, I.T. (2009), Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes*, 23(1), 78-94, doi: 10.1002/hyp.7128
- Stewart, I.T., D.R. Cayan, M.D. Dettinger (2004), Changes in snowmelt runoff timing in western north America under a 'business as usual' climate change scenario. *Climatic Change*, 62(1-3), 217-232 doi: 10.1023/B:CLIM.0000013702.22656.e8

Van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fule, M.E. Harmon, A.J. Larson, J.M. Smith, A.H. Taylor, T.T. Veblen (2009), Widespread increase of tree mortality rates in the western united states. *Science*, 323(5913), 521-524, doi: 10.1126/science.1165000

Welch, L.A., D.M. Allen (2014), Hydraulic conductivity characteristics in mountains and implications for conceptualizing bedrock groundwater flow. *Hydrology Journal*, 22, 1003-1026, doi: 10.1007/s10040-014-1121-5

Willaims, A.P., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, S.A. Rauscher, R. Seager, H.D. Grissino-Mayer, J.S. Dean, E.R. Cook, C. Gangodagamage, M. Cai, N.G. McDowell (2013), Temperature as a potent driver of regional drought stress and tree mortality. *Nature Climate Change*, 3, 292-297, doi: 10.1038/nclimate1693

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, G. Xian (2013), A comprehensive change detection method for updating the National Landcover Database to circa 2011. *Remote Sensing of Environment*, 132, 159-175

USCD (2015), U.S Climate Data, Available from: <http://www.usclimatedata.com/>

USGS (2014), U.S. Department of the Interior, U.S. Geological Survey, The National Elevation Dataset, Available from: <http://viewer.nationalmap.gov/viewer/>

USGS and AASG (2014), U.S. Geological Survey and Association of American State Geologists, The National Geologic Map Database, Available from: <http://ngmdb.usgs.gov/maps/mapview/>