DISSERTATION

# QUANTIFYING FUTURE WATER RESOURCES AVAILABILITY AND AGRICULTURAL PRODUCTIVITY IN AGRO-URBAN RIVER BASINS

Submitted by

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# ABSTRACT

## QUANTIFYING FUTURE WATER RESOURCES AVAILABILITY AND AGRICULTURAL PRODUCTIVITY IN AGRO-URBAN RIVER BASINS

Climate change can have an adverse effect on agricultural productivity and water availability in semi-arid regions, as decreases in surface water availability can lead to groundwater depletion and resultant losses in crop yield due to reduced water for irrigation. Competition between urban and agricultural areas intensifies groundwater exploitation as surface water rights are sold to growing municipalities. These inter-relationships necessitate an integrated management approach for surface water, groundwater, and crop yield as a holistic system.

This dissertation provides a novel integrated hydrologic modeling approach to quantify future water resources and agricultural productivity in agro-urban river basins, particularly in arid and semi-arid regions where surface water and groundwater are managed conjunctively to sustain urban areas and food production capacity. This is accomplished by i) developing an integrated hydrologic modeling code that accounts for groundwater and surface water processes and exchanges in large regional-scale managed river basins, and demonstrating its use and performance in the economically diverse South Platte River Basin (SPRB), a 72,000 km$^2$ river basin located primarily in the state of Colorado, USA; ii) using the model to understand possible future impacts imposed by climate variation on water resources (surface water and groundwater) and agricultural productivity; and iii) quantifying the combination impacts of agriculture-to-urban water trading and climate change on groundwater resources within the basin.

This dissertation presents an updated version of SWAT-MODFLOW that allows application to large agro-urban river basins in semi-arid regions. SWAT provides land surface hydrologic and crop yield modeling, whereas MODFLOW provides subsurface hydrologic modeling. Specific code changes include linkage between MODFLOW pumping cells and SWAT HRUs for groundwater irrigation and joint groundwater and surface water irrigation routines. This conjunctive use, basin-scale long-term water resources and crop yield modeling tool can be used to assess future water and agricultural management for large river basins across the world. The updated modeling code is applied to the South Platte River Basin, with model results tested against streamflow, groundwater head, and crop yield throughout the basin.

To assess the climate change impacts on water resources and agricultural productivity, the coupled SWAT-MODFLOW modeling code is forced with five different CMIP5 climate models downscaled by Multivariate Adaptive Constructed Analogs (MACA), each for two climate scenarios, RCP4.5, and RCP8.5, for 1980-2100. In all climate models and emission scenarios, an increase of 3 to 5 °C in annual average temperature is projected by the end of the 21st century, whereas variation in projected precipitation depends on topography and distance from the mountains. Based on the results of this study, the worst-case climate model in the basin is IPSL-CM5A-MR-8.5. Under this climate scenario, for a 1 °C increase in temperature and the 1.3% reduction in annual precipitation, the basin will experience an 8.5% decrease in stream discharge, 2-5% decline in groundwater storage, and 11% reduction in crop yield.

In recent decades, there has been a growing realization that developing additional water supplies to address new demands is not feasible. Instead, managing existing water supplies through reallocations is necessary to tackle water scarcity and climate change. However, third-party effects associated to water transfers has limited the growing water market. This study also quantifies the combination impacts of agriculture-to-urban water trading (widely known as ‘buy and dry’) and climate change on groundwater availability in semi-arid river basins through the end of 21st century, as groundwater pumping increases to satisfy irrigation water lost to the urban sector. For this analysis, we use the hydrological modeling tool SWAT-MODFLOW, forced by projected water trading amounts and two downscaled GCM climate models, each for two emission scenarios, RCP4.5 and 8.5. According to the results of this study, agriculture-to-urban water trading imposes an additional basin-wide 2% reduction in groundwater storage, as compared to changes due to climate. However, groundwater storage changes for local subbasins can be up to 8% and 10% through the mid-century and end of the century, respectively.

# ACKNOWLEDGEMENTS

This endeavor is the result of pursuing my dreams, however, it would not have been possible without supportive people throughout my life.

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I could not have undertaken this journey without the trust, sacrifice, and emotional support of my affectionate mom, my dearest husband, Alireza, my lovely son, Kian, and every member of my family in Iran. The way they believed in me made me believe in myself. I dedicate this dissertation to my late father who passed away a week before starting my Ph.D. program. Thank you dad for always reminding me that I am much stronger than I think I am.

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# Chapter 1. INTRODUCTION AND OBJECTIVES

## 1.1. INTRODUCTION

Uneven distribution of freshwater resources has caused competition between sectors of agricultural, municipalities, and industry, with this competition increasing annually due to changes in population, land use, and climate patterns. In recent years, water demand has been exceeded supply in many regions across the world, particularly in Africa, Middle East, and South Asia (De Teixeira & Bassoi, 2009), and will exacerbate in the upcoming years. According to the U.S. Intelligence Community Assessment of Global Water Security, by 2030, global fresh water demand will surpass the current water supply by 40 percent (ICA, 2012). Integrated management of surface water and groundwater is the key to achieving sustainable water resources and secure water availability, especially in arid and semi-arid regions of the world. With generally scarce surface water resources, groundwater often is the primary source of water supply in such regions. For example, in the western U.S., groundwater is a strategic water resource used for drinking, sanitation, and hygiene by nearly 10 million people. Groundwater is also critical to irrigated agriculture, especially at the time of drought. Unsustainable groundwater pumping is depleting many western U.S. groundwater aquifers. Current business-as-usual scenarios may lead to groundwater resource depletion while it is needed to aid in climate change adaptation efforts (Perrone & Jasechko, 2017). Climate change can have an adverse effect on agricultural productivity and water availability in semi-arid regions, as changes in surface water availability lead to groundwater depletion and resultant losses in crop yield. Since agricultural productivity is linked intrinsically to available water (Walthall et al., 2013), projections in crop yield must be preceded by projections in the water supply. The complex interaction between crop growth, climate and environment makes the projection of agricultural outcome to climate change a challenging study subject. These inter-relationships necessitate an integrated management approach for surface water, groundwater, and crop yield as a holistic system. In recent years, the increased awareness regarding the importance of having a holistic perspective on water resources and agricultural productivity for management purposes has triggered the development and use of coupled surface/ subsurface models that simulate physically-based, spatially-distributed land surface hydrologic processes and subsurface hydrologic processes.

In recent decades, there has been a growing realization that developing additional water supplies to address new demands is not feasible. Instead, managing existing water supplies through reallocations is necessary to tackle water scarcity and climate change. Traditionally, water demand for urban, industrial, and agriculture needs is supplied from local supplies of surface water (lakes, rivers, reservoirs) and groundwater; however, climate change, population growth, urbanization, increasing environmental demands and fiscal cost of water supply augmentations has limited the ability of communities to meet the demand by conventional methods. As the possibility of developing additional water supply is exhausted, keeping pace with increased demand necessitates the reallocation of existing water supply among competing demands through water trading. However, third-party effects associated to water transfers has limited the growing water market. As a way to minimize the direct and indirect effects on areas of water trading origin and maintain food production, for instance in the case of removing surface water irrigation from irrigated lands, producers can switch to an alternative water supply such as groundwater irrigation, using local groundwater wells drilled either into local unconfined or confined aquifers. However, this practice can also lead to detrimental effects, such as localized and regional groundwater depletion, which can exhaust future regional water supplies.

## 1.2. OBJECTIVES

Through this dissertation I aim to develop a hydrologic modeling platform that enables water resources managers to study the conjunctive variation of groundwater, surface water, and agricultural productivity in various climatic and non-climatic conditions. This dissertation aims to:

1. Present an integrated hydrologic model that accounts not only for surface water and groundwater hydrologic processes and their interaction, but also the management schemes that transfer water between the domains in a semi-arid, heavily managed agro-urban large river basin.
2. Provide insight into possible future impacts imposed by climate change on water resources and crop yield in basin-scale complex semi-arid river basins.
3. Assess the impacts of agriculture-to-urban water trading on local and regional groundwater storage and crop yield in a mixed agro-urban river basin through the 21st century, within the context of a changing climate.

The region of focus is the South Platte River Basin (SPRB) (72,000 km$^2$), a region of Colorado, USA. The basin dominated by large urban areas along the front range of the Rocky Mountains and agriculture regions to the east, with intensive irrigation and water right transfer practices. The SPRB is projected to experience the largest urban expansion in the state by 2050, straining already tight water supplies and enhancing competition among various water users such as municipal, industry, agriculture, environment and recreation (CWCB, 2019). The method presented here is applicable to similar regions across the world.

Each objective forms the basis for a journal article. The first objective is outlined extensively in a journal article entitled ‘Coupled SWAT-MODFLOW Model for Large-Scale Mixed Agro-Urban River Basins,” in *Environmental Modeling and Software (EMS) Journal*

(Aliyari et al., 2019) . The second objective is published in *Science of the Total Environment (STOTEN) Journal*: ‘Appraising Climate Change Impacts on Future Water Resources and Agricultural Productivity in Agro-Urban River Basins’ (Aliyari et al., 2021), and the third objective is delineated in an article entitled ‘The Hydrologic Impact of Agriculture-to-Urban Water Transfers on Groundwater Resources in a Large River Basin’ which is under review with *Water Resources Research*.

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# Chapter 2. COUPLED SWAT-MODFLOW MODEL FOR LARGE-SCALE MIXED AGRO-URBAN RIVER BASINS[1]

## 2.1. INTRODUCTION

A significant portion of the world's population lives in semi-arid and arid regions, with over half of the population living in urban areas (United Nations, 2014). This disproportionate distribution of people and allotment of water resources present a challenge in dry regions and mandate the implementation of strategies such as water reuse and desalination of salty water in such places to secure adequate water supplies to support growing populations (Shirazi et al., 2018). Moreover, often there is an aggressive competition within a single river basin from the municipal, agricultural, industrial, environmental, and recreational sectors over the use of the limited supply of water. Competition between urban and agricultural demand occurs worldwide (Florke et al., 2018). In the western United States, Chile and Mexico, increasing population has led to the transfer of water rights from irrigated agriculture to municipalities via agricultural lands dry-up or water leasing programs (Meinzen-Dick and Appasamy, 2002; Doherty and Smith, 2012). Groundwater in rural areas is particularly vulnerable as the transfer of surface water rights to urban areas increases reliance on groundwater resources, leading to a decrease in groundwater levels and overall groundwater storage (Knapp, 2003). Also, removing surface water irrigation decreases seepage from earthen irrigation canals and deep percolation from applied surface water irrigation,

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thereby removing a source of groundwater and leading to additional groundwater storage depletion.

In such a complex water resources network, wherein both surface water and groundwater resources are managed conjunctively to satisfy all social sectors, physically-based distributed hydrological models can be used to quantify water availability under current and future conditions and determine appropriate integrated water management policies. Hydrological models typically are developed based on (i) surface runoff models that consider groundwater in a simplistic manner, such as the Hydrologiska Byråns Vattenbalansavdelning [HBV] (Bergstrom and Forsman, 1973; Bergstrom, 1992), the Sacramento Soil Moisture Accounting Model [SAC-SMA] (Burnash et al. 1973), TOPMODEL (Beven and Kirby, 1979), the Variable Infiltration Capacity [VIC] (Liang et al., 1994), the Hydrologic Modeling System [HEC-HMS] (William et al., 1995; U.S. Army Corps of Engineers, 2016), the Soil and Water Assessment Tool [SWAT] (Arnold et al., 1998), the Soil and Water Integrated Model [SWIM] (Krysanova et al., 2000), the Hydrology Laboratory Research Modeling System [HL-RMS] (Koren et al., 2004), and the Water—Global Assessment and Prognosis [WaterGAP] (Verzano, 2009); or (ii) groundwater models that consider surface water in a simplistic manner, such as the Modular Finite-Difference Flow Model [MODFLOW] (Harbaugh, 2005), the Microcomputer Package for Multiple-Aquifer Groundwater Flow Modeling [MicroFEM] (Diodato, 2000), the Object-Oriented Quasi Three-Dimensional Regional Groundwater Model [ZOOMQ3D] (Jackson, 2001), the SoilVision Systems Ltd. Finite Element Seepage Analysis Program [SVFLUX] (Thode and Fredlund, 2013), and the Finite Element Heat and Mass Transfer Code [FEHM] (Zyvoloski et al., 2015).

Such analysis to quantify water supply for management purposes and vulnerability assessments in river basins can result in unrealistic inferences and subsequent ineffective decisions. Therefore, detailed representation of both surface water and groundwater processes, and also their interaction, must be included. In recent years a third category of hydrological models has emerged, in which surface water and groundwater processes are linked. Some of these models solve the groundwater and surface water equations simultaneously in a single software package, such as the Catchment Hydrology Model [CATHY] (Paniconi and Wood, 1993), the Integrated Hydrology Model [InHM] (VanderKwaak and Loague, 2001), HydroGeoSphere [HGS] (Therrien et al., 2010), OpenGeoSys (Kolditz et al., 2012), the PCRaster Global Water Balance Model [PCR-GLOBWB-MOD] (Sutanudjaja et al., 2014) and the Parallel Flow model [ParFlow] (Maxwell et al., 2016) , while others couple two or more different modeling codes to simulate the groundwater and surface water interactions, such as MIKE-SHE (Refsgaard and Storm, 1995; DHI, 2017), SWATMOD (Sophocleous et al., 1999), MODHMS (HydroGeoLogic, 2006), the grid-based Water Flow and Balance Simulation Model [WaSiM-ETH] (Schulla and Jasper, 2007), the Coupled Groundwater and Surface-Water Flow Model [GSFLOW] (Markstrom et al., 2008), the Finite Element subsurface FLOW system [FEFLOW] (DHI-WASY GmbH, 2016), and SWAT-MODFLOW (Kim et al., 2008; Guzman et al., 2015; Bailey et al., 2016). Several of these models have been applied at the river basin and even continental scale (Therrien et al., 2010; Maxwell et al., 2016), although the vast majority of model applications have been at the small regional scale, and largely restricted to either theoretical studies or studies aimed at specific governmental municipalities, with the latter often remaining unpublished (Guzman et al., 2015; Barthel and Banzhaf, 2016).

The development of a versatile integrated hydrological modeling code that accounts for all major water pathways and transfers in an agro-urban system at a large geographic scale river basin, such as in the updated version of coupled SWAT-MODFLOW presented in this study, is essential for quantifying and managing water resources. Only at this scale can anthropogenic, social and managerial factors along with complexity and heterogeneity of the system be reflected in simulations (Irvine et al., 2012; Barthel and Banzhaf, 2016). All previous versions and applications of SWAT-MODFLOW (e.g. Sophocleous et al., 1999; Sophocleous and Perkins, 2000; Menking et al., 2003; Galbiati et al., 2006; Kim et al., 2008; Luo and Sophocleous et al., 2011; Guzman et al., 2015; Bailey et al., 2016) have been applied to small watersheds or been used to estimate specific water balance components (runoff, recharge, groundwater-surface water exchange rates). None have been applied to large river basins of mixed agro-urban land use types with the accompanying water transfer complexity (e.g. groundwater pumped for irrigation, surface water diverted for irrigation, seepage from canals, seepage from artificial recharge ponds, etc.).

The overall objective of this paper is to present an integrated hydrologic modeling code that accounts not only for surface water and groundwater hydrologic processes and their interaction, but also the management schemes that transfer water between the domains in a semi-arid, heavily managed agro-urban large river basin. Specifically, this study: i) develops an integrated hydrologic modeling code that accounts for groundwater and surface water processes and exchanges in large regional-scale managed river basins, and ii) demonstrates the use and performance of the integrated model in the economically diverse South Platte River Basin (SPRB), a 72,000 km$^2$ river basin located primarily in the state of Colorado, USA. Although the model is based on the available SWAT-MODFLOW modeling code (Bailey et al., 2016), it has several key advances, including linkage between MODFLOW pumping and SWAT HRU applied irrigation; quantifying the irrigation amount based on both surface water (canal diversions) or groundwater (pumping); ability to store large arrays for linking MODFLOW grids and SWAT watersheds with thousands of grid cells and HRUs, respectively; and using the MODFLOW-PSB package that partitions groundwater stresses into specific surface water and groundwater water budget terms. Application to the SPRB is an ideal test for the model in that total volume of surface water diversions in the SPRB is about twice the primary surface water supply (i.e., snowmelt runoff), indicating a significant reliance on groundwater recharge to surface water (Dozier et al., 2017). Diverted surface water recharges the aquifer, which later discharges to the stream, repeating multiple times as surface water flows towards the outlet of the river basin (Waskom, 2013). The surface water and alluvial groundwater in the SPRB are in close interaction and are considered as a single resource of water by Colorado water law. In general, the results of this model demonstrate the applicability of integrated hydrological modeling for developing an improved understanding of linked groundwater and surface water systems and can be used in other studies to identify water management solutions.

## 2.2. SWAT-MODFLOW MODELING CODE FOR LARGE-SCALE RIVER BASINS

This section outlines the modification of the SWAT-MODFLOW modeling code (Bailey et al., 2016) for application to semi-arid agro-urban large-scale river basins. Theoretical descriptions of SWAT, MODFLOW, and SWAT-MODFLOW are provided, followed by a description of modifications and enhancements to SWAT-MODFLOW.

### 2.2.1. SWAT

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Arnold et al., 2012a), is a physically based quasi-distributed model that operates on a daily time step. It is designed to simulate the movement of water, sediment, nutrient and pesticide within a watershed and to predict the effects of climate change and best management practices on the quantity and quality of water at the watershed scale. The model divides the watershed into subbasins, with each subbasin divided into Hydrologic Response Units (HRUs) that is a unique combinations of land use, soil, and slope.

The overall hydrologic balance such as partitioning of precipitation, snowmelt water, irrigation water between surface runoff and infiltration, redistribution of water within the soil profile, interception of precipitation, and evapotranspiration are simulated for each HRU. Outputs from HRUs are lumped and directed to the subbasin stream for routing through the stream network to the outlet of the watershed.

SWAT has been used worldwide to address hydrologic and environmental problems. However, its application in assessing groundwater processes, quantities, and interaction with surface water is limited. As a quasi-distributed model, SWAT does not represent the heterogeneity of an aquifer, such as spatially-varying hydraulic conductivity and specific yield, nor the system response (hydraulic head). Moreover, SWAT is limited in simulating groundwater discharge to streams and stream seepage to the aquifer, because it compares shallow aquifer depth with a threshold to estimate the river recharge and does not consider the river bottom elevation and aquifer depth (Gassman et al., 2007; Kim et al., 2008; Arnold et al., 2012b; Gayathri et al., 2015).

### 2.2.2. MODFLOW

MODFLOW (Harbaugh, 2005) is a public domain numerical groundwater modeling code developed by the U.S. Geological Survey (USGS). The model is written in FORTRAN and solves the groundwater flow equation using the finite difference method. One of the most recent versions is MODFLOW-NWT (Niswonger et al., 2011), an algorithmic reformulation of MODFLOW-2005 that uses the Newton-Raphson method. This new algorithm performs well in highly nonlinear problems such as unconfined groundwater systems and the process of drying and rewetting of grid cells (Hunt and Feinstein, 2012).

MODFLOW simulates a variety of hydrologic processes in steady and transient states for different types of aquifers. Interactions between the land surface and groundwater and between surface water and groundwater are simulated using a variety of boundary condition packages, including the Recharge, Well, Drain, Lake, Reservoir, and Streamflow Routing packages.

### 2.2.3. SWAT-MODFLOW

The coupled SWAT-MODFLOW model (Bailey et al., 2016) links the SWAT2012 and MODFLOW-NWT model codes. The groundwater module inside the SWAT code is replaced by MODFLOW, making a single executable FORTRAN code and allowing for daily interactions between the two models without the need for writing and reading model data.

The linkage between SWAT and MODFLOW is based on mapping schemes that pass HRU-based variables (e.g. recharge from the soil zone) and subbasin-based variables (stream stage) to the MODFLOW grid, and grid-based variables (e.g. water table elevation, rate of water exchange between groundwater and the stream network) to SWAT HRUs and subbasin channels. The HRU-based recharge is mapped to MODFLOW's Recharge package, and the stream-aquifer water exchange is simulated by the River package. The geographic relation between the HRUs and grid cells and between the River cells and subbasin streams is quantified using geoprocessing routines, with the information stored in text files that are read in at the beginning of the SWAT-MODFLOW simulation. Prior to intersecting with the MODFLOW grid cells, the HRUs are split into geographically-defined Disaggregated HRUs (DHRUs).

### 2.2.4. Modified SWAT-MODFLOW Model for Agro-Urban River Basins

This section describes modifications to the original SWAT-MODFLOW code to allow for application to basin-scale agro-urban watershed systems. The overall flow of data within the code is presented in Figure 2.1. Specific modifications to the SWAT-MODFLOW code include:

i. Transfer of groundwater from the aquifer to irrigated fields, by linking MODFLOW pumping cells to SWAT HRUs (designated by "1" in Figure 2.1, and explained in detail in the last paragraph of this section);

ii. Working with the MODFLOW-PSB capability (Brown and Caldwell, 2017; Zeiler et al., 2017), in which the stresses are partitioned into multiple input files. This capability is essential for including all the groundwater sources/sinks existing in an agro-urban river basin, and for linking the soil percolation from SWAT HRUs to the correct Recharge grid (designated by "2" in Figure 2.1, and explained in detail in the last paragraph of this section);

iii. Modification of SWAT's auto-irrigation algorithms to allow surface water irrigation to supplement groundwater irrigation (i.e. if groundwater irrigation from pumping wells is not sufficient to meet crop water demands, then water will be diverted from the nearest subbasin stream);

iv. Modification of SWAT-MODFLOW subroutines that handle linking between grid cells and HRUs, to enable application to large watershed systems. For large watersheds, wherein MODFLOW grids can have hundreds of thousands of grid cells and SWAT can have tens of thousands of HRUs, extremely large arrays have resulted in insufficient memory errors when attempting to apply the original SWAT-MODFLOW code. The current change allows arrays to be allocated more efficiently, thereby enabling application to large systems such as the SPRB.

The code first reads in SWAT inputs, MODFLOW inputs, and information for mapping SWAT HRU and subbasin variables to the MODFLOW grid, and vice-versa. Compared to the original SWAT-MODFLOW code, one more text file is needed that lists MODFLOW grid cells that provide irrigation water and their associated SWAT subbasins and HRUs (“swatmf_irrigate.txt”; Figure 2.1), to enable linking for transferring pumped groundwater to the ground surface. SWAT runs through a year loop and then a day loop, with subbasin calculations performed for each day. For each subbasin, the HRU calculations are performed, including land surface hydrology, irrigation application, and soil/crop hydrologic processes. Percolation from the bottom of the soil profile and subbasin channel stage are then mapped to the MODFLOW grid cells and River cells, respectively, whereupon MODFLOW runs using the Partition Stress Boundary (PSB) capability and then maps groundwater/surface water exchange rates, groundwater irrigation depths, and water table elevation to SWAT subbasin channels and HRUs, respectively. Water entering each subbasin stream via surface runoff (SWAT), soil lateral flow (SWAT), or groundwater flow (MODFLOW) is then routed through the watershed stream network for the day.

As with the original version of SWAT-MODFLOW, SWAT is linked with MODFLOW-NWT. However, the PSB capability is implemented into the code, which enables tracking of separate stress components without lumping them into a single MODFLOW package. The PSB capability was originally developed for MODFLOW-CDSS (Banta, 2011), a version of MODFLOW-2005 designed to support groundwater models for Colorado’s Decision Support Systems (CDSS, 2017). The PSB capability was subsequently incorporated into MODFLOW-NWT as part of the South Platte Decision Support System (SPDSS) groundwater model update (Brown and Caldwell, 2017; Zeiler et al., 2017). The capability facilitates groundwater flow modeling in aquifer systems with a large variety of groundwater sources and sinks of similar type. Using the PSB capability, each stress-boundary package (e.g. Recharge Package, Well Package) can be partitioned into a selected set of packages, with volumetric flow rates for each individual stress listed in a separate input file. For example, the Well Package can be partitioned into municipal pumping, agricultural pumping, groundwater injection, etc. and the Recharge Package can be partitioned into reservoir seepage, recharge pond seepage, rainfall recharge, and irrigation recharge. The water budget component of each stress partition is tracked separately in the water budget tables printed in the MODFLOW output file.

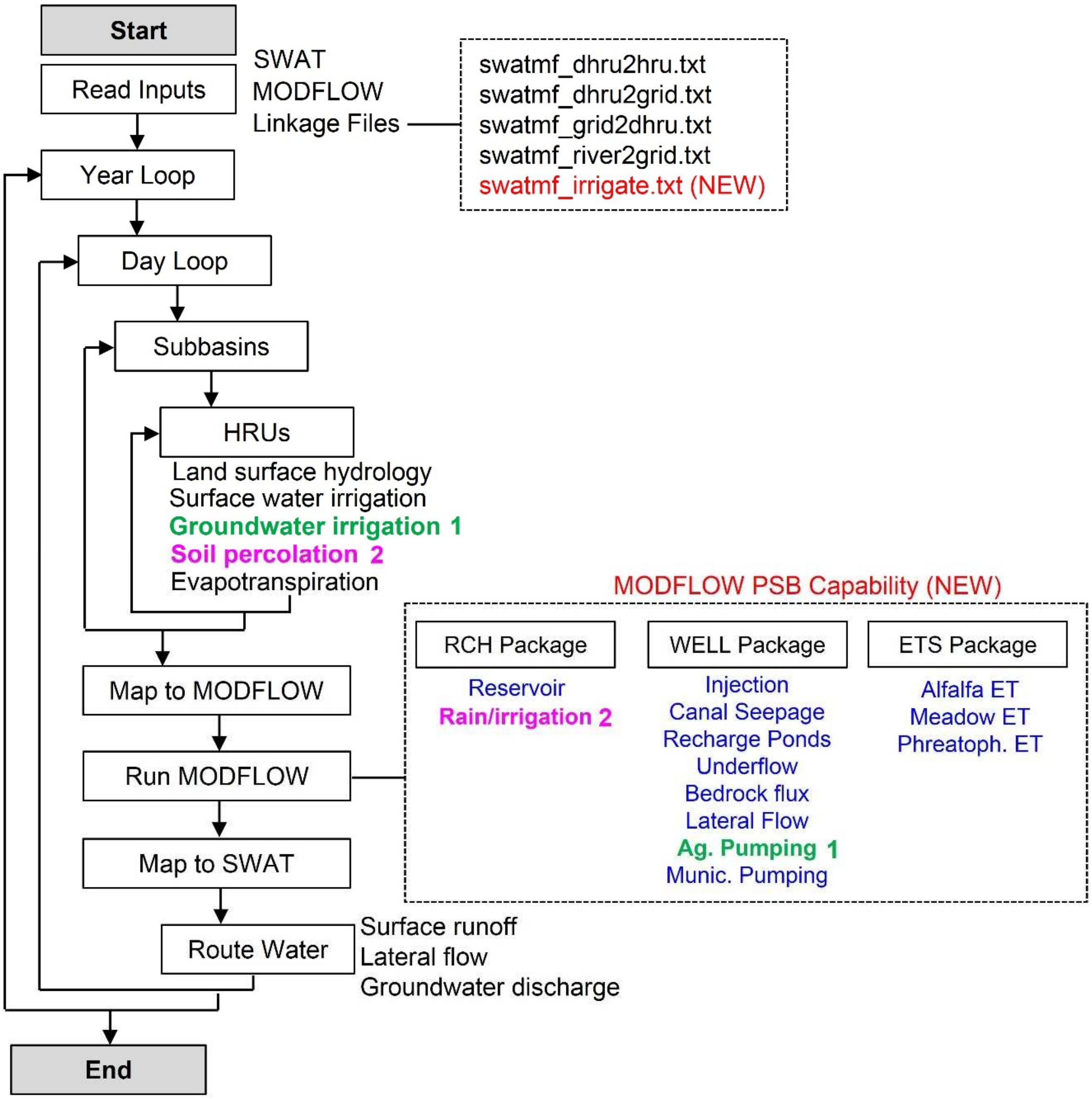

**Figure 2.1.** Data flow in SWAT-MODFLOW modeling code (FORTRAN), showing the calling of MODFLOW as a subroutine within the main SWAT modeling structure. The figure also shows the use of

the MODFLOW Partition Stress Boundary (PSB) capability that partitions main stress packages into individual stresses.

Packages supported by the PSB capability include Recharge (RCH), River (RIV), Well, (WEL), Drain (DRN), Drain Return (DRT), Evapotranspiration (EVT), Evapotranspiration Segments (ETS), and General Head Boundary (GHB). Within the SWAT-MODFLOW code, SWAT HRU soil percolation rates are mapped to the MODFLOW grid for rainfall and irrigation recharge (designated by "2" in Figure 2.1), and MODFLOW agricultural pumping rates are mapped to SWAT HRUs for groundwater irrigation (designated by "1" in Figure 2.1). When mapping rainfall and irrigation recharge from SWAT HRUs to MODFLOW grid cells, and pumped irrigation water from MODFLOW to SWAT HRUs, the appropriate stress "grid" must be specified, so as not to over-write cell-by-cell values for other stresses.

Irrigation water can be supplied by surface water via irrigation canals and/or by groundwater via pumping wells. Groundwater pumped using the agricultural pumping stress of the Well package can be mapped to SWAT HRUs. Pumped groundwater volumes are converted to applied irrigation depths and provided to HRUs for irrigation on the following day, using the spatial area of the HRU. Using the auto-irrigation algorithms of SWAT, surface water irrigation can be supplied by the nearest subbasin channel, representing surface water diverted from the stream via irrigation canals. The HRU receiving irrigation water from each MODFLOW pumping cell is specified in a list in the swatmf_irrigate.txt input file (see Figure 2.1). The user also specifies the runoff ratio (i.e. percent of irrigation water that runs off the field as tailwater) for groundwater irrigation in each sub-basin. However, there are many fields that use canal water instead of groundwater for irrigational purposes. The SWAT auto-irrigation subroutines were modified to include surface water (from a specified subbasin channel) after pumping water is applied so that the full specified depth of irrigation is met.

## 2.3. MODEL APPLICATION TO THE SOUTH PLATTE RIVER BASIN

### 2.3.1. Area of Study

#### *2.3.1.1. Geography and Demographics*

The South Platte River Basin (SPRB) has a spatial area of approximately 72,000 km$^2$ (Colorado's Water Supply Future, 2011), with 79% of the area in Colorado encompassing 17 Colorado counties and the remaining area in Nebraska (15%) and Wyoming (6%) (Dennehy, 1991) (Figure 2.2a). The South Platte River, 720 kilometers in length (Davitt, 2011), originates from the mountains to the southwest of Denver, with numerous tributaries joining as it flows northeast across the High Plains of Colorado. The river crosses the Colorado-Nebraska state line and eventually discharge to the North Platte River (Colorado Water Conservation Board, 2015) (Figure 2.2a).

The SPRB is the most populous basin in Colorado (West Sage Water Consultants, 2015). The total population of the basin within all three states in 2010 was approximately 3.4 million, of which 95 percent reside in Colorado. The population is expected to double by 2050 (Dennehy et al. 1995; Waskom, 2013), with dramatic growth in the urban and mountainous regions and static or declining rates in agricultural communities (Dennehy et al. 1993). Population growth is the biggest reason for the need for additional water supply in this region (West Sage Water Consultants, 2015).

#### *2.3.1.2. Climate*

The basin has a diverse hydrology pattern with periodic droughts and a climate that depends strongly on elevation (Davitt, 2011). The topographic elevation in the basin ranges from about 4300 meters in the Rocky Mountains in the west to about 850 meters in the eastern plains (Figure 2.2c). Due to the wide temperature ranges and irregular seasonal and annual precipitation, the climate is classified as continental-type (Waskom, 2013). The average annual precipitation ranges 0.25-0.5 meter per year in the plains in the east to as high as 1 meter per year near the continental divide where snow accumulates during the winter months (Davitt, 2011). Major precipitation events occur mid-winter and spring in the mountainous part, while the foothills receive most rainfall during the spring and early summer months.

Spring storms are important in the mountains, foothills and eastern plains for water supply. The difference between a wet year and dry year often is due to the occurrence or absence of a few major storms (Waskom, 2013). Temperature increases from the mountainous region on the west to the foothills and plains on the east. Average monthly temperature varies between -35 to 38 degrees Celsius (°C) (Dennehy et al. 1993). Warm summer temperatures, low relative humidity, high solar radiation, and wind, induce a high rate of evapotranspiration in the basin, averaging between 1-1.5 meters of potential or reference ET for the eastern plains (Waskom, 2013). In recent decades, the average yearly temperature increased by 1 °C in the last 30 years and 1.5 °C in the last 50 years across Colorado and an additional warming of 1.5 to 3 °C is expected by 2050 (Colorado Water Conservation Board, 2015). The impact of this changing climate may be manifest in altered river flows and groundwater recharge reduction due to changes in timing and magnitude of rain and snowfall, crop water use and evaporation rate (West Sage Water Consultants, 2015).

#### *2.3.1.3. Land Use*

According to the 2007 United States Census, the SPRB contains 7 of the 10 top value agricultural producing counties in Colorado. Based on the National Land Cover Dataset in 2011 (Homer et al., 2015), land use and land cover of the basin is classified into rangeland (48 percent), agricultural land (30 percent), forest land (13 percent), urban or built-up land (6 percent), and other lands (3 percent) including water, barren lands, tundra and perennial snow and ice (Figure 2.2b). The western portions of the basin are mostly forested, while the High Plains region is mainly grassland and planted or cultivated land (Colorado Water Conservation Board, 2015). Irrigated lands through the basin have encountered a reduction from a peak of slightly over 400,000 hectares in the mid-1970s to approximately 330,000 hectares in 2013 (Waskom, 2013). According to state projections, the SPRB could lose 35% of today's irrigated land by 2050 (Colorado's Water Supply Future, 2011). A significant reason for the decrease in irrigated lands is 1) urban growth along the Front Range and 2) the purchase of senior agricultural surface water rights and agricultural land dry-up (Waskom, 2013).

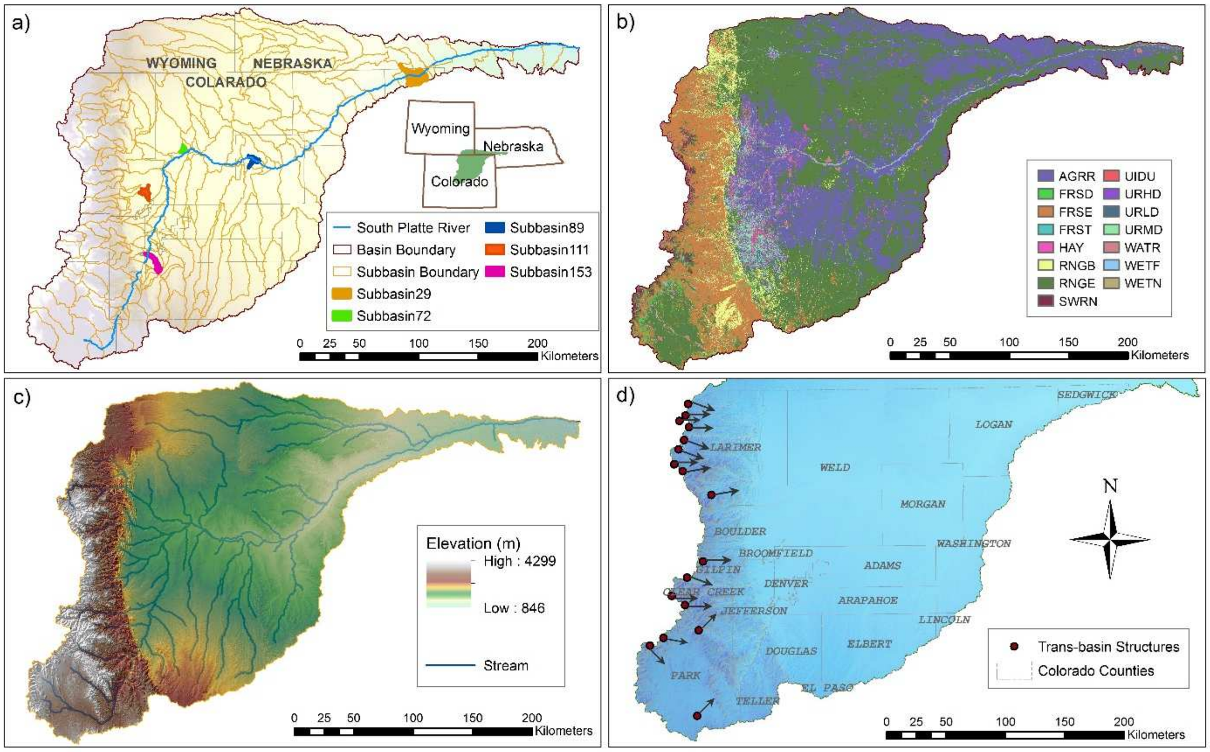

**Figure 2.2**. a) South Platte River Basin, located mainly in Colorado and partially in Wyoming and Nebraska (The highlighted subbasins are streamflow gage subbasins along the South Platte River); b) Land use types based on SWAT model categories; c) Topographic map, altitude range and stream network; d) Location of trans-basin structures and related flow directions to the basin.

#### *2.3.1.4. Water Resources*

The alluvial groundwater system of the South Platte River Basin covers approximately 10,400 km$^2$ (Figure 2.3b) based on a Colorado Geological Survey in 2003. The aquifer is mainly composed of silt, sand and gravel deposits of alluvial and aeolian origin with considerable heterogeneity. Hydraulic conductivity (K) values range from 30 to 610 m/day (CDM Smith, 2013). Saturated aquifer thickness varies from 6 to 13 meters at the upstream extent near Denver, to more than 61 meters adjacent to the Colorado-Nebraska border (CDM Smith, 2013; Waskom, 2013). The unconfined alluvial aquifer is hydraulically connected with the South Platte River along its main stem and major perennial tributaries (see Figure 2.3a for river network map). Groundwater discharge to the river channel creates baseflow for the river and is recharged by precipitation, leakage from streams, reservoirs, and ditches, and by percolation of applied irrigation water (Dennehy et al. 1995). Recharge from precipitation in the SPRB ranges from approximately 15% of total precipitation along the foothills to 2% in the lower basin (Waskom, 2013).

The SPRB likely faces a severe water supply gap in upcoming years. An inverse relationship exists between consumed groundwater and surface water, with groundwater used during dry periods when surface water is limited in the agricultural, municipal and environmental sectors (Waskom, 2013). Conjunctive use of groundwater and surface water presents an efficient solution to future water needs; However, other challenges, e.g. using groundwater without injuring senior water rights, also may arise (West Sage Water Consultants, 2015). This large economically diverse semi-arid basin, with large temperature ranges, irregular seasonal and annual precipitation (Dennehy et al. 1995) and 150 years of water management history is an ideal region to test the modified SWAT-MODFLOW model.

### 2.3.2. SWAT Model for the South Platte River Basin

#### *2.3.2.1. Model Construction*

A SWAT model for the SPRB was built using ArcSWAT (Soil and Water Assessment Tool, 2015). The National Elevation Dataset (NED) from the U.S. Geological Survey at a 90 meter resolution with burned in hydrography from high-resolution NHDPlus data (Moore and Dewald, 2016), STATSGO soil data (Soil Survey Staff et al., 2016) and the National Land Cover Dataset in 2011 (Homer et al., 2015) are used to obtain topography, soil and land use types respectively.

For weather inputs such as precipitation, wind, relative humidity, maximum and minimum air temperatures and solar radiation, different sources are employed such as climate stations from GHCND (Menne et al., 2012), SNOTEL (Snow Telemetry, 2017) and local entities such as CoAgMet (Andales et al., 2014) and the Northern Colorado Water Conservancy District (Northern Colorado Water Conservancy District, 2017).

In this study, the watershed is divided into 194 subbasins with areas ranging from approximately 0.13 to 1300 km$^2$. Each subbasin is further subdivided into HRUs, defined as unique combinations of soil, land cover, and slope within the subbasin. This configuration resulted in 1,994 HRUs.

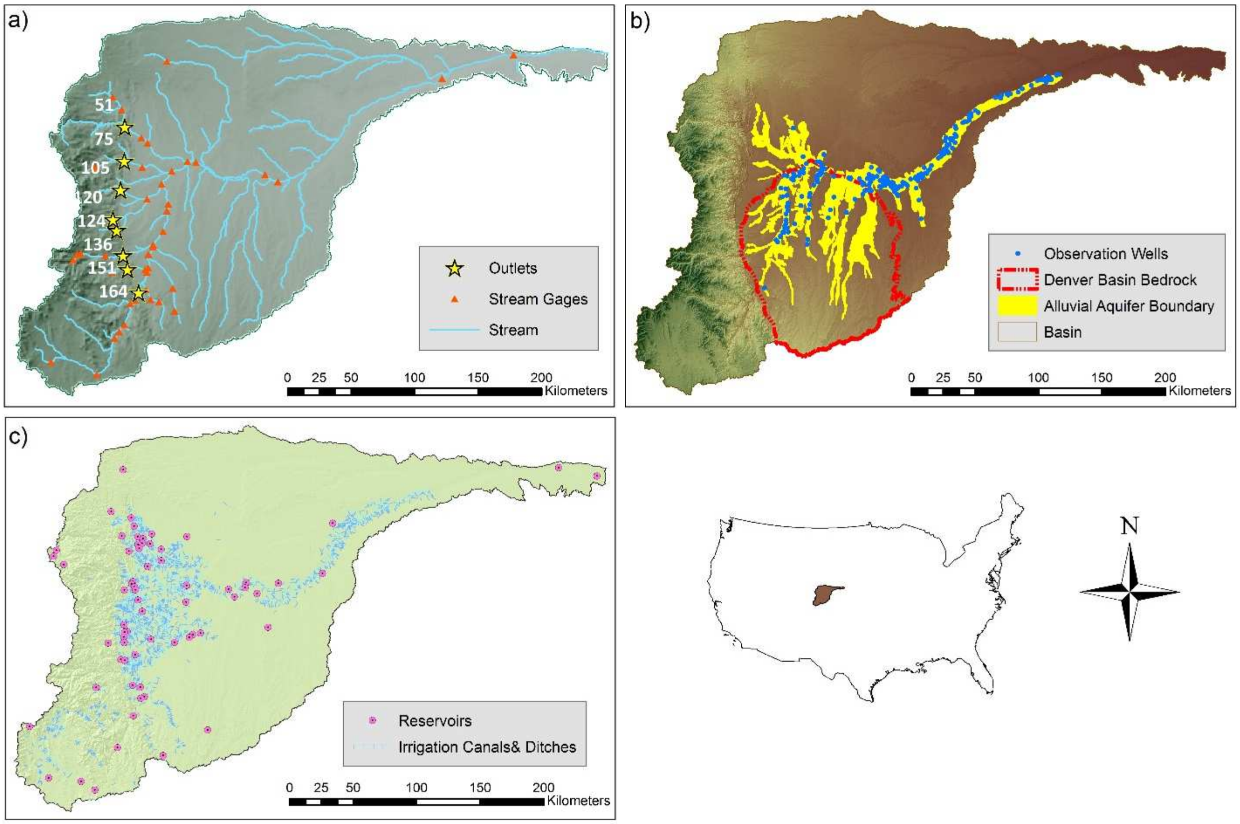

**Figure 2.3**. a) Location of outlets and stream flow gages; b) Alluvial aquifer extent, observation wells lay-out and Denver basin bedrock aquifer; c) Reservoirs and irrigated canals and ditches within the South Platte River Basin.

#### *2.3.2.2. Model Calibration*

To quantify water supply using the SWAT model, the model is calibrated by comparing model results with naturalized flow, with data obtained from streamflow gages located in the mouth of canyons along the front range of the SPRB. The time series of data are obtained from both the USGS and the Colorado Division of Water Resources (CDWR). Naturalized flow is determined by excluding human use and management. It is described by:

$$\mathrm{NF}=\mathrm{MF}+\sum \mathrm{DF}-\sum \mathrm{RF}-\sum \mathrm{TB} \qquad \text{(Eq. 1)}$$

where NF is the naturalized flow, MF is the measured gaged flow at the watershed outlet, ∑DF is the total diverted flow, ∑RF is the total released flow and ∑TB is trans-basin streamflow added before the stream reaches the outlet.

Calibration of the SWAT model is performed at eight outlets associated with the eight largest high elevation rivers for the periods of 1997-2015 on a daily time step, with 3 years for a warm-up period. The location of these gages is shown in Figure 2.3a. The largest catchment area is located along South Platte River at Waterton station (Outlet 164) with an area of 6,794 $km^2$, and the smallest is located at Builder Creek near Orodell (Outlet 120) with an area of 264 $km^2$.

The Dynamically Dimensioned Search (DDS) algorithm is used for model calibration. This optimization algorithm was developed by Tolson and Shoemaker (2007) for automatic calibration of complex water shed models and is written in MATLAB. To reach the goal of finding a proper global optimal solution, the DDS algorithm first samples the parameter space globally and as the number of iterations comes closer to the maximum allowable number defined by the user, the algorithm automatically tunes the scale of the search focusing on regions of the parameter space where better results were generated to find the most optimal parameter set. This transformation is adjusted by decreasing the number of varying model parameters to make a new search neighborhood (Tolson and Shoemaker, 2007). In this study, the number of iterations is limited to 3000, for 33 model parameters (Table 2.1). The parameters selected for calibration and their ranges were selected based on several previous studies that conducted sensitivity analysis for the SWAT model in the same region (Ahmadi et al., 2014).

The Nash-Sutcliffe Coefficient of Efficiency (NSE) is used as the objective function, as recommended by ASCE (ASCE task committee, 1993) for continuous-hydrograph modeling.

Additionally, the goodness of model performance is assessed using Relative Error (RE) and percent BIAS (Moriasi et al., 2007).

### 2.3.3. MODFLOW Model for the South Platte River Basin

The MODFLOW model of the SPRB alluvial groundwater flow system was developed in recent years as part of the state of Colorado's South Platte Decision Support System project (CDM-Smith, 2013; Brown and Caldwell, 2017). The model was originally developed for the 1950-2006 time period (CDM-Smith, 2013), but was extended through 2012 (Brown and Caldwell, 2017) using MODFLOW-NWT.

The MODFLOW model is constructed using a grid cell size of 1000-foot by 1000-foot (304.8 m x 304.8 m), dividing the alluvial aquifer system into 655 rows and 848 columns. The active model domain consists of 69,895 cells and is defined as areas with a saturated thickness of 3 meters or more and with production wells with yields greater than 11.5 m3/hr. The model domain is shown by the alluvial aquifer boundary in Figure 2.3b.

The model accounts for all major sources and sinks to the alluvial aquifer, including recharges from precipitation, surface water and groundwater irrigation, canal and reservoir seepage, well pumping for irrigation and municipalities, stream gains and losses, lateral boundary inflows and outflows, alluvial underflow fluxes, evaporation and Phreatophyte evapotranspiration (CDM-Smith, 2013). Precipitation, recharges and lateral boundary fluxes from unconsolidated material beyond the active grid cells are prepared in MODFLOW Recharge Package (RCH) format while Well Package (WEL) includes groundwater pumping, streamflow augmentation, bedrock and alluvial underflow fluxes, recharge ponds rate, and canal seepage. The MODFLOW Evapotranspiration Segment Package (ETS) includes input files from alfalfa and sub-irrigated meadow ET. Phreatophyte vegetation ET occurs when the water table rises up to the phreatophyte plants root zone and is assumed to be constant through time. Model calibration was achieved by refining aquifer properties, with groundwater head, streamflow, and stream gains and losses used as calibration targets.

**Table 2.1**. List of calibrated parameters of SPRB SWAT model and their adjusted values.

| **Symbol** | **units** | **Description** | Calibrated Value | Lower Bound | Upper Bound |
|---|---|---|---|---|---|
| ALPHA_BF | days | Baseflow alpha factor | 0.7312 | 0 | 1 |
| CANMX | mm | Maximum canopy storage (mm H2O) | 6.128 | 0 | 10 |
| CH_KI | mm/hr | Effective hydraulic conductivity in tributary | 276 | 0 | 300 |
| CH_KII | mm/hr | Effective hydraulic conductivity in main | 238.1 | -0.01 | 500 |
| CH_NI | - | Manning's "n" value for the tributary | 0.1185 | 0.016 | 0.2 |
| CH_NII | - | Manning's "n" value for the main channel | 0.1304 | 0.016 | 0.2 |
| CH_SII | % | Average slope of main channel (m/m) | 0.02397 | -0.02 | 0.05 |
| CN_F | % | Curve Number factor | 0.0179 | -0.1 | 0.1 |
| DEPIMP_BSN | mm | Depth to impervious layer for modeling perched water tables | 3202 | 0 | 6000 |
| EPCO | - | Plant uptake compensation factor | 0.9876 | 0.01 | 1 |
| ESCO | - | Soil evaporation compensation factor | 0.1554 | 0.01 | 1 |
| GW_DELAY | day | Groundwater delay | 53.89 | 0 | 60 |
| GW_REVAP | - | Groundwater "revap" coefficient | 0.1488 | 0.02 | 0.2 |
| GW_SPYLD | % | Specific yield of the shallow aquifer (m3/m3) | -0.4844 | -0.5 | 1 |
| GWHT | m | Initial groundwater height | 4.863 | 0 | 25 |
| GWQMN | mm | Threshold depth of water in the shallow aquifer for return flow to occur | 1838 | 0 | 5000 |
| OV_N | - | Manning's "n" value for overland flow | 0.3423 | 0.01 | 0.48 |
| RCHRG_DP | - | Deep aquifer percolation fraction | 0.972 | 0 | 1 |
| REVEP_MN | mm | Threshold depth of water in the shallow aquifer for percolation to the deep aquifer to occure | 79.87 | 0 | 500 |
| SFTMP | °C | Snowfall temperature | 4.336 | -5 | 5 |
| SLOPE | % | Average slope steepness (m/m) | -0.09296 | -0.1 | 0.1 |
| SMFMN | mm/°C-day | Minimum melt rate for snow during year | 0.2188 | 0 | 10 |
| SMFMX | mm/°C-day | Maximum melt rate for snow during year | 2.604 | 0 | 10 |
| SMTMP | °C | Snow melt base temperature | 4.476 | -5 | 5 |
| SNO50COV | mm | Snow water content that corresponds to 50% snow cover | 0.4026 | 0 | 0.9 |
| SNOCOVMX | mm | Minimum snow water content that corresponds to 100% snow cover | 530.8 | 0 | 650 |
| SOL_AWC | % | Available water capacity of soil layer (mm/mm) | 0.9136 | -0.1 | 1 |
| SOL_K | mm/hr | Saturated hydraulic conductivity of first soil layer | 0.1336 | -0.5 | 1 |
| SURLAG | day | Surface runoff lag time (days) | 6.985 | 1 | 12 |
| TIMP | - | Snow pack temperature lag factor | 0.1103 | 0.01 | 1 |
| CNCOEF | - | Plant ET curve number coefficient. | 1.886 | 0.5 | 2 |
| SOL_ALB | % | Moist soil albedo of soil layer | 0.4751 | -0.5 | 1 |
| SOL_Z | % | Depth to bottom of first soil layer (mm) | 0.9707 | -0.5 | 1 |

### 2.3.4. Coupled SWAT-MODFLOW Model for the South Platte River Basin

The coupled SWAT-MODFLOW SPRB model is run for the period 1997-2012. Initial cell-by-cell groundwater levels are obtained by using the estimated head values from MODFLOW model for the stress period prior to the starting date of the coupled model (December 1996). As vertical aquifer heterogeneity is neglected in the MODFLOW model (due to the use of a single layer), for the areas with clay lenses interbedded in the sandy material the hydraulic conductivity were manually adjusted to provide an acceptable match between simulated and observed groundwater head values.

The inflows and outflows to the model and the allocations between SWAT and MODFLOW are laid out schematically in Figure 2.4. Alluvial aquifer inflow occurs in the main stem of the South Platte River, in the area upgradient of the main tributaries due to fractures of weathered bedrock, and from the underlying Denver basin bedrock aquifer (Figure 2.3b). Aquifer outflow occurs near the outlet of the South Platte River. To account for the policy of well augmentation after the year 2006, the volumes of water diverted to managed recharge ponds and allowed to seep into the aquifer are included as a groundwater source in the MODFLOW model. The main water balance components handled by SWAT model are aquifer recharge, surface water inflow and outflow, and surface water discharges through different water user sectors (domestic, industrial and agriculture). Aquifer recharges consist of both precipitation and portion of irrigation water that percolates to the water table.

**Figure 2.4**. Water allocations and flow between surface water and groundwater in the South Platte River Basin. Navy-blue and yellow text represent processes simulated by SWAT and MODFLOW, respectively.

Figure 2.5 demonstrates the GIS coverages needed to facilitate the linking between SWAT and MODFLOW. The MODFLOW grid cells and all pumping wells within the alluvial aquifer are shown in Figure 2.5a. Figure 2.5b-e shows the detailed linkage process for SWAT subbasin 90. Figure 2.5b shows the delineation of the HRUs in the subbasin, with Figure 2.5c showing the individual polygons resulting from intersecting the MODFLOW grid cells with the disaggregated HRUs. This intersection determines the spatial relationship between the DHRUs and the grid cells, for passing SWAT recharge to MODFLOW and MODFLOW water table elevation to SWAT. Figure 2.5d shows the subbasin channel and the intersected River Cells. During the simulation, the stream-aquifer water exchange rate will be summed for all River Cells in this subbasin and provided to SWAT's subbasin channel for routing. Finally, Figure 2.5e shows the MODFLOW cells with pumping wells. The volume of pumped groundwater from these cells is applied as irrigation water to SWAT HRUs during the simulation. For all the HRUs in agricultural areas of SPRB, fields obtain irrigation water via either groundwater pumps or irrigation canals.

To demonstrate the usefulness of the model and the key features of the updated SWAT-MODFLOW modeling code, two additional irrigation scenarios are run.

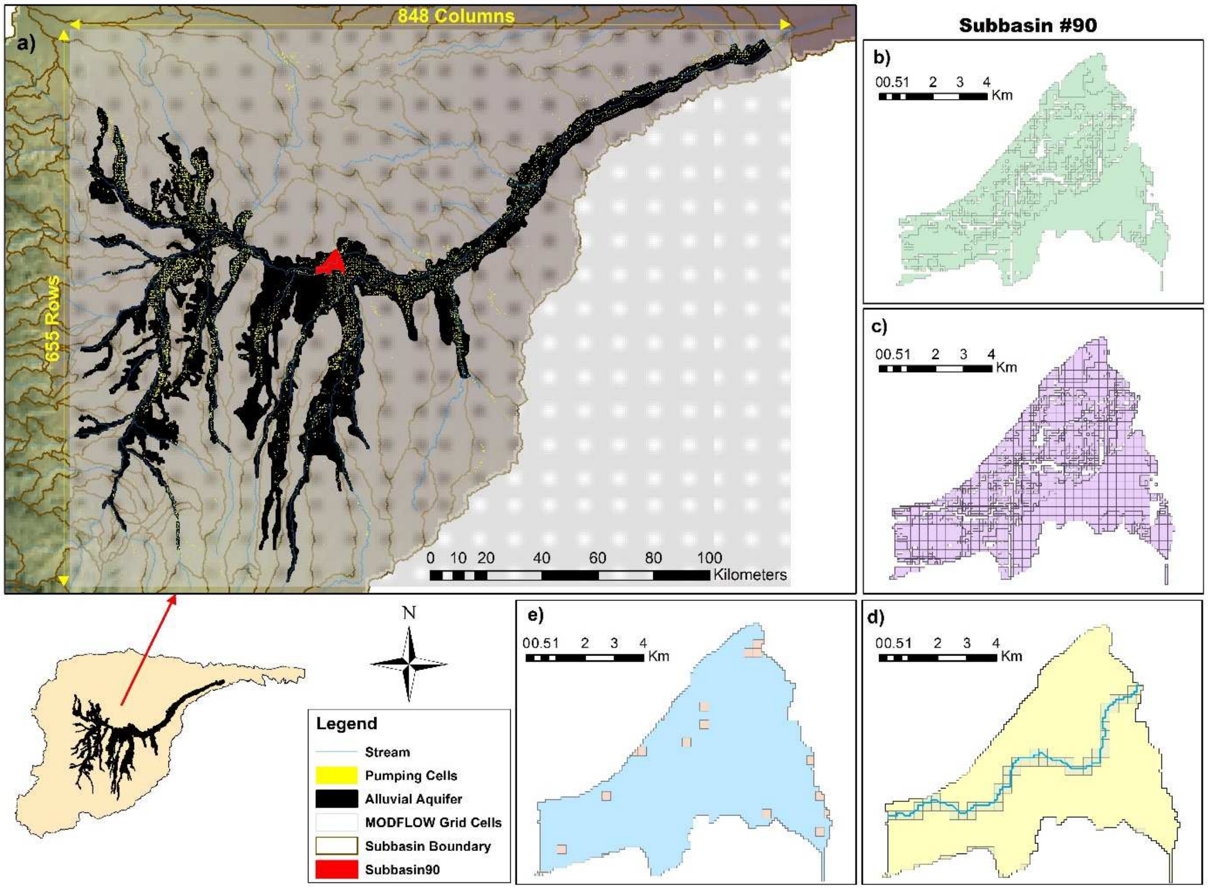

**Figure 2.5**. a) SPRB Alluvial aquifer, showing the MODFLOW grid cells, location of pumping wells in yellow and subbasin #90 in red (see legend); b) HRUs and DHRUs within subbasin 90; c) Intersection of MODFLOW grid cells and DHRUs within subbasin 90; d) River cells within subbasin boundary, and e) Pumping cells within subbasin 90 boundary.

## 2.3.5. Results and Discussion

### *2.3.5.1. Streamflow at Canyon Outlets*

The observed and simulated streamflow at the 8 mouth-of-canyon sites are shown in Figure 2.6, with performance statistics tabulated in Table 2.2. As per general performance rating, recommended by Moriasi et al. (2007) for NSE and by adjusting the proposed ranges to daily values of this study, one can conclude that outlets 136, 75, 51, 105 and 120 are categorized as “very good” and outlet 124 as “good’. The results for outlets 164 and 151 are “satisfactory”. For these two outlets, results cannot be improved because only one set of parameters is used for the entire basin.

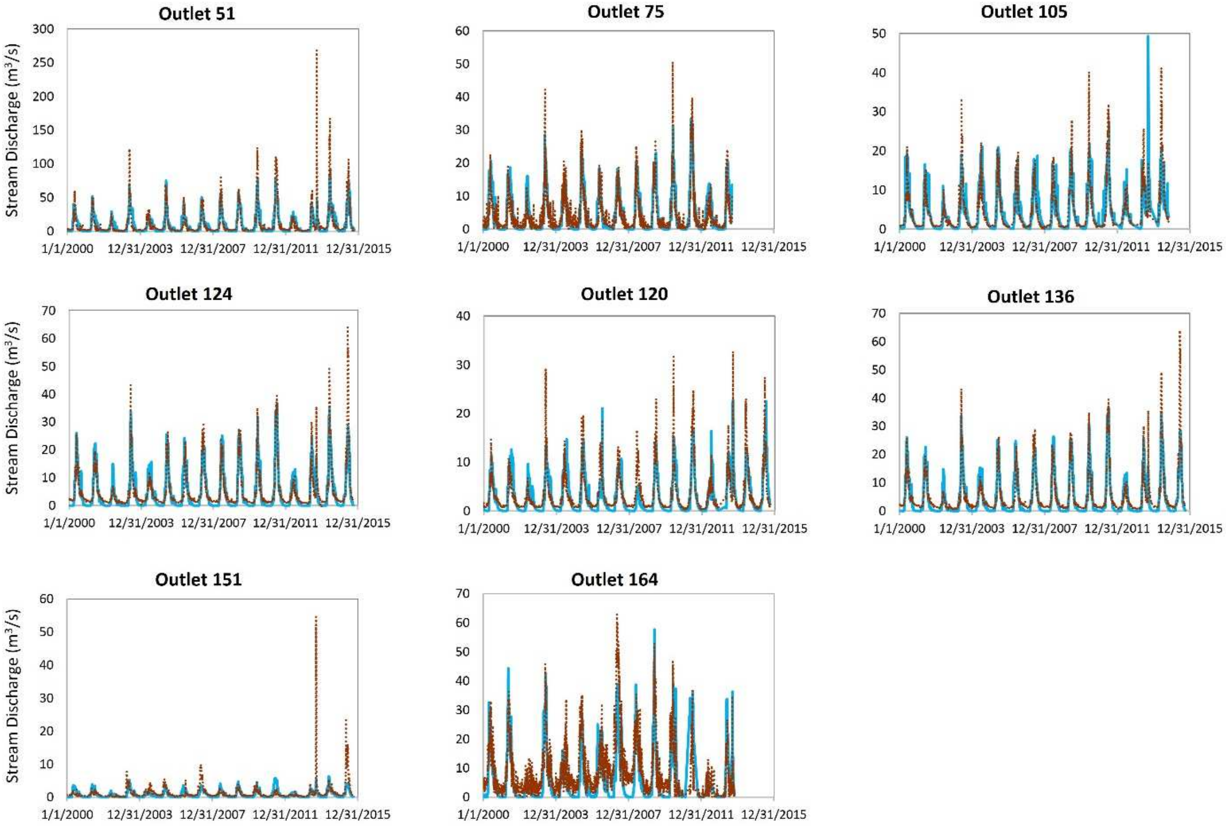

**Figure 2.6**. Comparison of simulated (solid blue) and observed (dotted brown) daily stream discharge at each mouth of the canyon outlet.

**Table 2.2**. Values of objective functions for evaluating the performance of SWAT model at each outlet.

| Outlet # | RE (%) | PBIAS | $R^2$ | NSE |
|---|---|---|---|---|
| 136 | 4.26 | 0.22 | 0.92 | 0.83 |
| 75 | -7.39 | -0.32 | 0.90 | 0.77 |
| 51 | 7.50 | 0.80 | 0.88 | 0.76 |
| 105 | 5.95 | 0.27 | 0.85 | 0.71 |
| 120 | 8.63 | 0.29 | 0.84 | 0.69 |
| 124 | -19.67 | -0.39 | 0.81 | 0.59 |
| 164 | 28.62 | 2.77 | 0.78 | 0.48 |
| 151 | 27.32 | 0.31 | 0.49 | 0.22 |

#### *2.3.5.2. Downstream Flow*

Streamflow is compared with observed streamflow within the basin at 5 different stream locations (Figure 2.2a) along the South Platte River (Figure 2.7). These streamflow measurements are influenced heavily by water management schemes, e.g. reservoir releases, canal diversions, etc. Corresponding flow duration curves for both simulated and observed streamflow are also plotted in Figure 2.7. Results from the calibrated SWAT model also are shown, to shown the improvement in streamflow prediction from the SWAT-MODFLOW model.

The SWAT-MODFLOW model shows a good fit in the upstream areas (Figure 2.7 a&b). The model performance in simulating average to high magnitude flows is satisfactory (note the log scale of the flow rates for the flow duration curve charts). Thus, the model performs well for the majority (> 80%) of flows experienced (the flows of high magnitude), and therefore is a good simulator of the timing and magnitudes of water volumes passing through gage sites. The one notable exception is the gage in subbasin 29 (Figure 2.7e), which overestimates flow, particularly for the drought years of 2002-2004. This subbasin, however, is in the far east region of the river basin where the flow is influenced by man-made diversions and return flows. The first four presented subbasins, for which the coupled model performs well, encompass the main agro-urban region of the river basin. The water yield in this subbasin is mostly dominated by lateral flow and groundwater return flow (Figure 2.8). Groundwater in all other subbasins has a high contribution to water yield (Figure 2. 8).

By means of the flow duration curves (Figure 2.7), one can observe that the coupled SWAT-MODFLOW model has a better performance in simulating stream flow in comparison with SWAT model itself, particularly for low flows. This is likely due to the simplistic treatment of groundwater flow and resulting baseflow in the original SWAT model.

#### ***2.3.5.3. Basin Water Balance***

The average annual water budget for the entire river basin is shown in Figure 2.9, with flux values (mm) normalized by dividing by the area of the basin. Well pumping is the largest stress on the South Platte River basin alluvial aquifer. The use of the PSB package enabled better tracking of the water budget components. Water yield to the river is dominated by groundwater return flow (173 mm), followed by lateral flow (19 mm) and surface runoff (8 mm). As such, groundwater accounts for 87% of water yield. The groundwater balance is effected principally by groundwater return flows (173 mm), seepage from canals and reservoirs (110 mm), lateral flow from surrounding areas (102 mm), and pumping for irrigation (88). The amount of river seepage (22 mm) is almost as much as what is diverted for surface water irrigation (32 mm). This water balance can help with understanding patterns and magnitudes of hydrological processes and water transfer in the basin, leading to strategies for managing water balance components.

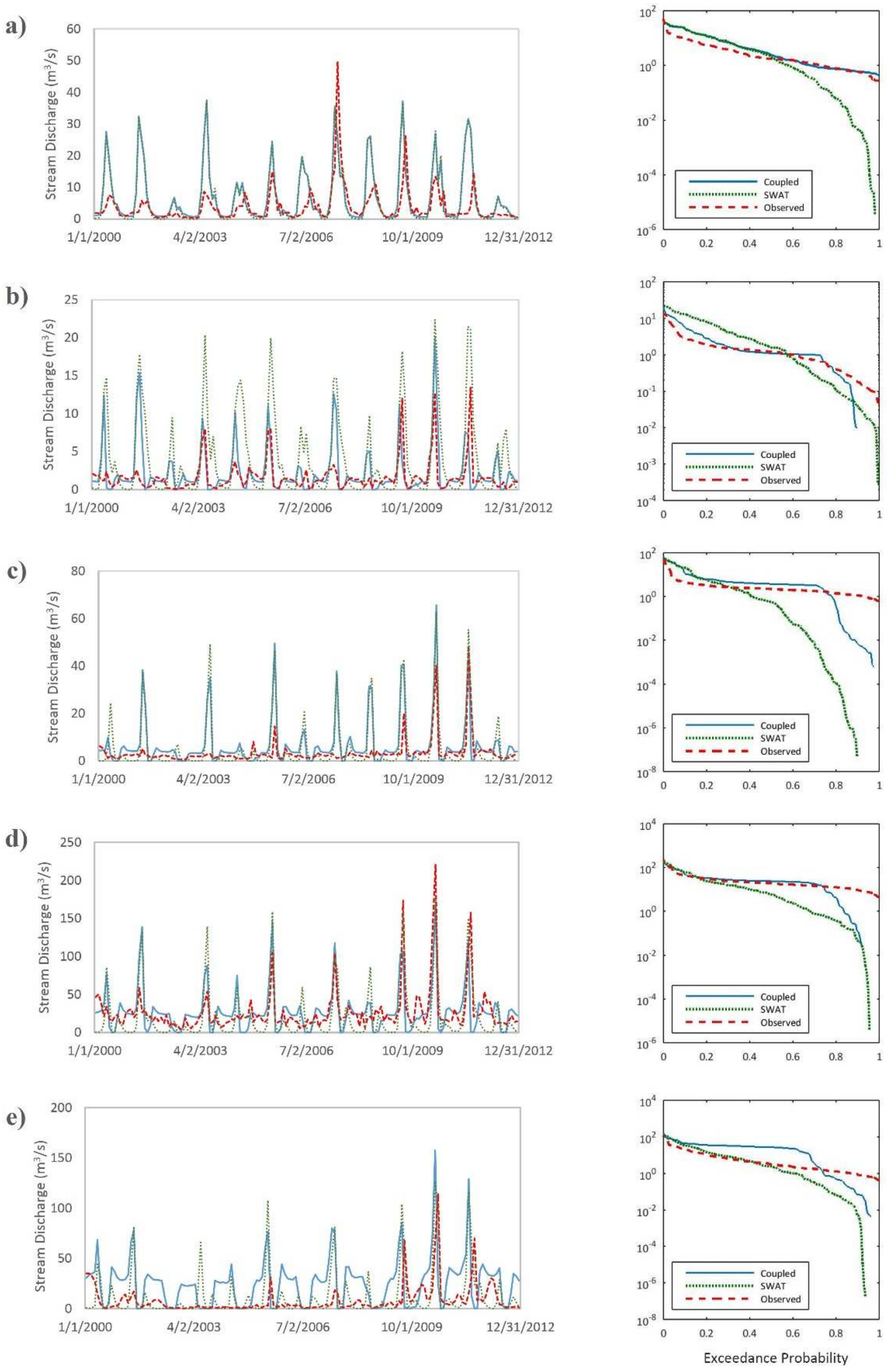

**Figure 2.7**. Coupled SWAT-MODFLOW (solid blue) and SWAT (dotted green) simulations vs. observed (dashed red) monthly stream discharge in stream gages a) 153, b) 111, c) 72, d) 89 and e) 29 and corresponding flow duration curves.

**Figure 2.8**. Percentage of surface runoff (SURQ), lateral flow (LATQ) and groundwater return flow (GWQ) contribution to water yield in subbasins 153, 111, 72, 89 and 29.

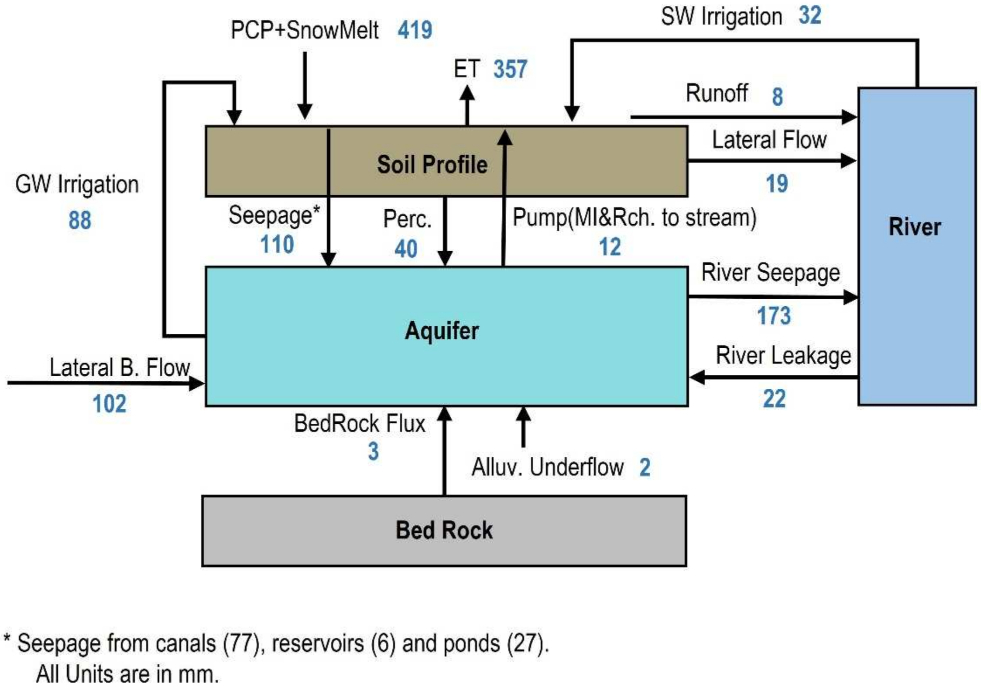

**Figure 2.9**. Water budget scheme for the entire river basin.

#### *2.3.5.4. Groundwater Head*

Model comparison with observed water table elevation is shown in Figure 2.10 for both the original MODFLOW model and the coupled SWAT-MODFLOW model. Water table elevation hydrographs for observation wells throughout the SPRB alluvial aquifer are shown, with Mean Absolute Error (MAE) values for both models reported in Table 2.3. The observed values are obtained from monitoring wells with adequate data within the modeling period (1997-2012), available from the CDWR. Visual inspection of the graphs shows the better performance of the SWAT-MODFLOW model than the MODFLOW model, with results from the coupled model often able to track the pattern and magnitude of groundwater level fluctuations from the start of the coupled model (1997). Comparison of MAE between the models shows that the coupled model improves results for 70% of the locations.

However, there are still significant residual between observed and simulated values in some parts of the basin. This could be due to uncertainties affiliated with using a grid-based model of large watersheds. In MODFLOW the pumping wells are assumed to be in the center of the cells in which they are located and thus, for the cells in which monitoring well location is at a significant distance from the cell centroid, the results cannot be compared precisely. Moreover, more discrepancies between observed and simulated groundwater levels occur for monitoring wells located far from the main stem of the South Platte River, likely due to lack of information in some of the tributaries of surface water and ungaged surface water inflow. Another possible reason is uncertainties within the spatial variability of inputs. The MODFLOW model uses one layer for the entire thickness of the aquifer, and therefore vertical heterogeneity in aquifer material and associated properties (e.g. hydraulic conductivity) is ignored. For example, the models under-predict the elevation of the water table in the LaSalle-Gilcrest area (orange polygon in Figure 2.10

map; W87 chart in Figure 2.10). This area has extensive clay lenses interbedded in the sandy material throughout the aquifer stratigraphy, causing high water tables. As this vertical heterogeneity is neglected in the model, this behavior cannot be simulated correctly. For the purpose of this study, which assesses water resources for the entire SPRB, local assessments are not essential, as the results aim to be used to quantify spatial water resources vulnerability in the basin and needs a broad overview to the water resources demands and supplies.

**Table 2.3**. Mean Absolute Error (MAE) values of MODFLOW and coupled model.

| **Well Number** | **MAE** | |
|---|---|---|
| | **MODFLOW** | **Coupled Model** |
| W7 | 0.68 | 0.71 |
| W56 | 1.35 | 0.77 |
| W68 | 5.74 | 3.97 |
| W71 | 1.02 | 0.78 |
| W87 | 0.29 | 1.33 |
| W90 | 0.58 | 0.45 |
| W120 | 5.05 | 5.74 |
| W136 | 6.63 | 4.17 |
| W154 | 1.28 | 1.12 |
| W172 | 5.61 | 5.75 |
| W179 | 1.66 | 1.03 |
| W181 | 8.78 | 4.55 |
| W183 | 5.20 | 3.14 |
| W184 | 4.27 | 7.48 |
| W189 | 4.35 | 3.08 |
| W197 | 0.36 | 0.99 |

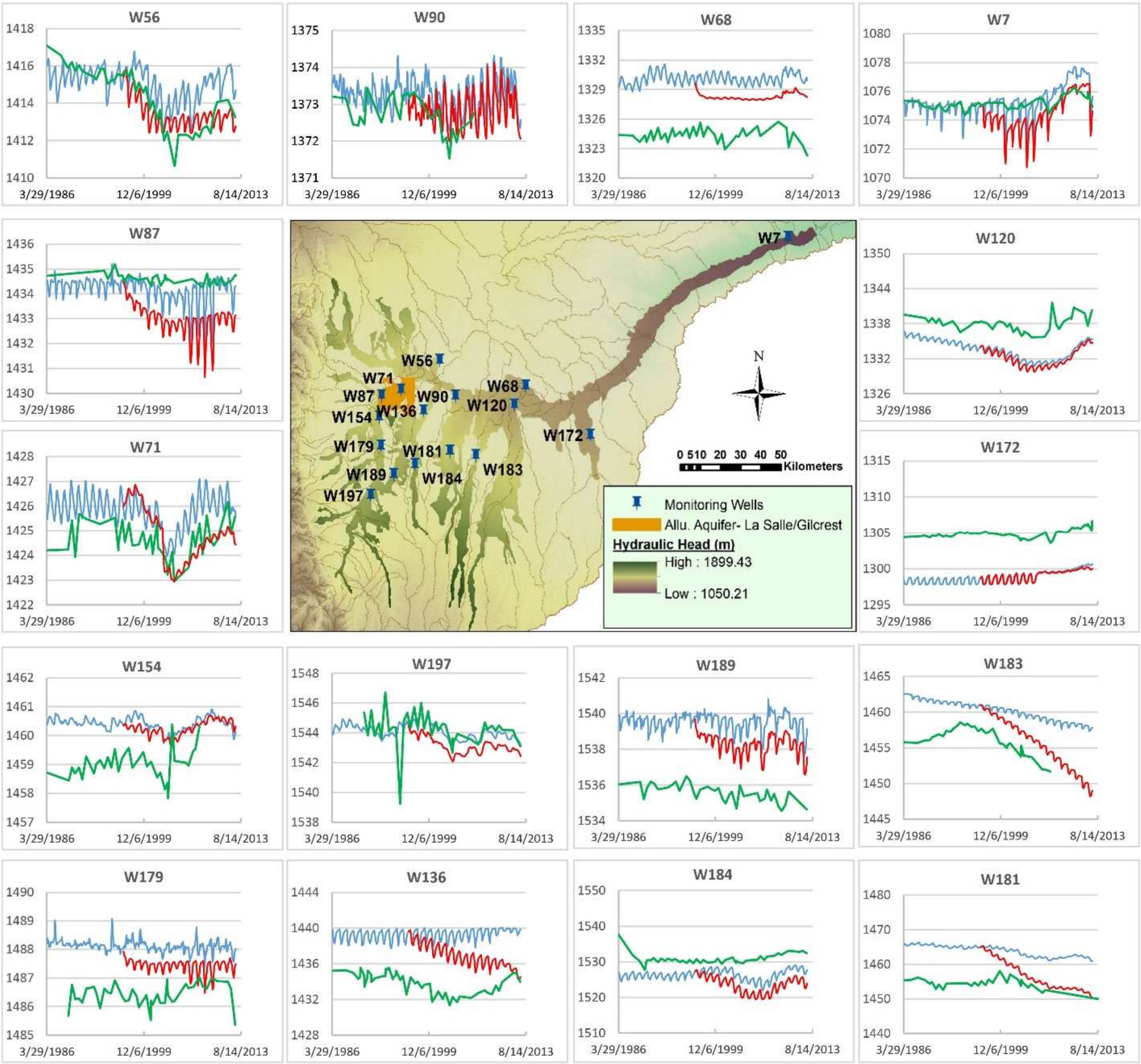

**Figure 2.10**. Temporally-averaged monthly water table elevation (hydraulic head, y-axis) simulated by coupled SWAT-MODFLOW for each grid cell (Map); Ground water level (meter) hydrographs, simulated by MODFLOW (Blue), simulated by coupled SWAT-MODFLOW model (Red) and observed data (Green) from different monitoring wells.

#### *2.3.5.5. Impact of irrigation*

One of the key features of the updated SWAT-MODFLOW model presented in this paper is the linkage between MODFLOW agricultural pumping cells and SWAT HRUs for groundwater irrigation. This modification is tested by looking at the changes in groundwater water table elevation (head), the changes in groundwater return flow and the changes in streamflow discharge under different scenarios of irrigation. The first scenario is the baseline simulation, with both surface water irrigation and groundwater irrigation. The second scenario explores the basin hydrologic system in which no irrigation occurs. The third scenario explores the basin hydrologic system in which irrigation water is supplied only by surface water, and hence no agricultural pumping is simulated.

Results are shown in Figure 2.11 and 12. As expected, groundwater head increases significantly in the absence of agricultural pumping (maximum increase of 33.4 m; spatial average increase of 2.7 m) (Figure 2.11a1& 11a2). As a result of the higher groundwater levels and thus groundwater head gradients, the flux of groundwater return flows is also higher (Figure 2.11b1& 11b2). This is also seen in Figure 2.12, which shows an increase of 51 mm in groundwater return flow to streams (increase of 30% from the baseline value of 173 mm).

To observe the effects of irrigation on streamflow discharge, the average daily hydrographs of streamflow for the entire basin is plotted for all irrigation scenarios (Figure 2.11c1& 11c2). Compared to the baseline simulation, the two irrigation scenarios experienced much more baseflow, due to the added groundwater return flows from the increased groundwater head. For the scenario with no irrigation (Scenario 2), the hydrographs have a longer recession time, as surface water runoff lags due to the lack of concentrated inputs of surface water irrigation volumes.

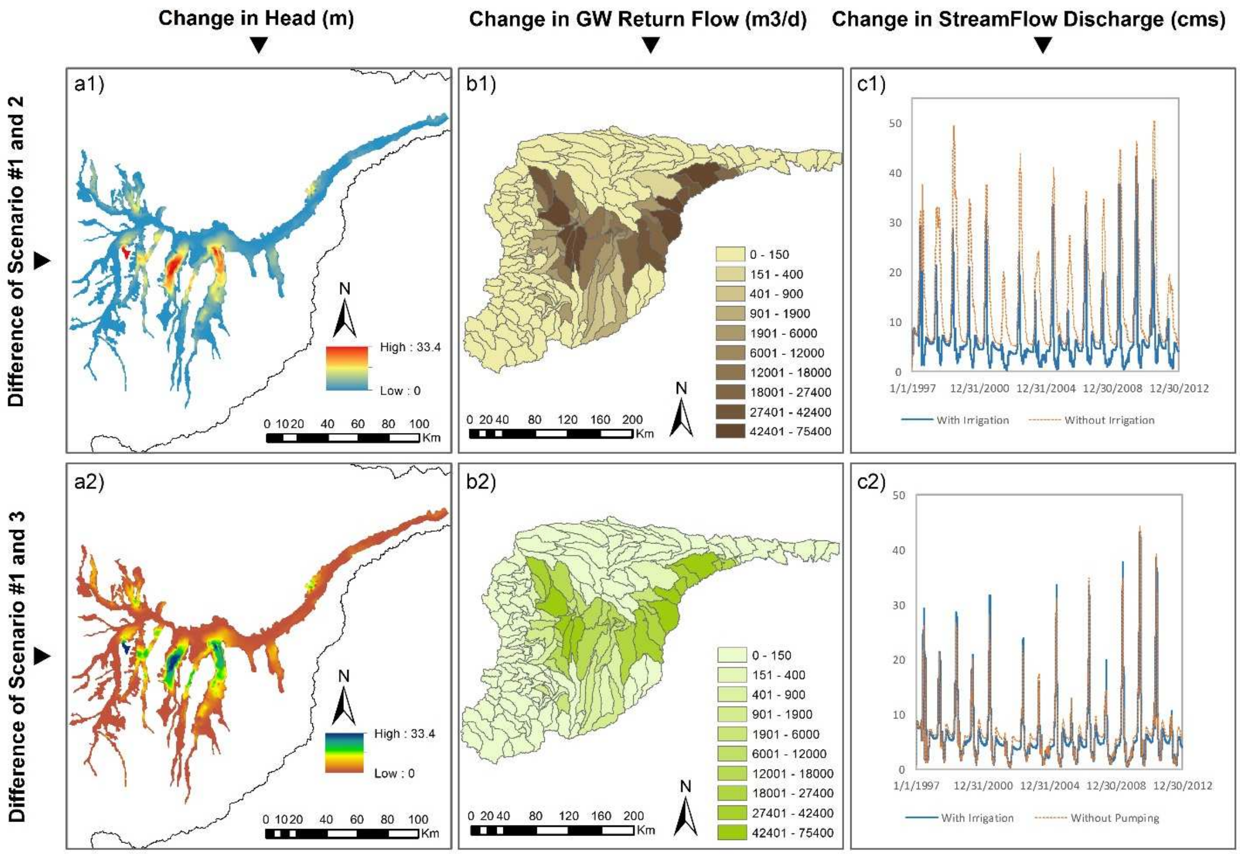

**Figure 2.11**. Impact of Irrigation results: Change in head, groundwater return flow and stream flow discharge under different scenario of irrigation patterns (Scenario1 (baseline): with irrigation from SW and GW; Scenario2: no Irrigation; Scenario3: with irrigation from SW and not GW). (c1) and (c2) are daily hydrographs of streamflow discharge.

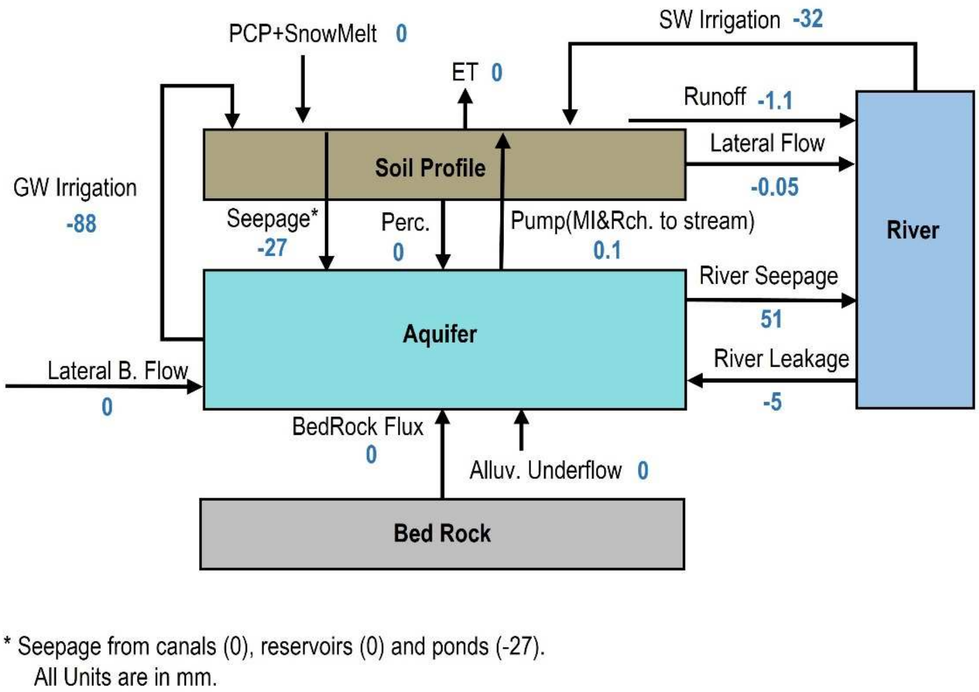

**Figure 2.12**. Difference in water budget components in absence of irrigation (scenario2 minus scenario1)

## 2.4. SUMMARY AND CONCLUSIONS

The SWAT-MODFLOW code (Bailey et al., 2016) was modified for application to large-scale agro-urban river basins, with model use and performance demonstrated for the South Platte River Basin in northeastern Colorado, USA. The modeling code is designed to handle water management schemes in large river basins, such as conjunctive use of surface water and groundwater for irrigation. All major water transfer pathways (pumping, injection into aquifer, bedrock inflow, canal seepage, stream-aquifer water exchange) are included in either the SWAT model or the MODFLOW model, with daily interactions between the models occurring for soil recharge to the water table, pumped groundwater applied as irrigation water, and stream-aquifer water exchange rates. For better representation of the groundwater and surface water stressors the water budget scheme of the basin is presented, and two limited-irrigation scenarios show the impact of irrigation on water balance components in the river basin. The model was run for the

1997-2012 period and by tested against groundwater elevation and streamflow discharges at monitoring wells and stream gages, respectively, located throughout the basin. The results of the coupled SWAT-MODFLOW model are satisfactory in regard to simulating streamflow and groundwater elevations. The presented model can be applied for management purposes, enabling the water resources managers to quantify spatial groundwater vulnerability in large complex managed basins.

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# Chapter 3. APPRAISING CLIMATE CHANGE IMPACTS ON FUTURE WATER RESOURCES AND AGRICULTURAL PRODUCTIVITY IN AGRO-URBAN RIVER BASINS[1]

## 3.1. INTRODUCTION

Climate change is comprised of four main climatic factors: increasing atmospheric temperature, variation in precipitation patterns, increase in atmospheric $CO_2$ concentration, and upsurging in tropospheric ozone ($O_3$) level (Lobell & Gourdji, 2012). According to the Intergovernmental Panel on Climate Change (Hoegh-Guldberg et al., 2018), arid and semi-arid regions of the world are particularly vulnerable to climate change due to the potential decrease in water resources as a result of decreasing rainfall magnitudes and increasing surface temperature. Specifically, flow patterns in rivers and associated agricultural irrigation in such areas are sensitive to these climate stressors. For example, agricultural irrigation demand in arid and semi-arid regions of East-Asia is anticipated to rise by 10% for a 1 °C increase in temperature (IPCC, 2007). Cereal production in Africa, which has a key role in food security, is projected to decrease by 2-3 percent (FAO, 2017). In Iran, the total cultivated area is predicted to decrease by 6% (Afzali et al., 2020), and FAO (2017) reports a 10-25% reduction in yield for many crops in semi-arid countries.

As agricultural productivity is linked intrinsically to available water (Walthall et al., 2013), projections in crop yield must be preceded by projections in the water supply. In recent years, the negative effect of climate variability and other non-climatic factors (e.g., political and social instability, land-use change, population growth, and overfertilization) on both groundwater and

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surface water quality and quantity has intensified (Ahmed et al., 2016; Aslam et al., 2018; Hoegh-Guldberg et al., 2018; Lund et al., 2021; Shukla et al., 2019). Climate change impact on surface water is immediate and visible and therefore has been given more focus than groundwater systems (Chanapathi et al., 2020; Collet et al., 2014; Guo et al., 2020; Haleakala et al., 2017; Kristvik et al., 2019; Peres et al., 2019; Samimi et al., 2018; Summerton & Schulze, 2009). However, in arid and semi-arid regions of the southwest United States, China, India, Australia, Brazil, and many countries in Africa and the Middle East with generally scarce surface water resources, groundwater often is the primary source of water supply (Scanlon et al., 2006). Thus, assessing the impact of long-term climate change on groundwater supply and flow patterns in these regions is vital for proper water management for agricultural, industrial, and municipal use. Impacts on groundwater include the shift in timing and magnitude of peak groundwater recharge (Crosbie et al., 2013; Meixner et al., 2016; Moseki, 2018; Taylor et al., 2013), reduction in groundwater discharge to rivers (baseflow), and associated reduction in river discharge (Abdelhalim et al., 2020; Boubacar et al., 2020; Riddell et al., 2020), and a decrease in groundwater storage (Alam et al., 2019; Joshi et al., 2020; B. Li et al., 2019; A. Nair & Indu, 2020). The slow renewal time for groundwater, often years to centuries in semi-arid regions necessitates long-term forecasting of groundwater storage and associated water management in the face of increasing demands and climate change (Mays, 2013; Turner et al., 2019). As surface water and groundwater are used conjunctively in many semi-arid regions, with either source being used depending on the time of year, drought, or economic constraints, integrated water management based on both water sources must be considered (Lloyd, 2009).

In addition to affecting crop productivity through impact on water supply, climate change impacts crop growth patterns via changes in solar radiation, soil temperature, $CO_2$ levels in the atmosphere, and the intensity and frequency of precipitation. Each plant has specific temperature tolerances beyond which yields will decline (Hatfield et al., 2014). For example, the optimum temperature for corn, soybean, and cotton is 29 °C, 30 °C, and 32 °C, respectively, and higher temperatures will decrease crop yield (Schlenker & Roberts, 2008). Although rises in atmospheric $CO_2$ level and solar radiation may benefit the growth of some plants such as rice(Hatfield et al., 2014; Tariq & Rashid, 2020), it will affect crops' nutritional value by reducing the concentration of protein and minerals such as phosphorous, magnesium, and calcium (Tariq & Rashid, 2020). Short-term climatic effects such as drought, storms, floods, and waterlogging can decrease crop yield and the overall quality and fertility of agricultural soils (Tariq & Rashid, 2020). The complex interaction between crop growth, climate, and environment makes the projection of agricultural outcome to climate change a challenging study subject.

Assessment of climate-impacted future water supply and agricultural productivity at the river basin scale requires the use of a process-based watershed model. Each watershed model simulates a combination of the following processes and associated system-response variables: evapotranspiration and crop growth (crop yield), surface runoff, infiltration and percolation (soil moisture), recharge, groundwater flow in the aquifer (ground storage, water table elevation), groundwater discharge to streams, stream seepage to the aquifer, and streamflow (stream discharge). Models are tested against historical data, often streamflow at various points in the river basin stream network, groundwater head at monitoring wells located through the river basin, crop yield, and soil moisture. However, watershed modeling studies aimed at assessing the influence of climate change have deficiencies when considering future water supply and agricultural productivity: 1) models that simulate crop growth do not simulate groundwater hydrology in a physically based manner, and 2) models that include physically-based land surface, soil, and groundwater hydrology are used for surface water supply and groundwater supply, but do not simulate crop growth. These two deficiencies will now be described.

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) simulates daily crop growth and annual crop yield for hydrologic response units (HRUs) throughout the watershed. Each HRU can be assigned a different crop type, and crop types can be updated each year in the simulation. SWAT has been used to estimate watershed-wide water supply and crop yield under the influence of climate change (Y. Chen et al., 2019; Niknamian, 2019; Samimi et al., 2020; Srinivasan et al., 2010; Sun & Ren, 2014; Wang et al., 2016). However, SWAT uses a lumped, steady-state representation of aquifers and groundwater flow and therefore is not adequate for quantifying climate change impacts on groundwater storage, spatially distributed groundwater flow, and groundwater-surface water interactions. Other limitations of the SWAT model include simplistic snowmelt modules, a general neglect of effects of in-stream hydraulic structures, and simplified pollutant routing within a subbasin.

In recent years, the increased awareness regarding the importance of the interaction between surface water and groundwater and the necessity to have a holistic perspective on water resources for management purposes has triggered the development and use of coupled surface/ subsurface models that simulate physically-based, spatially-distributed land surface hydrologic processes and subsurface hydrologic processes. Several of these models include the Catchment Hydrology Model [CATHY] (Paniconi & Wood, 1993), HydroGeoSphere [HGS] (Therrien et al., 2010), and MIKE-SHE (Refsgaard et al., 1995). These models, however, do not include crop growth simulators and, therefore, cannot be used to estimate crop yield in a dynamic system. A variety of other watershed models are available for assessing climate change impacts on water supply, such as SWAT (Aawar & Khare, 2020; Bhatta et al., 2019; F. Li et al., 2016; Marin et al., 2020), the Variable Infiltration Capacity [VIC] (Liang et al., 1994), the Soil, Water Integrated Model [SWIM] (Krysanova et al., 1998), and HEC-HMS (Charley et al., 1995; Scharffenberg, 2016), but they simulate groundwater flow in a simplistic way such that model results cannot be compared to observed groundwater head and cannot be used to estimate groundwater storage in the watershed aquifer system.

Table 3.1 provides a list of studies that have used integrated surface water and groundwater hydrologic models to study the impact of climate change over a range of scales. For each study, the following information is provided: spatial area (km$^2$), study period, focus of study (surface water, groundwater, or agricultural productivity), the number of climate models and emission scenarios used in the forecast analysis, and the main sector of water use (agriculture, urban, industry). Despite agriculture being the main water used in the identified study region, these studies have not combined the assessment of water supply and crop production in river basins due to the lack of crop growth algorithms. Only SWAT-MODFLOW (Bailey et al., 2016) has this capability due to the crop algorithms used in SWAT, but no study using SWAT-MODFLOW has assessed climate change impacts on agricultural productivity. The following elements also are important for appropriate forecasting: the size of the watershed, the number of climate models used, and performing the study over the "climate normal." These will now be discussed.

Larocque et al. (2019) highlighted the importance of spatial variability and modeling scale in simulating the recharge and baseflow under climate change conditions. The boundary effect in small-scale simulations is a serious issue (Chen, 2015). In hydrological modeling, subbasin-scale simulations need fewer input data and computational requirements, and the model calibration is simplified (Chen, 2015). However, at the basin or regional scale, the greater number of possible combinations of climate, geology, land use, and environmental factors increase the complexity of the simulation. Barthel and Banzhaf (2015) use the term regional-scale to describe the areas of 103 to 105 km$^2$, and Persyn et al. (2008) assigned the term basin-scale to areas over 2600 km$^2$. As per these metrics, most of the studies listed in Table 3.1 are at the subbasin scale (Boubacar et al., 2020b; Cochand et al., 2019; Goderniaux et al., 2009; Guevara-Ochoa et al., 2020; Persaud et al., 2020; Sulis et al., 2012; Sultana & Coulibaly, 2011). Nevertheless, basin-scale assessment is important in climate change impact studies as water use patterns across urban, agricultural, and industrial sectors influence are dependent on each other.

**Table 3.1**. List of climate change studies using coupled groundwater/surface water modeling tools.

| **Research** | **Model Used** | **Area of Study Scale** | | **Study Period** | **Study Focus** | | | **# of Climate Models & (Emission Scenarios)** | **Main Water Use Sector** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Area (km$^2$)** | **El. (m)** | | **GW** | **SW** | **Ag** | | **Ag** | **Urban** | **In** |
| Guevara-Ochoa et al., 2020 | SWAT-MODFLOW | 1024 | 142-366 | 2020-2050 | x | x | | 1 (2) | x | | |
| Boubacar et al., 2020b | HydroGeoSphere | 1,900 | 172-286 | 2020-2050 | x | x | | 3 (1) | x | | |
| Petpongpan et al., 2020 | SWAT-MODFLOW | 58,783 | 25-2091 | 2021-2045 | x | x | | 3 (2) | x | | |
| Persaud et al., 2020 | HydroGeoSphere | 130 | 189-266 | 2045-2060 | x | x | | 8 (1) | x | | |
| Saha& Quinn 2020 | MIKESHE-MIKE_11 | 23,985 | 302-1024 | 2021-2036 | x | x | | 1 (2) | | | x |
| Chunn et al., 2019 | SWAT-MODFLOW | 11,494 | 475-1400 | 2010-2034 | x | x | | 5 (1) | x | | x |
| Cochand et al., 2019 | HydroGeoSphere | 553 | 0-800 | 2070-2100 | x | x | | 1[Average of 24 GCMS] (3) | x | x | |
| Sridhar et al., 2018 | VIC-MODFLOW | 186,479 | 884-1829 | 1986-2042 | x | x | | 2 (2) | x | x | |
| Sulis et al., 2012 | CATHY | 960 | 30-400 | 1971-2070 | x | x | | 12 (-) | x | | |
| Sultana& Coulibaly, 2011 | MIKESHE-MIKE_11 | 291 | - | 1961-2065 | x | x | | 2 (1) | | x | |
| Goderniaux et al., 2009 | HydroGeoSphere | 465 | - | 2010-2100 | x | | | 6 (1) | x | | |
| ***This Study*** | ***Updated SWAT-MODFLOW*** | ***72,000*** | ***850-4350*** | ***1980-2100*** | ***x*** | ***x*** | ***x*** | ***5 (2)*** | ***x*** | ***x*** | ***x*** |

The use of different climate scenarios from multiple global and regional climate models is recommended (J. Chen, 2015; Climatology Lab, 2020; Larocque et al., 2019). The mismatch between hydrological modeling scale and climate models' resolution causes a statistical bias and uncertainties in outputs, especially for decadal time spans and large spatial scales (Hawkins & Sutton, 2009). Using various climate models and emission scenarios is essential to provide a more complete representation of possible future conditions. Despite this recognized importance, most of the studies listed in Table 3.1 use outputs from only a small number of climate models (Boubacar et al., 2020b; Guevara-Ochoa et al., 2020; Saha & Quinn, 2020; Sridhar et al., 2018). Abatzoglou & Brown (2012) developed a statistical technique for downscaling Global Climate Models (GCMs), Multivariate Adaptive Constructed Analogs (MACA), which is used in this study and will be explained in Section 2-3. On their official website, they recommend using at least ten climate models to predict future changes (Climatology Lab, 2020).

One other significant consideration is performing a study over the "climate normal," which is the average of climate elements over at least three consecutive ten-year periods (WMO, 2018). For long-term climate variability evaluation and climate change tracking, climatological standard normal as a stable reference period is vital (WMO, 2018). The recent averaging period based on the World Meteorological Organization (WMO) is 1981-2010. In contrast, the study period of investigations listed in Table 3.1 since 2017 (column 5 of Table 3.1) either focus on the near future period (Boubacar et al., 2020b; Chunn et al., 2019; Guevara-Ochoa et al., 2020; Petpongpan et al., 2020; Saha & Quinn, 2020; Sridhar et al., 2018) or some specific period in the mid-century (Persaud et al., 2020) or the end of the century (Cochand et al., 2019). These short study periods, for instance, are not adequate to evaluate aquifers' slow response to changes in recharge and other boundary conditions due to climate variability (Larocque et al., 2019). Chunn et al. (2019) studied groundwater and surface water interaction by using a coupled SWAT-MODFLOW model under climate conditions from 2010 to 2034. They reported no significant impact from climate change and related it to the short study period, pointing to the need for a longer assessment period.

The objective of this study is to quantify the impacts of climate change on water resources (surface water and groundwater) and agricultural productivity in a semi-arid river basin through the 21st century. The approach presented can be used in other river basins worldwide. Recommendations for future studies that use integrated hydrologic models to assess the impacts of climate change also will be provided. The study basin is the South Platte River Basin (SPRB) (72,000 km$^2$), USA, which is a mixed agro-urban-industrial river basin with intensive irrigation practices. A previously constructed, and calibrated SWAT-MODFLOW model for the SPRB, tested against streamflow and groundwater levels (Aliyari et al., 2019), is run using output from five different climate models, each for two climate forcing scenarios, RCP4.5, and RCP8.5, covering the period of 1980-2100 and therefore including the "climate normal" for the study region. Climate data used in this study are the outputs of the Coupled Model Inter-Comparison Project Phase 5 (CMIP5) GCMs, downscaled by Multivariate Adaptive Constructed Analogs (MACA) (Abatzoglou & Brown, 2012). Working with various climate models and emission scenarios can provide water resources managers and growers with a better understanding of the full array of possibilities that a community may face in the future.

In this study, the following limitations from previous climate-focused hydrologic modeling studies are addressed by using SWAT-MODFLOW: lumped, steady-state groundwater flow; neglecting land surface hydrological processes; neglecting spatially-distributed groundwater-surface water interactions; and not relating available water supply to crop growth and overall food production. One of the primary benefits of using this model is the ability to estimate crop yields as a function of soil moisture, weather conditions, topography, crop type, and the applied land and water management practices (e.g., irrigation, pesticide, nutrient, and fertilizer practices and tillage operation). This model integrates groundwater and surface water and considers various interactions between water resources, climate, irrigated plants, and human activities. The analysis results are reported in four temporal periods: the current period of 2000-2020, near future of 2021-2040, midcentury of 2041-2070, and end of the century of 2071-2100. In general, the results of this study enable water resources managers to study the conjunctive variation of groundwater, surface water, and agricultural productivity in various climatic conditions.

## 3.2. MATERIALS AND METHODS

This section provides an overview of the water supply and demand infrastructure of the South Platte River Basin (SPRB), an explanation of the SWAT-MODFLOW hydrologic modeling tool for surface and subsurface hydrologic fluxes and water supply, and the use of the model to estimate future water supply and crop yield throughout the 21st century as affected by changes in climate patterns.

### 3.2.1. Area of Study

SPRB in the United States (Figure 3.1) has a spatial area of 72,000 $km^2$ and extends from the Rocky Mountains with an elevation of 4,350 meters at Mt. Lincoln on the west to the Great Plains with an elevation of 850 meters in the east, covering parts of Colorado, Wyoming, and Nebraska. The basin is located in a semi-arid region and is ranked as medium to highly vulnerable in terms of drought (Davitt, 2011). With a large spatial area but limiting water, the SPRB faces unique water management challenges. The topographic diversity of the basin creates large spatial variability in climatic patterns. Mean temperature increases from west to east and in the eastern part from north to south. In the last 50 years, the mean annual temperature has risen by 1.5 °C across Colorado, and additional warming of 1.5–3 °C is projected by 2050 (Lukas et al., 2014).

Annual precipitation, including snowfall, is about 760 mm in the mountains at the Continental Divide and decreases to 170-380 mm in the southwest regions of the basin (Dennehy et al., 1998). Precipitation type in the plains is mainly rain, which occurs primarily between April and September, while in the mountains, it is typically as snow, which falls primarily between October and March. Projected warmer temperatures in future decades may shift the precipitation type from snow to rain at certain elevation ranges and change temporal patterns of spring-time snowmelt to earlier in the season (Clow, 2010; Kenney et al., 2008; Qin et al., 2020), modifying reservoir releases and diversions for irrigation in downstream areas. These effects will intensify by higher temperature, evapotranspiration, and lower precipitation.

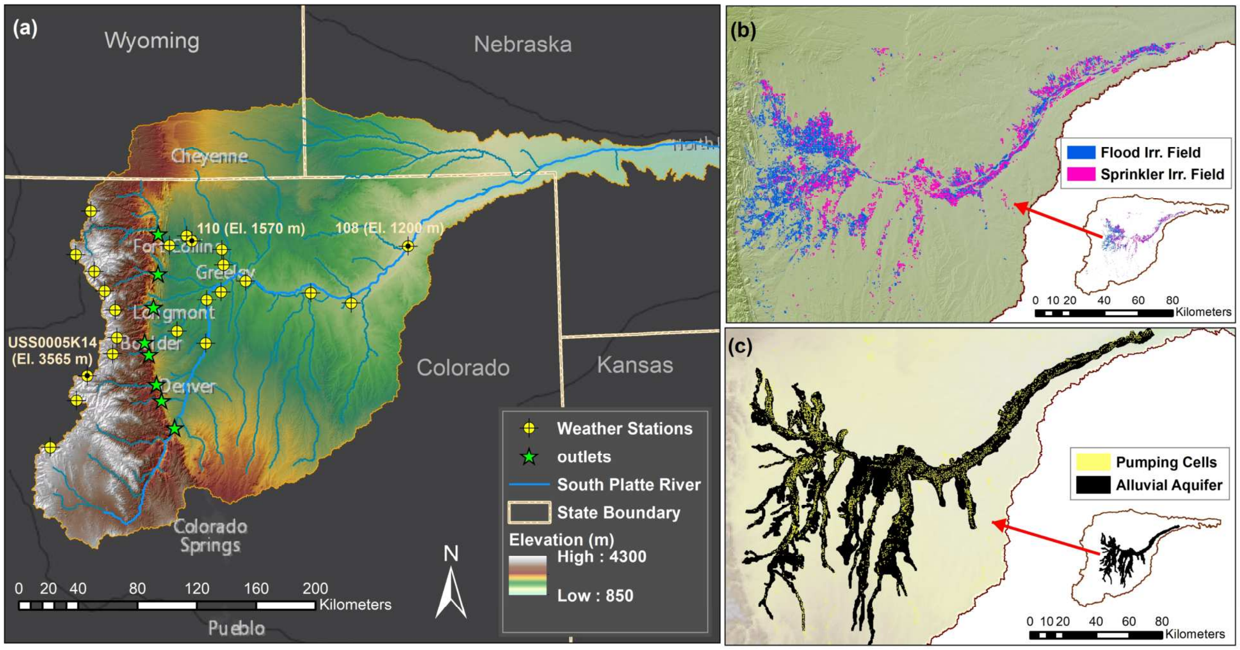


**Figure 3.1**. (a) South Platte River Basin extent among three States; Mouth of each canyon outlets, and weather stations across the SPRB; (b) Cultivated fields outline classified by type of irrigation; (c) Alluvial aquifer boundary + pumping wells location. [Maps are created by use of ArcMap software].

As in many other river basins with a semi-arid climate, the critical water management issues in the future of the SPRB are meeting water demand for the municipal, industrial, and agricultural sectors (Homeland Security, 2015). In agricultural settings, farmers divert surface water and pump groundwater to irrigate the cultivated lands. The SPRB, with approximately 345,600 ha of irrigated lands, is the most productive basin in the state of Colorado (Colorado's Water Plan, 2019). The transformation toward using more efficient irrigation systems, such as sprinkler irrigation, started in the 1950s, which changed the historical patterns of recharge, surface runoff, and groundwater return flows to streams (Waskom, 2013). However, as seen in Figure 3.1b, which shows a map of irrigation type for each cultivated field in the SPRB, flood irrigation still accounts for 55% of the total irrigated acreage. The source of flood irrigation is generally surface water, while groundwater is used for either flood or sprinkler irrigation. In the SPRB, the total surface water used for irrigation is approximately twice the surface water supply volume that originates from the mountains, reflecting the high reliance of surface water availability on groundwater return flow to streams (Dozier, 2017). Figure 3.1c shows the extent of the alluvial aquifer and the location of pumping wells. Most of these wells are used to supply irrigation water. Groundwater consumption increases during periods of drought, although this consumption is tempered by instituted water rights, with groundwater rights often being junior to owners of river water rights.

### 3.2.2. SWAT-MODFLOW Hydrologic Simulation Tool

This section describes the SWAT-MODFLOW hydrologic model for the SPRB and a brief explanation of its previous testing in the study region (Aliyari et al., 2019). Additional model testing and use of the model to simulate water supply and crop yield through 2100 are described in Section 2.3.

The SWAT model (Arnold et al., 1998) is a semi-distributed watershed model that simulates the hydrological processes that lead to streamflow generation. A watershed is divided into subbasins and associated streams, with each subbasin, further divided into hydrologic response units (HRUs) representing unique land types, for which daily water and nutrient balances are calculated for the land surface, soil, and aquifer zones. Water generated from each HRU as surface runoff, soil lateral flow, and groundwater flow is routed to the subbasin stream, whereupon all streamflow in the watershed is routed through the stream network to the watershed outlet. MODFLOW (Niswonger et al., 2011) is a groundwater flow model that simulates groundwater head throughout an aquifer system. The aquifer domain is divided into grid cells, representing a volume of the aquifer, for which water balances are calculated at a time step specified by the model user. If streams pass through the aquifer domain and stream stage elevation and stream bottom elevation are provided, water exchange between the streams and the aquifer can also be simulated. The constructed MODFLOW model consists of 69,895 grid cells each with an area of 1000-foot by 1000-foot (304.8 m*304.8 m), arrayed in 655 rows and 848 columns. Despite being used worldwide for many years, SWAT does not simulate groundwater in a satisfactory manner for many watersheds in which groundwater discharge is a significant component of streamflow, and MODFLOW does not include land surface hydrological processes. Therefore, these models often are linked to provide a more comprehensive simulation of hydrology in a watershed.

This study uses as its base code the SWAT-MODFLOW code of Bailey et al. (2016). The original SWAT-MODFLOW model links the SWAT and MODFLOW-NWT (Niswonger et al., 2011) model codes, with MODFLOW routines called as subroutines within the main SWAT modeling code. MODFLOW therefore replaces the original groundwater module subroutines in the SWAT code. SWAT simulates land surface, soil profile, and in-channel hydrological processes (evapotranspiration, surface runoff, infiltration, percolation, crop uptake, recharge to the water table), whereas MODFLOW simulates groundwater hydrological processes (groundwater flow, groundwater-surface water exchange). MODFLOW's River package is used to simulate exchange flow rates between the aquifer and the streams. For each day of the simulation:

1. SWAT simulates land surface, soil profile, and in-channel hydrology;
2. Recharge (i.e., percolation at the bottom of the soil profile) from HRUs are mapped to MODFLOW grid cells; stream stage from channels are mapped to MODFLOW River cells;
3. MODFLOW simulates groundwater head and groundwater storage for each grid cell based on groundwater inputs (recharge, surface water seepage), groundwater outputs (pumping, groundwater discharge to surface water), boundary conditions, and lateral flow through the aquifer using Darcy's Law;
4. Groundwater-surface water exchange rates calculated by MODFLOW for each River cell are mapped to SWAT channels;
5. SWAT routes stream water through the channel network.

A watershed-wide water balance is computed each day of the simulation. Figure 3.2 shows required GIS datasets to execute a SWAT-MODFLOW simulation, using SPRB data as an example. Figure 3.2a and 3.2b show the spatial distribution of SWAT subbasins and HRUs, respectively; Figure 3.2c shows the extent of the alluvial aquifer, which is discretized into square grid cells; Figure 3.2d shows the location of MODFLOW River cells, which intersect SWAT channels and are locations of groundwater-surface water interaction; and Figure 3.2e shows the location of pumping wells in the aquifer system. The location of pumping wells is also shown in Figure 3.1c.

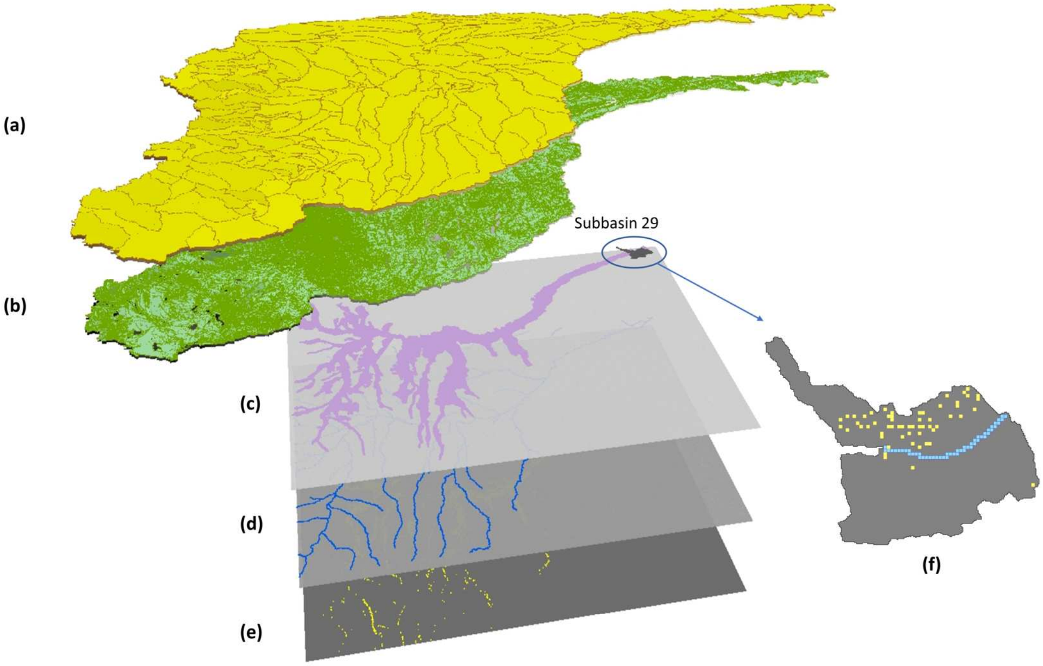


**Figure 3.2**. (a) SWAT subbasin; (b) HRUs; (c) MODFLOW grid cells and alluvial aquifer active cells in purple; (d) River cells in blue; (e) Pumping cells in yellow; (f) River (blue) and pumping (yellow) cells in subbasin 29.

A new version of SWAT-MODFLOW was presented by Aliyari et al. (2019) to represent hydrological processes more accurately in a large-scale agro-urban river basin such as the SPRB. The first key modification was to include the Partition Stress Boundary (PSB) capability (Zeiler et al., 2017), which partitions individual stresses into multiple stresses to account for the large variety of groundwater stresses in a highly managed aquifer system. For example, recharge to the water table is partitioned into recharge from rainfall, recharge from surface water and groundwater irrigation, recharge from reservoir seepage, and recharge from canal seepage. The second key modification was to link MODFLOW pumping wells to SWAT cultivated HRUs so that pumped groundwater removed from the aquifer (m3/day) is applied to farmland as an irrigated depth (mm). This requires an additional input file that lists each MODFLOW pumping cell and a corresponding HRU that receives the pumped irrigation water. The third modification was to alter the irrigation routines of SWAT so that groundwater irrigation can be enabled when available surface water is not sufficient to supply irrigation water to the HRU cropping system.

The modified version of SWAT-MODFLOW was calibrated and tested for the SPRB for the 1997-2012 time period in the previous study of Aliyari et al. (2019). Specific hydrologic fluxes simulated by the model are listed in Table 3.2. This model was tested against groundwater head from monitoring wells located across the basin and discharge in the South Platte River at multiple stream gages located at the base of the Rocky Mountains and throughout the urban and agricultural areas. The Dynamically Dimensioned Search (DDS) algorithm, developed by Tolson and Shoemaker (2007), was used to calibrate the model for streamflow discharge. To assess the performance of the model in linking the MODFLOW agricultural pumping cells and SWAT HRUs for groundwater irrigation, the water balance across the basin was compared under various additional irrigation scenarios. These irrigation scenarios include i) both surface water irrigation and groundwater irrigation, ii) no irrigation, and iii) only surface water irrigation. For detailed information regarding the model calibration results and performance, please refer to Aliyari et al. (2019).

**Table 3.2**. The hydrologic fluxes within the SPRB and the corresponding model that handles the flux within SWAT-MODFLOW.

| Hydrologic Flux | Simulated by |
|---|---|
| Precipitation/ Evaporation/ Evapotranspiration | SWAT |
| Surface runoff to streams | SWAT |
| Lateral flow to streams | SWAT |
| Streamflow | SWAT |
| Stream water diversion for surface water irrigation | SWAT |
| Aquifer recharge (from precipitation and irrigation) | SWAT |
| Groundwater discharge to streams | MODFLOW |
| Stream seepage to the aquifer | MODFLOW |
| Canal seepage to the aquifer | MODFLOW |
| Groundwater pumping from the aquifer | MODFLOW |
| Groundwater ET from shallow water table | MODFLOW |
| Reservoir seepage to the aquifer | MODFLOW |
| Alluvial aquifer boundary inflow/outflow | MODFLOW |
| Bedrock upflow to alluvial aquifer | MODFLOW |

### 3.2.3. Estimating Water Supply and Crop Yield during the 21st Century

The tested SWAT-MODFLOW model of the SPRB is used in conjunction with projected climate data to quantify surface water resources, groundwater resources, and crop yield throughout the 21st century. A primary tool in meteorological projections of precipitation and temperature is Global Climate Models (GCM). However, the coarse spatial resolution of these models limits their application in local areas (Larocque et al., 2019). To reduce the inherent statistical bias due to this spatial mismatch, GCM outputs should be adjusted to a finer, more accurate scale by downscaling post-processing methods. Downscaling is particularly essential in regions characterized by highly spatial meteorological variability (Larocque et al., 2019), such as the SPRB.

A statistically downscaled climate model method for the contiguous United States is the Multivariate Adaptive Constructed Analogs (MACA) (Abatzoglou & Brown, 2012) that links GCM outputs to local meteorological variables. This method downscales the outputs of the twenty Coupled Model Inter-Comparison Project Phase 5 (CMIP5) GCMs from their original resolution to either 4 or 6 kilometers for two future Representative Concentration Pathways (RCP4.5 and RCP8.5) scenarios for 2006–2100. The historical MACA archive contains data from 1950-2005.

The RCPs represent the potential future of greenhouse gas and $CO_2$ emission concentration and are categorized based on reaching a specific radiative forcing at the end of the century (year 2100). The change in radiative forcing by 2100 in an environmentally moderate optimistic scenario, RCP4.5, is +4.5 watts per square meter (Wm-2), and in the extreme pessimistic scenario, RCP8.5, it rises to +8.5 Wm-2 in 2100 (Hayhoe et al., 2017). In general, statistically downscaled data do not capture the impacts of land-surface variation such as snow-albedo on local climate (Climatology Lab, 2020). In MACA method, the statistical downscaling should be derived from a representative sample distribution of observations, thus any defects from non-climatic factors in the historical dataset will be passed on to the downscaled dataset, especially while using the short period of records. Moreover, a robust capability in observed period downscaling may not remain constant with climate change scenarios. However, using MACA method is advantageous because it enhances the physical relationships between variables rather than treating variables independently, and is well suited for using in approaches that are sensitive to a spectrum of climatological variables (Abatzoglou & Brown, 2012).

To encompass a better understanding of the predicted future changes, we adopt the combination of five different climate models under the RCP4.5 and RCP8.5 emission scenarios. The selected climate models for this study (Table 3.3) are widely used GCMs based on the least warm projection, hottest projection, driest projection, wettest projection, and finally, a mild projection that represents the middle of temperature and precipitation variability projected by all others at conterminous scale (Joyce & Coulson, 2020).

**Table 3.3**. The list of climate models and descriptions.

| Core Model | | Emission Scenarios | Country | Agency |
|---|---|---|---|---|
| **WARM** | MRI-CGCM3 | RCP4.5, RCP8.5 | Japan | Meteorological Research Institute<br>(Yukimoto et al., 2012) |
| **HOT** | HadGEM2-ES365 | RCP4.5, RCP8.5 | UK | Hardly Center<br>(Collins et al., 2008) |
| **DRY** | IPSL-CM5A-MR | RCP4.5, RCP8.5 | France | Institute Pierre Simon Laplace (Dufresne et al., 2013) |
| **WET** | CNRM-CM5 | RCP4.5, RCP8.5 | France | National Center of Meteorological Research<br>(Voldoire et al., 2013) |
| **MILD** | NorESM1-M | RCP4.5, RCP8.5 | Norway | Norwegian Climate Center<br>(Bentsen et al., 2013) |

The projected values of precipitation, minimum and maximum air temperature by the models in Table 3.3 are downloaded from the MACA dataset for the closest grid cell to the weather stations within the SPRB. The data from the downscaled climate models are inserted into the weather input files of SWAT. The MODFLOW model input files for the previous study (Aliyari et al., 2019), which used 192 monthly stress periods for 1997-2012, were modified to account for monthly stress periods through 2100. Table 3.4 lists the general model information and groundwater stresses for which input files were modified. The available observed data are used to expand each package and are assumed to be repeated over the same observed period in the future. The coupled SWAT- MODFLOW model is run from 1980 through 2100 for each of the 10 scenarios listed in Table 3.3. Each simulation is assessed for stream discharge, stream seepage to groundwater, groundwater hydraulic head, saturated thickness, groundwater storage, groundwater discharge to stream, and crop yield. To verify the accuracy of the downscaled climate models for the SPRB, simulated streamflow is compared with measured streamflow at stream gages located at the base of the Rocky Mountains (outlets in Figure 3.1a) for the historical time period 1980-2005.

**Table 3.4**. The List of modified MODFLOW packages for climate change studies.

| **Package Description** |
|---|
| Specified times for model output |
| Time step and stress period information |
| Bedrock upflux |
| Boundary conditions |
| Agricultural pumping |
| Municipal pumping |
| Recharge pond seepage |
| Alluvial aquifer underflow |
| Injection wells for water rights |
| Reservoir seepage |
| Canal seepage |

The major crop types in the study area are corn, alfalfa, wheat and other grains, sugar beets, barley and sunflower. Based on the 'cropland and pasture' class of Anderson Land Use/ Land Cover Classification, these crops are categorized as row crops (Gilliom & Thelin, 1997). Thus, all crops are combined and designated as 'Agricultural Land-Row Crops' in the SWAT model. To account for annual growth variation, the SWAT model utilizes the Environmental Policy Integrated Calculator (EPIC) crop growth model (Williams et al., 2006). Initially, SWAT estimates the potential crop growth given ideal growing conditions. If these conditions are not available, SWAT imposes stress and thereby decreases potential biomass (S. S. Nair et al., 2011). For a crop to grow, the base temperature in each day should be greater than the sum of the model heat units and the average temperature in the model (Parajuli et al., 2013). The crop yield is calculated by use of the Harvest Index (HI) of the crop on the day of harvest, defined as the aboveground plant dry biomass fraction that is removed on the day of the harvest. HI is the function of the potential heat units' fraction that is accumulated for the plant on a given day during the growing season (Neitsch et al., 2011). In this study, the crop yield data from the HRU output of the SWAT-MODFLOW model is summed up for each year to calculate the total annual crop yield across the basin.

Although the original SWAT-MODFLOW model (Aliyari et al., 2019) was not calibrated or tested for crop yield, the simulated and observed crop yield is compared in this study to allow for the model to be used for estimating crop production under future climate scenarios. The available crop production data from the 'Colorado Agriculture Profile', a joint publication between USDA and Colorado Department of Agriculture accessible through the USDA National Agricultural Statistics Service website (USDA-NASS, 2018), are compared to crop yield simulated by SWAT-MODFLOW.

## 3.3. RESULTS AND DISCUSSION

### 3.3.1. Overview of Future Climate in the SPRB

The broad view of climate change impacts on total annual precipitation and annual average maximum/ minimum temperature is shown in Figures 3.3 and 3.4. The precipitation regime and maximum and minimum temperature for all climatic models and scenarios are graphed in Figure 3.3 for three different weather stations across SPRB. The stations are selected from different locations with various altitudes, from 3,565 meters in the mountainous area to 1,200 meters in the plains (Figure 3.1a). The distribution of precipitation (snow and rain) is directly related to the topography and distances from the mountain. The total annual precipitation based on the observational values is about 800 mm at station USS0005K14S with an altitude equal to 3,565 m, and it reaches to a magnitude of 345 mm (56% decrease compared to mountainous high latitude) at station 101 with an altitude equal to 1,570 m. The precipitation increasing rate is larger in the higher altitude than in lower elevations (Figure 3.3a). The maximum increasing rate from the climate normal is related to the most elevated station (USS0005K14S) and is equal to 10 % and 8% by the end of the century under the RCP4.5 and RCP8.5 scenarios, respectively. These results are consistent with the previous studies in Colorado (Christensen et al., 2004). By contrast, the minimum rise happens in lower altitudes (Station 108) under the RCP8.5 scenario by the end of the century and is less than 1%.

In contrast to precited precipitation, each climate model in both emission scenarios projects an increase in annual average temperature, which agrees with other studies in this region (Lukas et al., 2014). Previous studies projected the warming of 1.5-3 °C by 2050 across Colorado (Lukas et al., 2014), which agrees with the results shown here. Temperature presents a clear increasing trend throughout the 21st century. According to the charts shown in Figures 3.3b& c, and as expected, temperature increases are greater in the RCP8.5 scenarios regardless of altitude. The SPRB's temperature will rise by 3 to 5 °C by the end of the century under RCP4.5 and RCP8.5 scenarios, respectively. An estimated 3-5 °C increase in the mountainous region means the temperature is raised by more than 70%, which brings the average annual minimum temperature from -5.5 °C to -0.9 °C, and the average annual maximum temperature from 7 °C to 12 °C.

To better understand and compare climate scenarios, the mean values of all climate models for RCP4.5 and RCP8.5 scenarios are plotted on the graphs in Figure 3.3. The "climate normal," the average annual observed values in each station for 1981-2010, is also shown. The climate normal for each station is listed in Table 3.5.

**Table 3.5**. The climate normal values for selected stations.

| Station | Max. Temp. (°C) | Min. Temp. (°C) | PCP (mm) |
|---|---|---|---|
| USS0005K14S | 6.9 | -5.5 | 800 |
| 101 | 17.2 | 1.21 | 345 |
| 108 | 18.4 | 1.4 | 400 |

The total average annual precipitation (PCP) and actual ET simulated by the SWAT-MODFLOW model across the entire basin through the end of the 21st century for each of the 10 climate models is shown in Figure 3.4. As seen from these charts, the projected results for precipitation are not unanimous across the climate models. The precipitation slightly increases across the entire basin except for the dry (IPSL-CM5A-MR) climate model. As is evident by precipitation trendlines in this figure (dashed green), the dry climate model (IPSL-CM5A-MR) is the only one that projects a decline in average annual precipitation for the entire basin with the rates of 5% and 6.5% under the RCP4.5 and 8.5, respectively. On the other hand, the rate of average annual ET remains almost unchanged compared to the current climate period; however, the potential evapotranspiration (PET) will increase by 21% by the end of the century under this specific dry climate model.

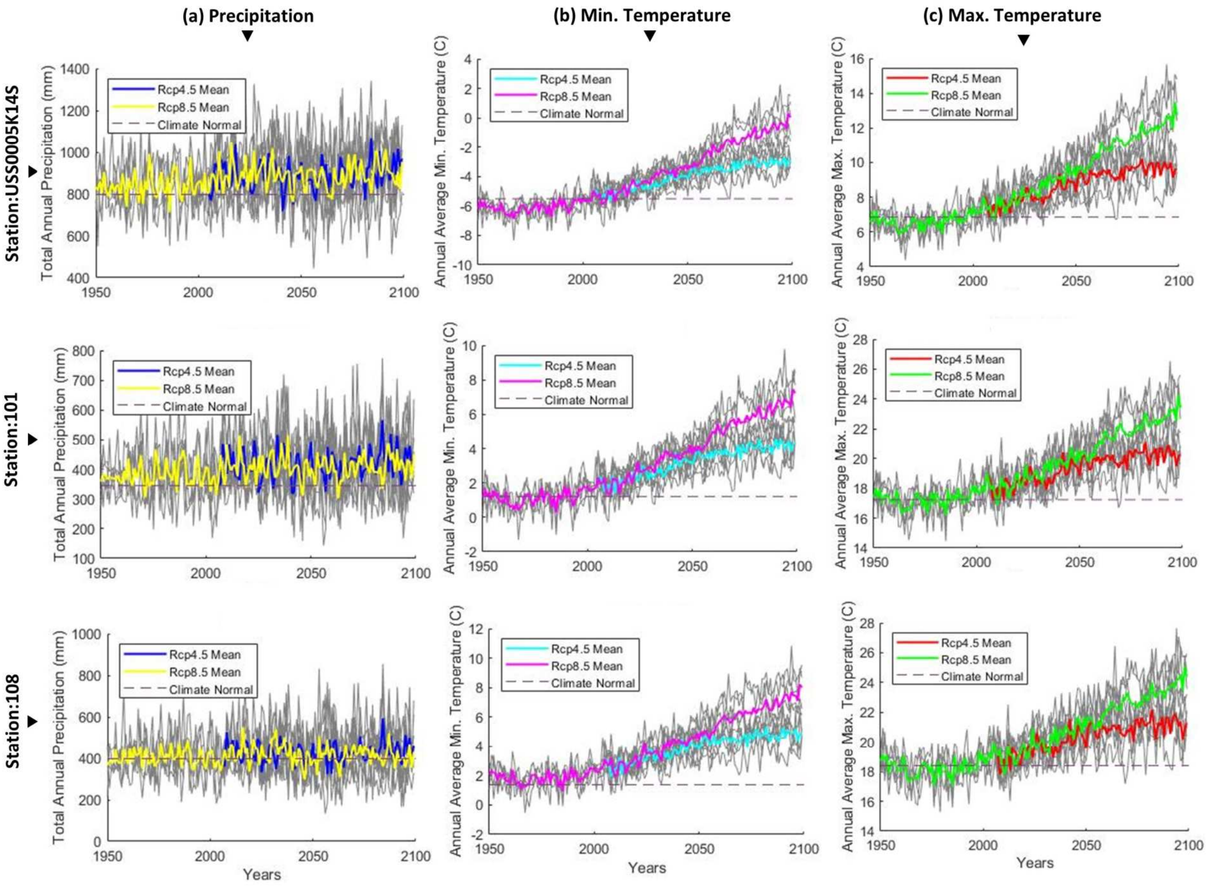
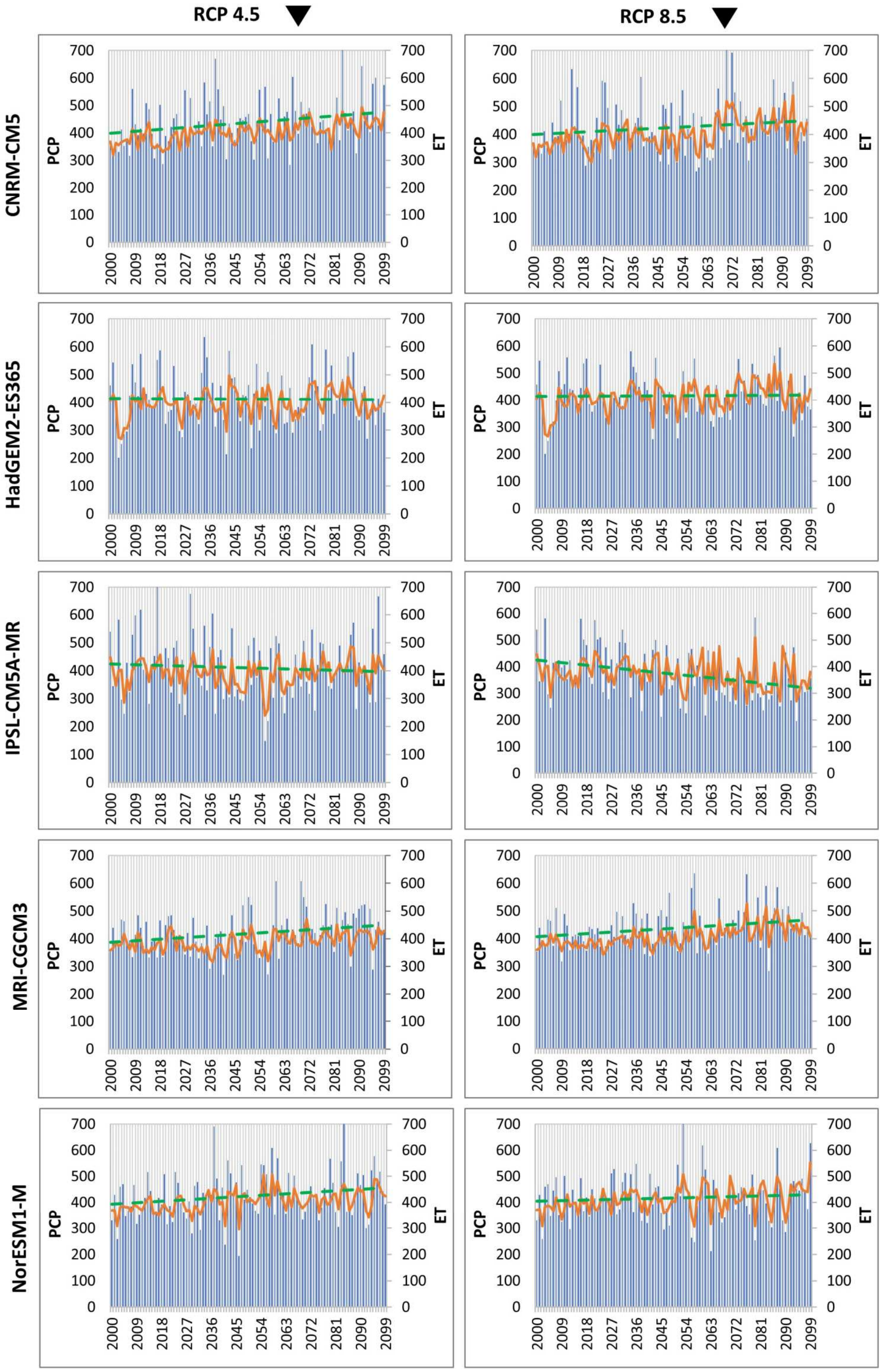


**Figure 3.3**. (a)Projected total annual precipitation; (b)& (c) Projected total average maximum and minimum temperature for all climate models under RCP4.5 and RCP8.5 scenarios (grey lines) for stations 101, 108, and USS0005K14S; RCP4.5 scenarios mean values (blue, red and cyan lines in precipitation., max. and min. temperature graphs, respectively) and RCP8.5 scenarios mean values (yellow, green and magenta lines in precipitation, max. and min. temperature graphs, respectively).



**PCP & ET units are in mm.**

**Figure 3.4**. Total average annual precipitation (PCP; blue bar), precipitation trendline (dashed green), and average annual actual evapotranspiration (ET; orange line) across the entire basin for each climate model and forcing scenario through the end of the 21st century.

### 3.3.2. SWAT-MODFLOW Performance in Estimating Crop Yields

Figure 3.5 shows the historical average annual crop yield (tons/ha) for the end of the calibrated SWAT-MODFLOW model period (2017), compared to average annual yields simulated by SWAT-MODFLOW for all 10 emission scenarios. Considering the inherent uncertainty of climate models, we believe there is an acceptable agreement between simulations and historical records. The total annual row crop yield across the basin, according to 'Colorado Agriculture Profile', is 500 tons/ha, and the breakdown by crop is shown in Figure 3.5.

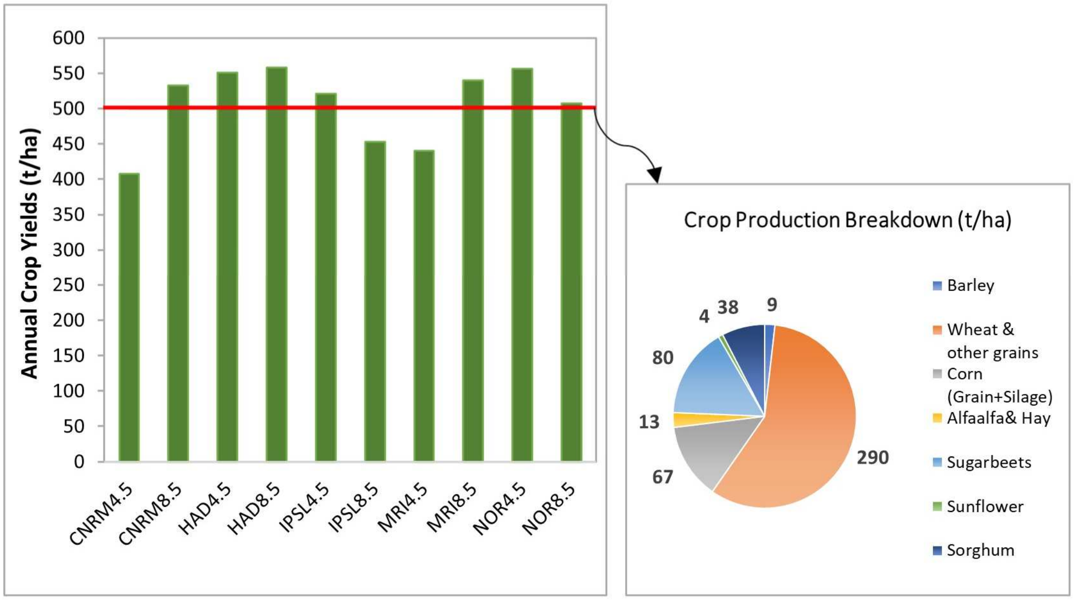


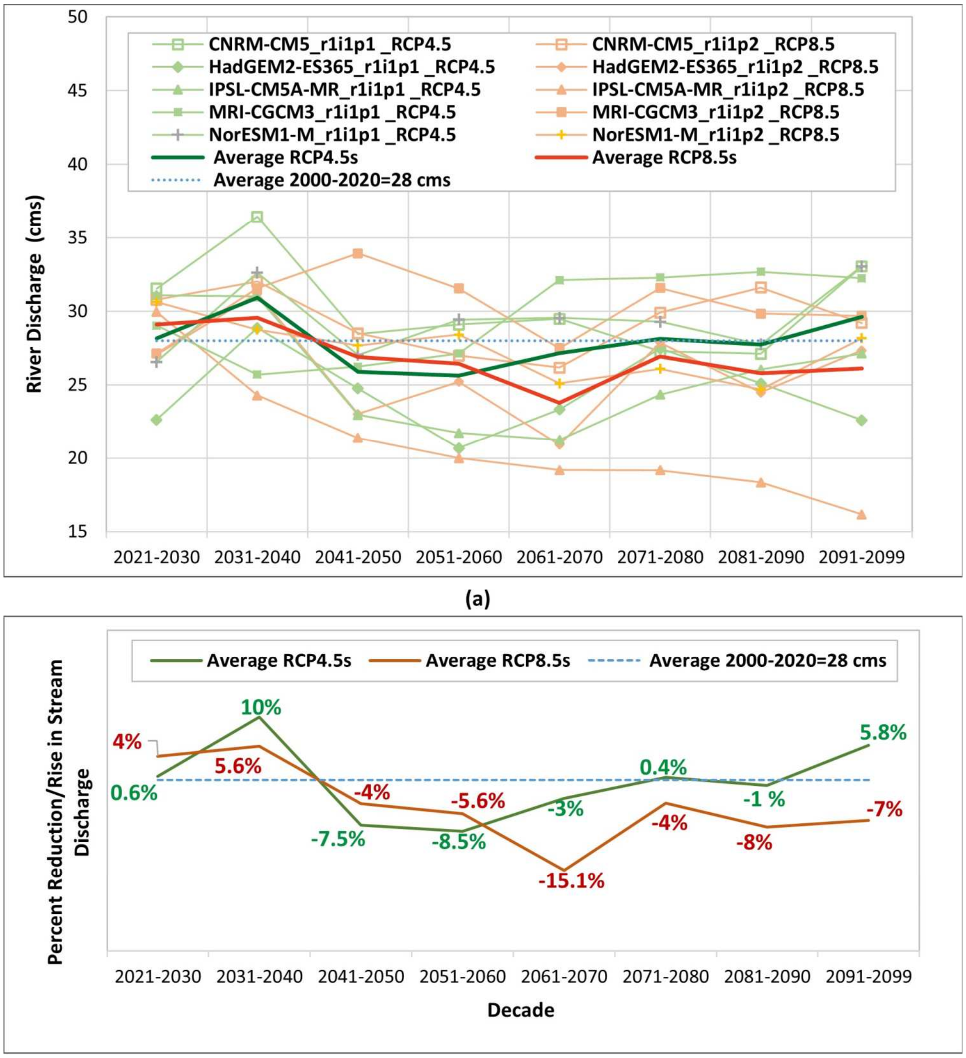
**Figure 3.5**. Total simulated annual crop yield for all climate models and emission scenarios (Green bars), vs. the historical records (Red line) and its breakdown.

### 3.3.3. SPRB Water Resources in the 21$^{st}$ Century as Impacted by Climate

#### *3.3.3.1. Surface Water Resources*

The total annual average stream discharge from the canyon outlets, and the comparison between the projected average stream discharge under RCP8.5 with RCP4.5 for each RCP in three future time periods: 2006-2040, 2041-2070 (midcentury), and 2071-2100 (end of the century) are shown in Figure 3.6a and b, respectively. These results are refined to decadal stream discharges from 2021 through the end of the 21st century. The average decadal stream discharge projected by all climate models under each RCP scenario is also plotted in this figure (red lines). A notable inter-decadal stream discharge variation is observed: in the average stream discharge plot under RCP4.5 scenarios in Figure 3.6a& b, the sharp increase in the 2020s follows a dramatic drop during the 2030s. The stream discharge under RCP4.5 is projected to reach its minimum in the mid-century and then increases with different rates through the end of the century. However, this increase will not surpass the current average stream discharge (2000-2020) (blue dashed line) until 2090. The patterns of increase and decrease in discharge are also observed under the RCP8.5 scenario (Figure 3.6a& b). The average stream discharge plot in this figure shows a mild increase through the mid-2030s and drops below the current average stream discharge (2000-2020) until the end of the century. Figure 3.6b compares the projected average stream discharge under RCP8.5 with RCP4.5 and reflects the percentage of decrease/increase in average stream discharge for each decade. The decrease/increase percentages are calculated by comparing the projected values of average stream discharge in each decade with the average stream discharge from 2000 to 2020. The results show a significant gap between these two scenarios in projecting the streamflow after the mid-century. The higher emission scenario (RCP8.5) results in a more remarkable decline in stream discharges and reaches its maximum (15.1%) in the 2060s.

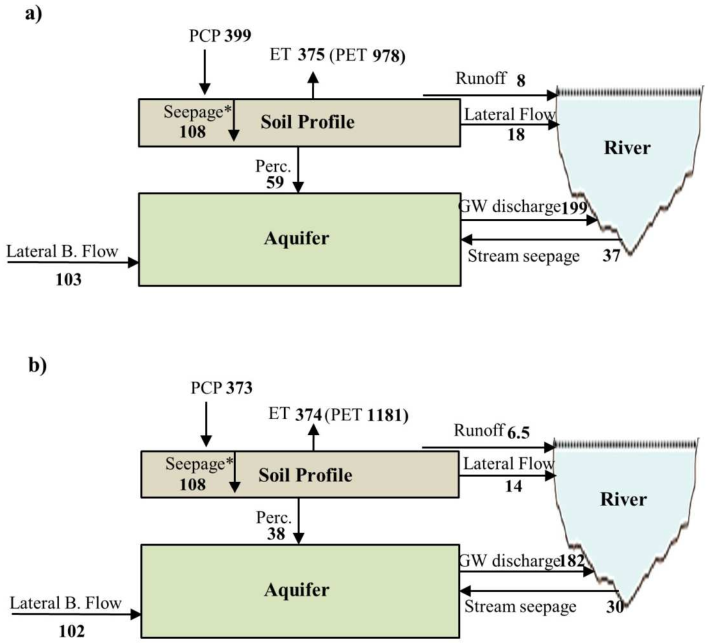
Based on these figures, the maximum reduction in projected stream discharge from canyon outlets happens under the IPSL-CM5A-MR-RCP8.5 climate model and is about 43% by 2100. This implies that under this climate scenario for a 1.3% reduction in annual precipitation and 1 oC increase in temperature, the average stream discharge from the mountainous headwaters will decline by 8.6% by the end of the century. This can be explained by the decreased average annual precipitation (Figure 3.4) that is combined with a rise in temperature through the 21st century under this scenario. The effects of these combined stressors on the basin's water balance are reflected in Figure 3.7. Based on this figure, surface runoff, recharge to the water table, lateral soil flow, and groundwater discharge will decrease by approximately 20%, 35%, 20%, and 9%, respectively, by 2100 across the basin. The total water yield (surface runoff + lateral flow + net groundwater flow) decreases from 188 mm to 172 mm, a decrease of 8% in the entire basin.



(a)

(b)

**Figure 3.6**. (a) Decadal total streamflow (m3/s) from canyon outlets under all downscaled GCM climate models for each RCP, plus average values for 2000-2020 and average values of all RCP4.5s& RCP8.5s; (b) percent reduction/rise in average decadal total stream discharge through the end of the century under RCP4.5 and 8.5 scenarios compared to the average total stream discharge during the current period of 2000-2020.



* Seepage from canals, reservoirs and ponds.
All Units are in mm.

**Figure 3.7**. water budget scheme under IPSL-CM5A-MR-RCP8.5 climate model for the entire basin during (a) the current period; and (b) the end of the century.

### *3.3.3.2. Groundwater Resources*

Total available groundwater in the alluvial aquifer (see Figure 3.1c for spatial extent) of the SPRB is calculated using the saturated thickness and specific yield of each MODFLOW grid cell, where the saturated thickness is equal to the vertical distance from the bedrock to the simulated groundwater head. Figure 3.8 shows total groundwater storage in the SPRB for each decade from 2021 through the end of the 21st century, for each climate model. The average for each emission scenario also is shown. Under all downscaled GCM models except for the warm climate model, MRI-CGCM3, in both RCP scenarios, a steep increase in groundwater storage by 2030s is followed by a sharp reduction and continues to the end of the century. Compared to the average groundwater storage from 2000 to 2020 (shown by the dotted blue line), the maximum loss is happening during the last decade of the century under hot (HadGEM2-ES365) and dry (IPSL-CM5A-MR) climate models in both RCPs. During this decade, the rate of loss under the

HadGEM2-ES365-RCP4.5 climate model is -11% and drops to -23% under RCP8.5. This rate varies from 8% to 25% reduction in the IPSL-CM5A-MR climate model under RCP4.5 and RCP8.5, respectively, by 2100. It suggests that in the worst-case climate scenario for a 1.3% reduction in annual precipitation and 1 oC increase in temperature, the groundwater storage will decrease 2 to 5% by the end of the century. This outcome is from the combined effect of the decline in average annual precipitation and increasing temperature that will lead to a 36% reduction in the water that percolates through the bottom of the soil profile and recharges the water table by 2100 (Figure 3.7).

The spatial distribution of the average saturated thickness from 2000 through 2020 under the worst-case climate scenario, IPSL-CM5A-MR-RCP8.5, is presented in Figure 3.9a as a base map. To address the most affected regions across the basin, the changes in saturated thickness through different future time intervals, near future (2021-2040), mid-century (2041-2070), and end of the century (2071-2100), are reported in Figures 3.9b, c, and d as well. The visual observation of Figure 3.9b indicates that in the near-future period (2021-2040), groundwater levels decline in some areas of the basin but also rise in other areas. Consequently, the average saturated thickness across the aquifer remains the same as during 2000-2020, approximately 14 m. However, the average saturated thickness decreases to 11 m and 9 m during 2041-2070 and 2071-2100, respectively. The central region of the basin experiences the most decline by the end of the century (Figure 3.9d). The percent change in saturated thickness throughout the aquifer is shown in Figure 3.10 for the three future time periods under the IPSL-CM5A-MR-RCP8.5 climate model. The percent reduction in saturated thickness in the central parts of the basin ranges from 80 to 100 percent by the end of the 21st century, indicating a complete depletion of groundwater in many parts of the aquifer. Even the regions which experience an increase in saturated thickness during the near future period (2021-2040) will be adversely impacted by the end of the century.

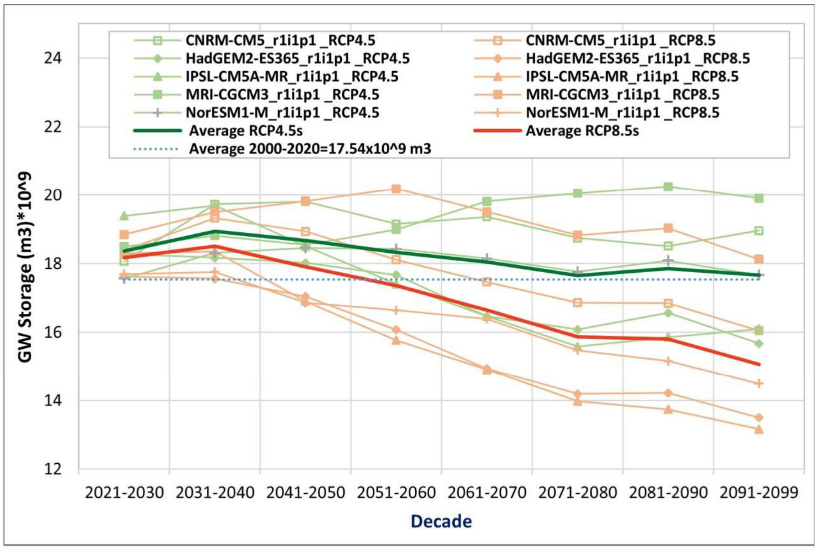
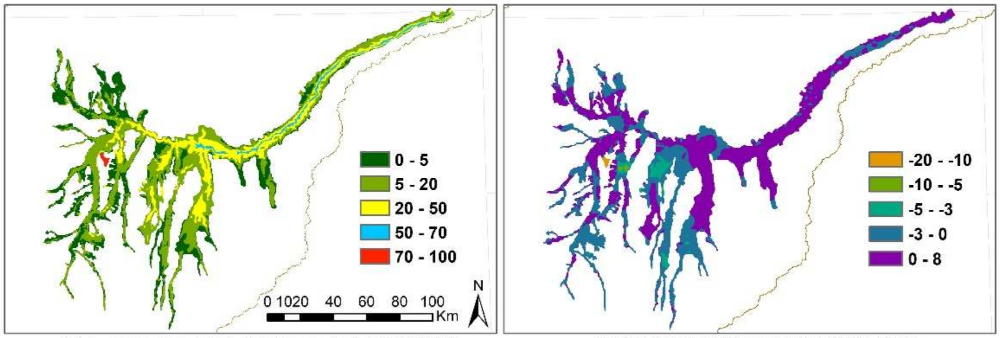
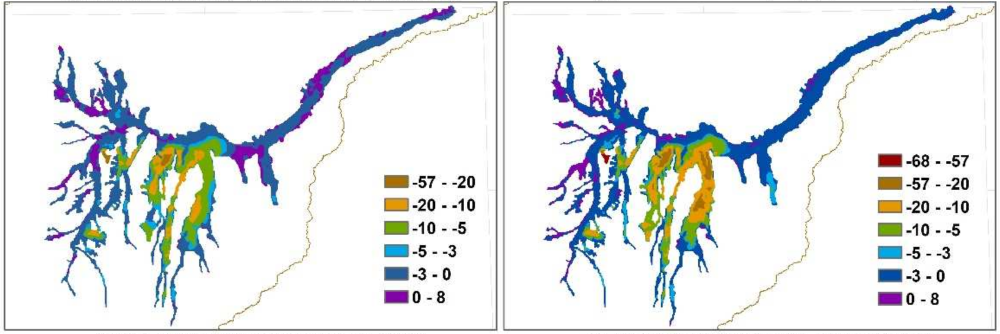


**Figure 3.8**. Decadal groundwater storage under all downscaled GCM climate models and RCP scenarios through the end of the century; The average of RCP4.5s (green line); The average of RCP8.5s (red line); and Average groundwater storage for the period of 2000-2020 (dotted blue line).



(a) Average Saturated -Thickness (m) (2000-2020)

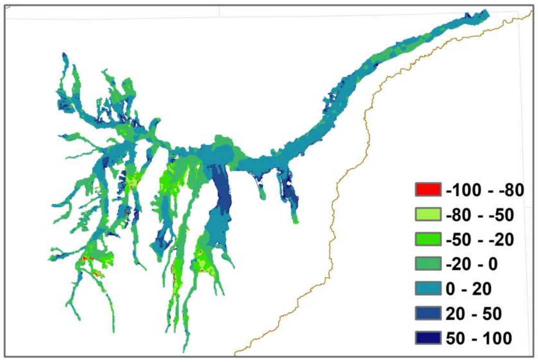
(b) Near-Future Changes (m) (2021-2040)



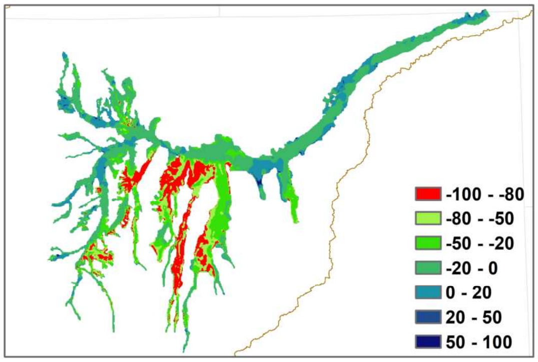
(c) Mid-Century Changes (m) (2041-2070)

(d) End of Century Changes (m) (2071-2100)

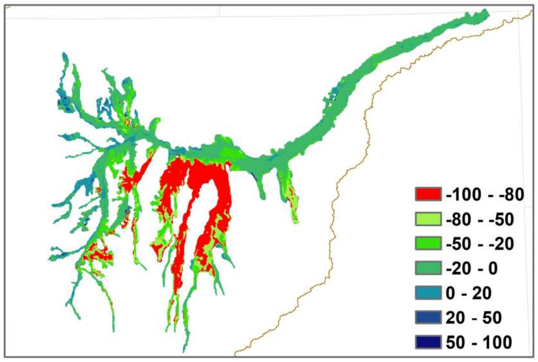
**Figure 3.9**. (a) Average saturated thickness across the aquifer boundary from 2000 through 2020 (base map) under IPSL-CM5A-MR-RCP8.5; (b), (c) and (d) The changes in saturated thickness compare to the base map for periods, near future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100), respectively.



(a) Near-Future % Changes (2021-2040)



(b) Mid-Century % Changes (2041-2070)



(c) End of Century % Changes (2071-2100)

**Figure 3.10**. Percent changing in saturated thickness compared to the average saturated thickness in 2000-2020 under IPSL-CM5A-MR-RCP8.5 for (a) near future, (b) mid-century, and (c) end of the century.

#### *3.3.3.3. Groundwater-Surface Water Exchange*

As surface water resources depend strongly on the quantity of groundwater return flows to the stream in the SPRB, the future patterns of groundwater-surface water (GW/SW) interactions are an important aspect of water management. This is shown in the water balance components of Figure 3.7, which show that groundwater return flow to the river system accounts for 85-90% of all return flows. Figure 3.11 presents the projected GW/SW fluxes from 2000 through the end of the century in 4 different time intervals along the South Platte River and its tributaries- current (2000-2020), near future (2021-2040), mid-century (2041-2070), and end of the century (2071-2100)- under the worst climate condition in this region, IPSL-CM5A-MR-RCP8.5, in months February and May. Conditions for these two months are shown due to the seasonal variation in GW/SW fluxes. Values are shown for each MODFLOW grid cell that intersects a river channel. Positive values show the volume of water entering the stream from the aquifer, and the negative values indicate the volume seeps from the stream to the aquifer. These maps show that the majority of groundwater discharge occurs along the main stem of the South Platte River and mostly in the central agricultural area of the basin as irrigation-induced high water tables drive groundwater into the river. Conversely, seepage occurs mainly in areas of tributaries, where water tables are deep. The average projected groundwater discharge and stream seepage for each period tabulated in Table 3.6 show the dynamic interaction of GW/SW. The higher groundwater discharge fluxes indicate that the South Platte River is a gaining river and will stay gaining through the end of the century.

As expected, the net average groundwater discharge and seepage flux in the wet month of the year, May, is higher than the dry month, February; however, the increase rate is more elevated in seepage than groundwater discharge. The changes in the seepage fluxes in dry and wet months of the year follow different patterns. In the dry month of February, the stream seepage will increase from mid-century toward the end by 133% (2.3 fold higher), while in the wet month of the year, May, the stream seepage will decrease to the end of 21 century by 68% (3.13 fold less) compare to the current period (2000-2020). These results suggest that the higher precipitation in May will be offset by higher evaporation due to elevated temperatures than in February. It will lead to a lower river stage through the end of the century than the current climate condition.

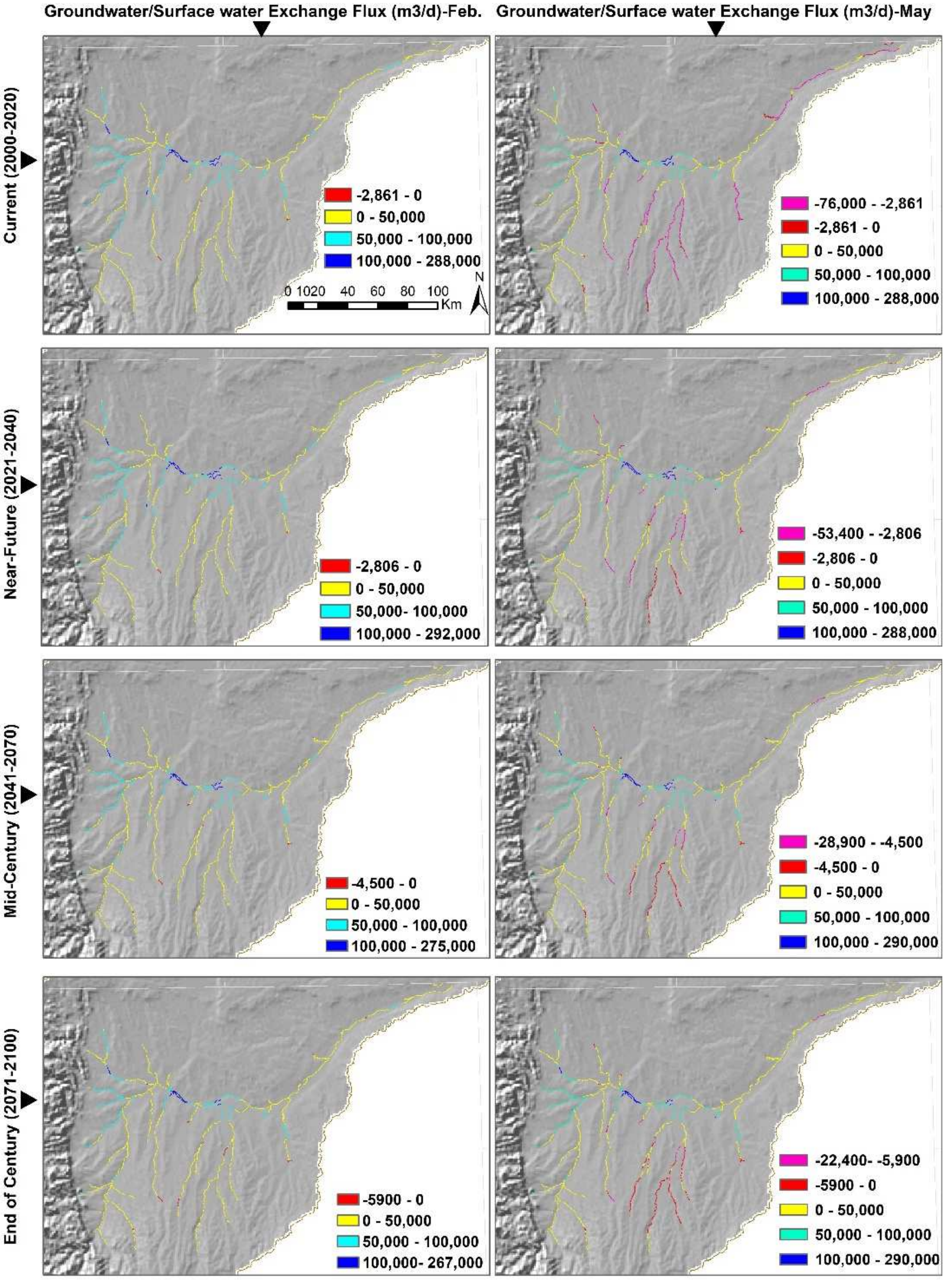


**Figure 3.11**. The spatial distribution of GW/SW exchange fluxes in February and May along the South Platte River and its tributaries in different time intervals- current (2000-2020), near future (2021-2040), mid-century (2041-2070), and end of the century (2071-2100) under IPSL-CM5A-MR-RCP8.5 climate model.

**Table 3.6**. The average projected groundwater discharge and stream seepage for each period, IPSL-CM5A-MR-RCP8.5 climate model.

| | | Stream Seepage ($m^3/d$) | Groundwater Discharge($m^3/d$) |
|---|---|---|---|
| **Feb.** | **2000-2020** | -634 | 38600 |
| | **2021-2040** | -580 | 39300 |
| | **2041-2070** | -1070 | 36700 |
| | **2071-2100** | -1470 | 35200 |
| **May** | **2000-2020** | -16600 | 39400 |
| | **2021-2040** | -12300 | 40100 |
| | **2041-2070** | -6930 | 40400 |
| | **2071-2100** | -5320 | 39600 |

### 3.3.4. Agricultural Productivity in the 21st Century as Impacted by Climate

Annual agricultural productivity projections through the 21st century are summarized in Figure 3.12 as crop yield term for all downscaled GCM climate models and RCP emission scenarios. The long-term horizon of RCP8.5 scenarios shows a likely noticeable reduction in crop yield, especially in hot (HadGEM2-ES365) and dry (IPSL-CM5A-MR) conditions. This remarkable decline under the RCP8.5 scenario ranges from 7% for warm (MRI-CGCM3) climate conditions to 57% for dry (IPSL-CM5A-MR) climate conditions by the end of the 21st century. The rate of reduction in the other models is 10%, 16% and 28% for wet (CNRM-CM5), mild (NorESM1-M), and hot (HadGEM2-ES365) models, respectively. Across all climate models, wet (CNRM-CM5) and warm (MRI-CGCM3) RCP4.5 scenarios show crop yield gaining trend by 2100; however, they also experience sharp rises and falls through the decades. The range of reduction under the RCP4.5 scenario range from 4% for mild (NorESM1-M) climate model to 26% for dry one (IPSL-CM5A-MR) by the end of the century. As expected, the higher emission scenario (RCP8.5) leads to a higher crop yield reduction.

Figure 3.13 shows decadal values of crop yield, stream discharge from the canyon outlets, and groundwater storage for the two worst-case scenarios in agricultural productivity: HadGEM2-ES365 (hot) and IPSL-CM5A-MR (dry). These results demonstrate the clear and obvious link between water availability and crop yield, as the marked reduction in water availability after 2040 is followed by a sharp decline in crop yield. The stressor behind this notable impact is the surging hot temperature and, in the case of the dry climate model, reduction in annual precipitation that reduces water availability and, consequently, crop yield. The highest decline in crop yield occurs under the dry climate model (IPSL-CM5A-MR) RCP8.5. In this case, the combined effect of a 5 °C rise in temperature and 6.5% reduction in average annual precipitation by the end of 21 century produces a 57% reduction in crop yield. It implies that in the worst-case condition, under a dry climate model like IPSL-CM5A-MR-RCP8.5, for 1 °C elevation in temperature and 1.3% reduction in average annual precipitation, crop yield will drop averagely by 11%.

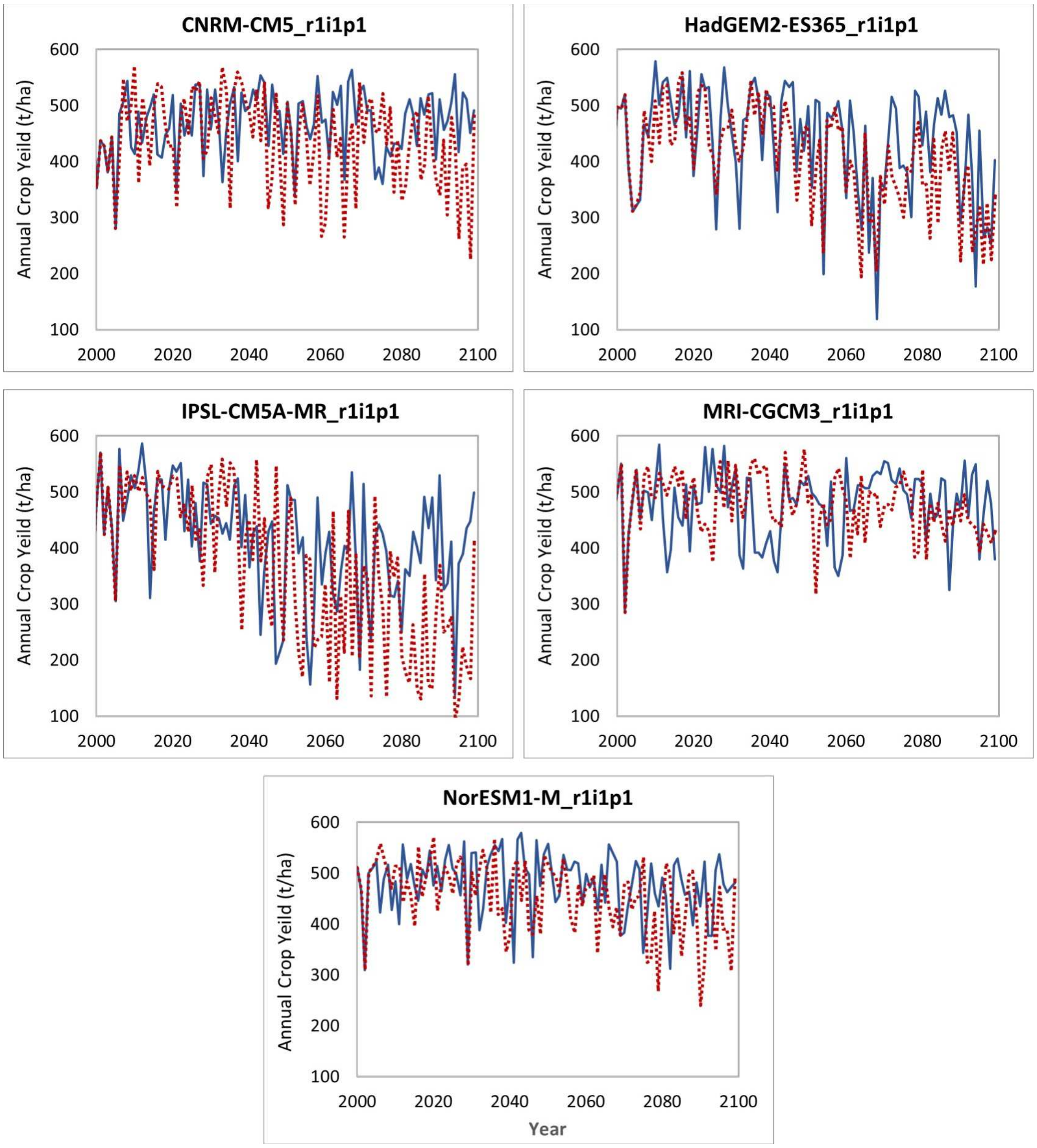


**Figure 3.12**. Annual crop yield simulated by Coupled SWAT-MODFLOW model for each downscaled GCM climate model and emission scenarios RCP4.5 (solid blue line) and RCP8.5 (dashed red line).

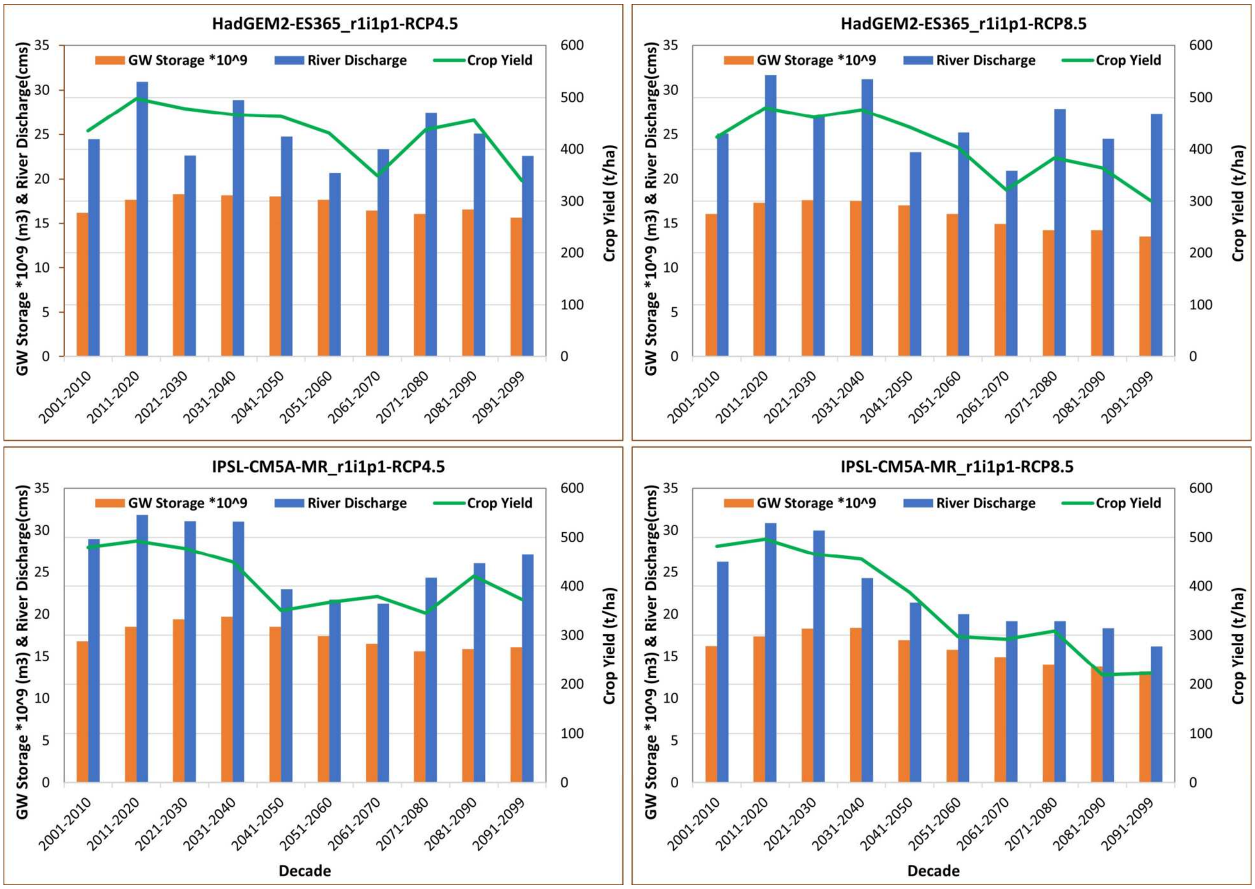
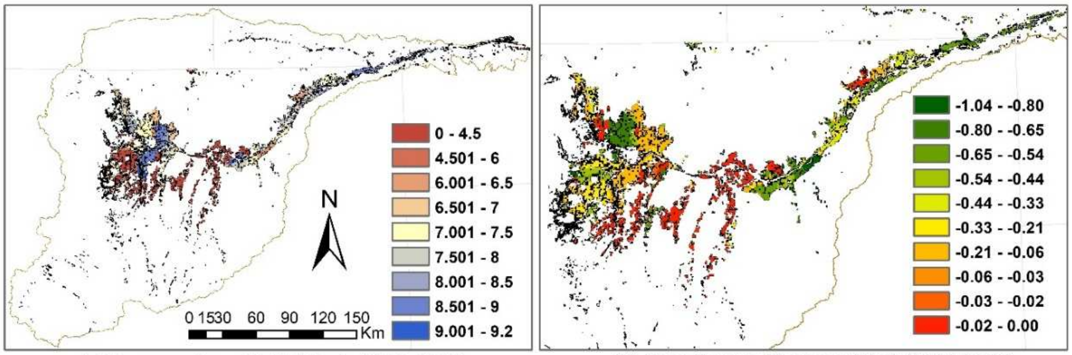
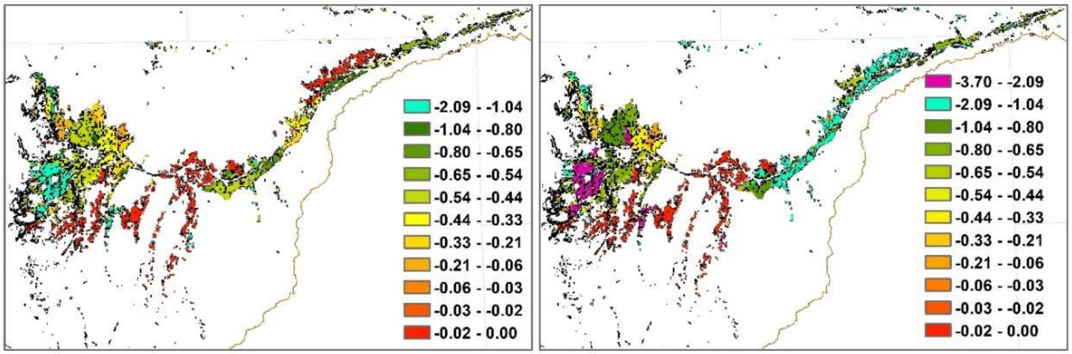


**Figure 3.13**. Decadal crop yield vs. water availability (stream discharge and groundwater storage) for hot (HadGEM2-ES365) and dry (IPSL-CM5A-MR) downscaled GCM climate models and emission scenarios.

The spatial distribution of projected average crop yield in the SPRB is shown in Figure 3.14 for the worst-case climate condition, IPSL-CM5A-MR-RCP8.5. The crop yield over the period of 2000-2020 is shown in Figure 3.14a and is considered as baseline conditions against which future conditions can be compared. The crop yield changes for the near future (2021-2040), mid-century (2041-2070), and end of the century (2071-2100), are calculated by subtracting the average crop yield values during various temporal periods from the corresponding base map values, and are shown in Figures 3.14b, c, and d, respectively. Figure 3.14b shows that the crop yield is impacted adversely across the entire basin from 2021 through 2040 (near-future). The maximum reduction occurs on the east side of the basin and close to the Colorado-Nebraska border, which experiences warmer weather, and on the west along the front range, where the urban areas such as Denver, Boulder, and Fort Collins are located (Figure 3.1a). This substantial decline in crop yield continues to evolve during mid-century (2041-2070) and the end of the century (2071-2100) in both locations at a higher rate (Figure 3.14c and d). The least impacted area is in the center of the basin, where the average agricultural productivity is already low (Figure 3.14a). Addressing the basin-wide impacts of climate change under the worst climate conditions is critical for managing the food-producing capacity. In 2012, the agricultural sales in SPRB were 75 percent of the total across the Colorado state (WestSage, 2015), which shows Colorado's dependency on viable agriculture in SPRB.



**(a) Average Crop Yield (t/ha) (2000-2020)** **(b) Near-Future Changes (t/ha) (2021-2040)**



**(c) Mid-Century Changes (t/ha) (2041-2070)** **(d) End of Century Changes (t/ha) (2071-2100)**

**Figure 3.14**. (a) Spatial distribution of crop yield from 2000 to 2020 under IPSL-CM5A-MR-RCP8.5 climate model; (b), (c) and (d) The projected changes compared to (a) in 3 different temporal periods: near future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100), respectively, under IPSL-CM5A-MR-RCP8.5 climate model.

## 3.4. SUMMARY AND CONCLUSIONS

Conjunctive basin-scale long-term water resources and crop yield modeling, using hydro-agronomic watershed models, can be used as tools to aid in future water management for large river basins. Our objective is to provide insight into possible future impacts imposed by climate change on water resources and crop yield in basin-scale complex semi-arid river basins. The results of this study enable the water resources and agricultural managers to address the most vulnerable regions under various climatic conditions. The methodology consists of estimating future surface water discharge, groundwater storage, and crop yield using the SWAT-MODFLOW model. The model is forced with five different CMIP5 climate models downscaled by MACA, each for two different climate emission scenarios, RCP4.5 and RCP8.5.

From analyzing different outputs and simulation results, it is concluded that in all climate models and emission scenarios, an increase of 3 to 5 °C in annual average temperature is projected. While the projected precipitation (snow and rain) variation depends on topography and distances from the mountain, the average annual precipitation across the entire basin is increasing under all climate models and emission scenarios except in the dry climate model (IPSL-CM5A-MR). Considering the worst-case scenario is critical for water and agricultural managers to identify possible risks in the future. Based on the results of this study, the worst-case climate model in the SPRB is IPSL-CM5A-MR-8.5, in which the basin experiences the combination of 2 climatically stressors, reduction in precipitation, and increase in temperature. Under this climate model, 1 °C elevation in temperature and 1.3% reduction in annual precipitation will result in 11% reduction in crop yield, 8.6% decline in average stream discharge, and 2 to 5% decrease in the groundwater storage.  Spatial analysis across the basin indicates that the least impacted in terms of agricultural productivity is in the central region of the basin due to the current abundance of groundwater storage, despite that this region also experiences the largest decline in saturated thickness by the end of the century. The changes in stream seepage and groundwater discharge fluxes in dry and wet months of the year follow different patterns, as groundwater discharge to streams decreases during the dry months as the water table elevation declines. Overall, under the most extreme climate condition, surface runoff, recharge to the water table, lateral soil flow, and groundwater discharge will decrease by approximately 20%, 35%, 20%, and 9%, respectively, by 2100.

Limitations of this study include: the use of statistically downscaled climate data, which is subject to biases; the assumption that all current water management practices (irrigation amounts and timing) remain the same throughout the 21st century; and the transfer of water rights from agricultural areas to urban areas, being practiced with increasing frequency in the western United States, has not been considered. The change in water management and land use will be addressed in a future study.

Ultimately, the results of this study provide a roadmap for future climate change studies at the basin scale while using coupled surface water and groundwater modeling tools:

1) Use various climate scenarios from multiple global and regional climate models covering different levels of projections such as warm, hot, dry, wet, and mild.
2) Apply the model at a basin or regional scale instead of subbasin, watershed, and sub-watershed scales.
3) Set a stable reference period for climate change tracking, such as climatological standard normal as recommended by the World Meteorological Organization.

4) Set a long-term study period, e.g., through the end of the 21st century, especially when the study focus is groundwater storage due to the long travel times of groundwater and overall system response to hydrological forcings.

5) Assess the conjunctive variation of water resources and agricultural productivity when the primary water user sector is agriculture.

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# Chapter 4. THE HYDROLOGIC IMPACT OF AGRICULTURE-TO-URBAN WATER TRANSFERS ON GROUNDWATER RESOURCES IN A LARGE RIVER BASIN[1]

## 4.1. INTRODUCTION

Traditionally, water demand for urban, industrial, and agriculture needs is supplied from local supplies of surface water (lakes, rivers, reservoirs) and groundwater; however, climate change, population growth, urbanization, increasing environmental demands and fiscal cost of water supply augmentations has limited the ability of communities to meet the demand by conventional methods. As the possibility of developing additional water supply is exhausted, keeping pace with increased demand necessitates the reallocation of existing water supply among competing demands through water trading. Water trading is the act of buying and selling water rights or water allocation entitlements which are either permanent or seasonal/temporary (Varghese, 2013). Transfer of water can be between different agricultural sectors or from agricultural sector to other sectors such as urban and industry through a process known as 'buy and dry', implying that agricultural areas that release water rights typically go fallow or revert to dryland farming. Water transfer may occur for a prescribed number of years or can be recalled at the time of drought (Howe & Goemans, 2003). Some agricultural sectors continue to irrigate using improved system efficiency (Lund et al., 2021; Tidwell et al., 2014).

Water trading markets are used in various countries to tackle water scarcity and drought crises. Large markets have been developed in the USA and Australia, principally for transferring

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irrigation water rights to urban areas, followed by Chile, India, South Africa, China, Mexico, the United Kingdom, and Spain. Australia is one of the leaders in water marketing on a large scale, especially in the Murray-Darling Basin (MDB) (Easton & Pinder, 2022; Wheeler et al., 2014). The southern water regions of the MDB accounts for about 90% of water rights trading in Australia (Varghese, 2013). In Chile, China, and Mexico, proportional water rights are employed in which supply is allocated to different users as a quantified share of the total water availability (Smith, 2021). In the United States, western states such as Oregon, Texas, Idaho, Arizona, California, and Colorado are the largest water traders (Delacámara et al., 2014; Maestu, 2012; Young, 2021), with 73% of the total volume transacted occurring in the agricultural sector (Schwabe et al., 2020). These western states may experience a 5% reduction in total irrigated agriculture as a result of losing irrigated lands to municipalities and permanent water rights sales (CWCB, 2019; Tidwell et al., 2014), with higher rates in several river basins.

Rapid urbanization has dwindled local water supplies, developing the need for acquisition of water from other sectors, such as agriculture. While water transfer from the agricultural sector to municipalities can be beneficial in coping with water scarcity in the near-term, long-term detrimental effects of this transfer can occur for both the geographic area where water is no longer used (direct effects) and for parties that are not involved in the transaction but that have relied on resources from these areas (third-party effects) (Gould, 1988; Hung et al., 2014). Some of these effects include: decrease in farming, which results in lowered crop production for growing populations, speculation and increase in food prices, and depression of local economies (Doherty & Rod, 2012; Hanak, 2012); and decrease in irrigation recharge, leading to decreased groundwater gradients and associated groundwater discharge rates to streams, which in turn lowers environmental streamflows and associated ecosystem services (Heaney et al., 2006; Hung et al., 2014; Varghese, 2013).

As a way to minimize the direct and indirect effects on areas of water trading origin and maintain food production, for instance in the case of removing surface water irrigation from irrigated lands, producers can switch to an alternative water supply such as groundwater irrigation, using local groundwater wells drilled either into local unconfined or confined aquifers. However, this practice can also lead to detrimental effects, such as localized and regional groundwater depletion, which can exhaust future regional water supplies. Although many studies have investigated the feasibility of mitigation climate change impacts via water trading (Bruno, 2018; Delacámara et al., 2014; Delorit & Block, 2018; Howe & Goemans, 2003; Islam et al., 2007; Minucci, 2020; Schwabe et al., 2020), none have quantified the adverse effect of water trading on water resources in areas of origin. In general, although the effects of drought and related climate change on crop productivity and food security have been reported extensively (Aggarwal et al., 2019; Aliyari et al., 2021; Ejaz Qureshi et al., 2013; Thornton et al., 2018; Vano et al., 2010), no study has quantified the combined effects of climate change and water trading on water resources of the area of water transfer origin.

The objective of this study is to assess the impacts of agriculture-to-urban water trading on local and regional groundwater storage and crop yield in a mixed agro-urban river basin through the 21st century, under the impacts of climate change. In doing so, we assume that, to maintain food production for a growing population, removed surface water irrigation is replaced by groundwater irrigation. To the knowledge of the authors, this is the first study that combines the impact of climate change together with human-induced agricultural-to-urban water transfer on future groundwater supply. Our region of focus is the South Platte River Basin (SPRB) (72,000 km$^2$), a region of Colorado, USA, a mixed agro-urban-industrial river basin with intensive irrigation and water right transfer practices. The SPRB is projected to experience the largest urban expansion in the state by 2050, straining already tight water supplies and enhancing competition among various water users such as municipal, industry, agriculture, environment and recreation (CWCB, 2019). The method presented here is applicable to similar regions across the world.

In this study we adopt a holistic framework to model groundwater and surface water as a single resource, using the previously tested SWAT-MODFLOW model for the SPRB (Aliyari et al., 2019). The SWAT-MODFLOW simulates the major surface and subsurface hydrologic fluxes in the basin and considers various interactions between water resources, climate, irrigation schemes, and human activities. The model is run for two scenarios for the period of 2000-2100: 1) climate change without water trading, using the output from two different climate models, each for two climate forcing scenarios, RCP4.5, and RCP8.5; and 2) climate change with water trading, where projected amounts of surface water irrigation trading are replaced by additional groundwater withdrawals. The analysis results are reported in two temporal periods: “mid-century” (2021–2060) and “end-of-century” (2061–2100). In general, the results of this study enable water resources managers to study the conjunctive variation of groundwater, surface water, and agricultural productivity in areas of water trading, under the influence of changes in climatic conditions.

## 4.2. MATERIALS AND METHODS

This section provides an overview of agricultural, water resources challenges, and water trading status in the South Platte River Basin (SPRB), followed by an explanation of the SWAT-MODFLOW hydrologic modeling tool, data analysis methodology and the application of the model to estimate future groundwater storage throughout the 21st century as impacted by agriculture-to-urban water trading and climate variability.

## 4.2.1. Study Area: The South Platte River Basin

### *4.2.1.1. Overview*

The South Platte River Basin (SPRB), with spatial area of approximately 72,000 km$^2$ is a large, highly managed, economically diverse, and semi-arid basin. As depicted in Figure 4.1a, the SPRB is mainly located in Colorado (79%), and partially covers Nebraska (15%) and Wyoming (6%) (Dennehy et al., 1998). With 345,600 hectares of irrigated agricultural lands (over 25% of the irrigated lands in Colorado), SPRB is the most productive basin across Colorado in terms of sold agricultural products (CWCB, 2019). Approximately 85% of the total population of Colorado lives in the SPRB, making it the most populous basin in Colorado (WestSage, 2015). The basin's population is projected increase by 42% to 70% by 2050. The SPRB has a diverse hydrology pattern that is highly impacted by the topography and human management. The elevation ranges from 850 m in the eastern plains to 4,300 m in the western mountains (Figure 4.1b). Annual precipitation is about 760 mm in the mountains at the Continental Divide and reduces to 170–380 mm on the plains east of Denver (Dennehy et al., 1998). Temperature, on the other hand, rises from the mountainous region to the foothills and plains. Average monthly temperature varies between −35 and 38 degrees Celsius (ºC), and is projected to be warmer by 1.5-3 ºC by 2050 (Lukas et al., 2014).

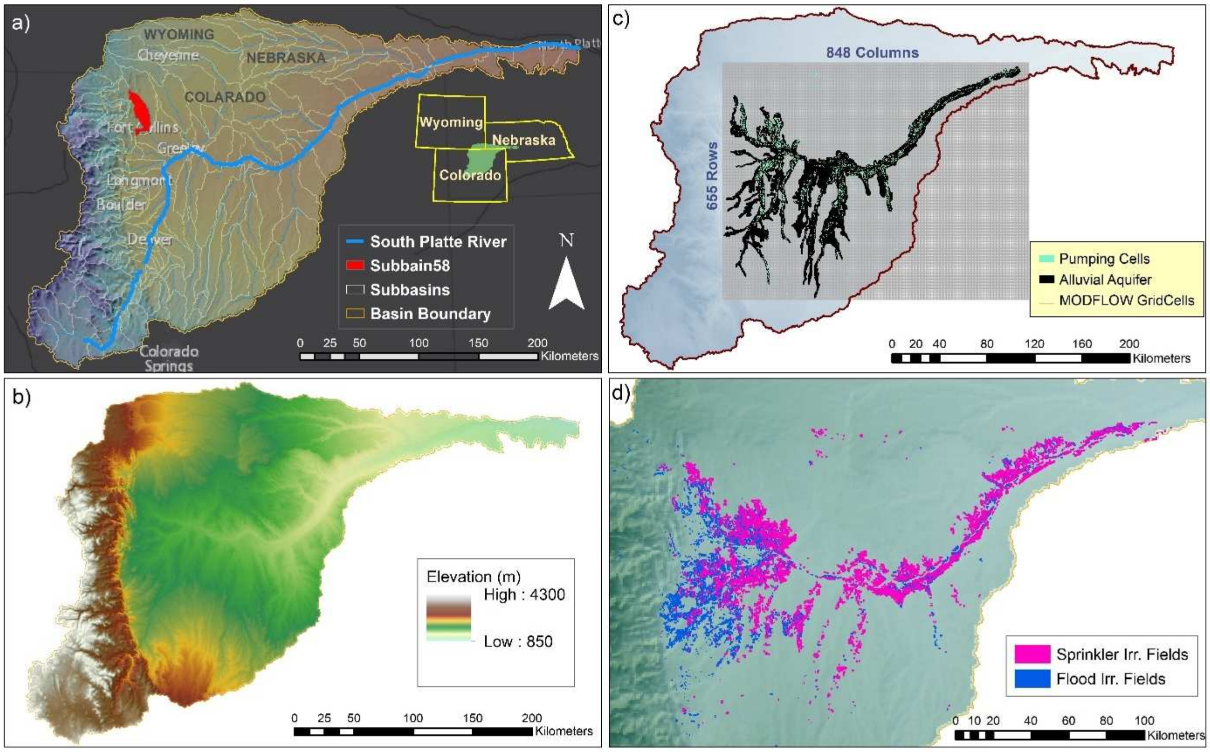

**Figure 4.1**. a) South Platte River Basin location map, subbasins, stream network, and Subbasin58; b) Topographic map and altitude range; c) Alluvial aquifer boundary and location of pumping wells; d) Cultivated fields, classified by type of irrigation.

#### *4.2.1.2. Water resources challenge and water market*

The South Platte River originates from the Mosquito Range of central Colorado with numerous tributaries joining as it flows northeast to connect with the North Platte River after a course of 711 km (Britannica, 2022). The SPRB contributes to water needs of various sectors within the state, including municipalities, industry, agriculture, environment, recreational and tourism. Of these sectors, agriculture is the prevalent water user in the basin. To address water demands across the basin, water is used successively along the South Platte River. Figure 4.1d shows a map of irrigation type across cultivated fields in the SPRB. While surface water generally is the source of flood irrigation, groundwater generally is the source of sprinkler irrigation. Figure 4.2 shows the average historical pumping rate for fields using groundwater irrigation, for the 1997-2012 period. On average, SPRB water is utilized seven times successively before it leaves

Colorado's (WestSage, 2015). Diverted water from the South Platte River recharges the alluvial aquifer, which later discharges to the river, repeating multiple times as the river flows towards the outlet of the basin. Groundwater is also used extensively throughout the SPRB for municipal and agriculture needs. With 150 years of water management history and 18,600 decreed points of diversion, SPRB is one of the most complex water resources networks in Colorado (Waskom, 2013).

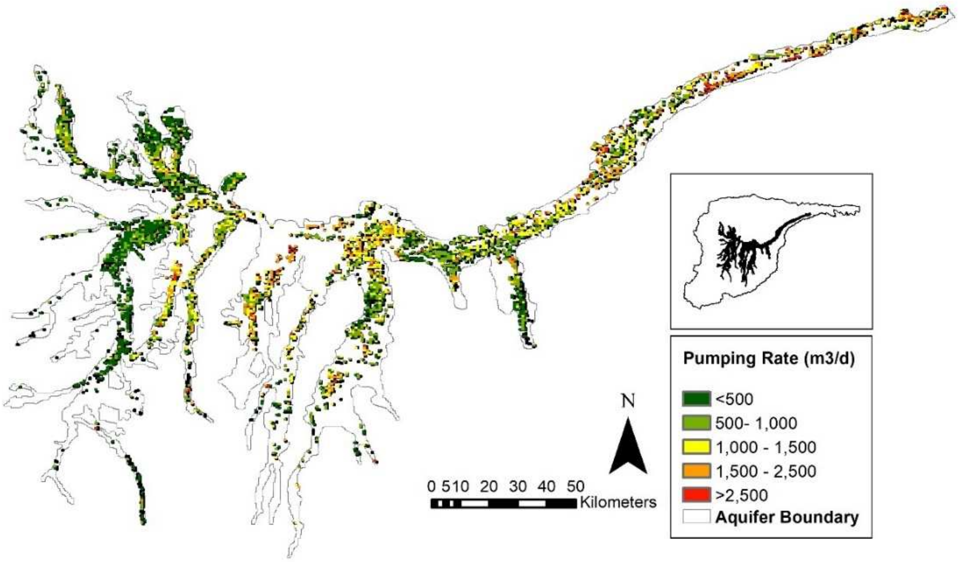

**Figure 4.2**. Spatial distribution of the historical pumping rates within the SPRB

The surface water and alluvial aquifer in the SPRB are in close interaction and are considered as a single resource of water by Colorado water law. Historically, alluvial aquifer has been used conjunctively with the South Platte River to fulfill the users' water demand, particularly during dry periods (Waskom, 2013). The SPRB alluvial aquifer covers approximately 10,400 $km^2$ (Figure 4.1c). Hydraulic conductivity (k) values vary from approximately 30 m/day to 610 m/day, and saturated thickness of the alluvial aquifer ranges from 6 to 13 m at the upstream extent near Denver, to more than 61 m adjacent to the Colorado-Nebraska border (CDMSmith, 2013).

As all water in the SPRB has been appropriated (CWCB, 2019), new water demands, imposed by increasing population, developing industries, and other activities, must be fulfilled by either water transfers between sectors or by importing water from other basins (WestSage, 2015). The vast majority of transfers across the basin (64 percent) is from agriculture to municipalities, through the 'buy and dry' process, with remaining occurring as internal transfers withing the agricultural sector (Howe & Goemans, 2003). In Colorado, water trades are controlled by short-term leases rather than permanent water right sales. For every 4.5 $m^3$ of leased water transfer in Colorado, 1 $m^3$ was transferred under permanent water right trades (Hansen et al., 2012).

### 4.2.2. Hydrological Simulation Tool: SWAT-MODFLOW Model

In a basin such as SPRB with significant hydrological interaction between surface water and groundwater, and with complex management schemes, using a fully integrated hydrological modeling tool is essential. The hydrological model not only should account for surface water and groundwater hydrological processes modeling, but also consider water transfers between various domains (Aliyari & Bailey, 2021) . This section briefly outlines the SWAT-MODFLOW hydrological tool use for this study. This model has been calibrated and tested in a previous study (Aliyari et al., 2019), and used to quantify water supply and crop yield through the year 2100 under climate change (Aliyari et al., 2021). In this study, the modeling code and model inputs are further modified to account for water trading.

The SWAT-MODFLOW model links the SWAT (Arnold et al., 1998) and MODFLOW-NWT (Niswonger et al., 2011) model codes (Bailey et al., 2016). The Soil and Water Assessment Tool (SWAT) is a quasi-distributed physically-based model that simulates the quality and quantity of available water resources, nutrient and pesticides transport, and regional management in various spatial scales, from small watersheds to large river basins (Arnold et al., 1998). The smallest spatial unit of the model is called Hydrologic Response Unit (HRU) and lumps similar slopes, land uses, and soils within a subbasin. Outputs from HRUs such as surface runoff, soil lateral flow, and groundwater flow accumulate and are directed to the subbasin stream for routing to the outlet of the watershed via the stream network. The SPRB SWAT model consists of 194 subbasins and 1,994 HRUs. Although SWAT's applications are versatile, its application in evaluating groundwater processes, quantities, and surface water-groundwater interaction is limited. On the other hand, MODFLOW simulates a variety of groundwater related hydrologic processes in steady and transient state. MODFLOW (Harbaugh, 2005) is a public domain modular finite-difference groundwater flow modeling code developed by the U.S. Geological Survey (USGS). MODFLOW-NWT (Niswonger et al., 2011) is a Newton reformulation of MODFLOW-2005 that uses the Newton-Raphson method. This new algorithm performs well in solving high nonlinearities such as problems involving unconfined groundwater systems and the grid cells drying and rewetting processes (Hunt & Feinstein, 2012). The original MODFLOW model was constructed for the 1950-2006 time period (CDMSmith, 2013) and then through 2012 (Brown&Caldwell, 2017) as part of the state of Colorado's South Platte Decision Support System project. Aquifer properties, groundwater inflows and outflows, and general water management were obtained from various sources listed in Table 4.1. The SPRB MODFLOW model is composed of 55,440 grid cells (of which 69,895 are active grid cells) each with an area of 304.8 m x 304.8 m (1000-ft by 1000-ft), arrayed in 655 rows and 848 columns (see Figure 4.1c). The active model domain corresponds to the spatial extent of the alluvial aquifer (see Figure 4.1c). Table 4.1 provides a list of datasets used in the construction of the model.

**Table 4.1**. Datasets used in the construction of the model.

| **Data** | **Data Source** |
|---|---|
| **Topography** | The National Elevation Dataset (NED) from the U.S. Geological Survey (USGS) at a 90-meter resolution for SWAT & 30-meter resolution for MODFLOW |
| **Soil** | STATSGO soil data (U.S. Department of Agriculture, 2015) |
| **Land use** | National Land Cover Dataset in 2011 (Homer et al., 2015) |
| **Observed groundwater head and stream discharge** | CDWR Website (CDWR, 2022) |
| **Historical irrigated land dry-up rates** | South Platte Basin Implementation Plan (Implementation Plan, 2015) |
| **Bedrock elevation& alluvial extend** | Reports from (Bjorklund et al., 1957; Duke & Longenbaugh, 1966; Erker & Romero, 1967; Owens, 1967; R. Theodore Hurr & Paul A. Schneider, 1972; Robson, 1996; Robson et al., 2000; Schneider & Petri, 1964), and well permit logs (CDWR, 2022) |
| **Alluvial aquifer property** | Reports from the U.S. Geological Survey (USGS), Conference proceedings such as (Fox, 2003), and well permits (CDWR, 2022) |
| **Alluvial groundwater inflow at tributary boundaries** | Calculated based on data obtained from the Phase 3 Task 42.3, 43.3, and 44.3 Technical Memoranda (SPDSS, 2006a-c) |
| **Inflows to/outflows from the base of the alluvial aquifer and the underlying bedrock aquifers** | Derived from a numerical model, G2GFLOW tool, of the Denver Basin aquifers (Banta,2008) developed by the USGS (Paschke, 2011) |
| **Stream Inflows** | HydroBase (HydroBase, 2022) |
| **Groundwater ET** | The ET curve for the study area is based on one developed for the San Luis Valley and modified for the SPRB using data from field stations in Fort Lupton, Fort Collins, Greeley, and Holyoke (CDMSmith, 2013). |

The coupled SWAT-MODFLOW modeling code of Bailey et al. (2016) links SWAT and MODFLOW for simulating surface and subsurface hydrologic fluxes and state variables. Groundwater recharge is passed from HRUs to grid cells, groundwater head is passed from grid cells to HRUs, and groundwater discharge and surface water seepage are passed between cells and subbasin channels, using MODFLOW’s River package. During the simulation, the sequence of operations for each daily time step is:

1) SWAT calculates land surface and soil hydrology for each HRU; surface runoff and soil lateral flow directed to streams;
2) Recharge and unsatisfied ET is passed from HRUs to grid cells;
3) MODFLOW is called to simulate changes in groundwater storage, new groundwater head, cell-to-cell flow rates, and exchange rates between the groundwater and surface water;
4) Exchange rates between groundwater and surface water are provided to subbasin channels;
5) SWAT routes accumulated water through the subbasin stream network, to the watershed outlet.

To prepare models inputs, SWAT HRUs and subbasin channels are connected to MODFLOW cells via GIS routines. For the version of SWAT-MODFLOW used for the SPRB in (Aliyari et al., 2019, 2021), the Partition Stress Boundary (PSB) package of MODFLOW (Kurt et al., 2017) was used to enable handling of groundwater sources and sinks that are typical in agro-urban highly managed river basins. The updated version also linked MODFLOW pumping cells to SWAT HRUs, enabling the transferring of groundwater from the aquifer to irrigated farmland. Finally, the auto-irrigation algorithms of SWAT were changed to allow groundwater to be used during times of surface water deficit. The model was calibrated and tested against streamflow and groundwater head throughout the basin (Aliyari et al., 2019).

The GIS coverages required to execute the linking between SWAT and MODFLOW are shown in Figure 4.3 for one of the SWAT subbasins (subbasin 58; see Figure 4.1a for location). Figure 3-a and 3-b illustrate the boundary of SWAT subbasin 58 and enclosed HRUs, respectively; the extent of the alluvial aquifer (in coral) and active model domain (in olive green) within subbasin 58 are shown in Figure 4.3c; Figure 4.3d presents the location of MODFLOW River cells within the subbasin; Figure 4.3e shows the location of pumping wells. The pumped groundwater is applied as irrigation water to SWAT HRUs via these cells during the simulation.

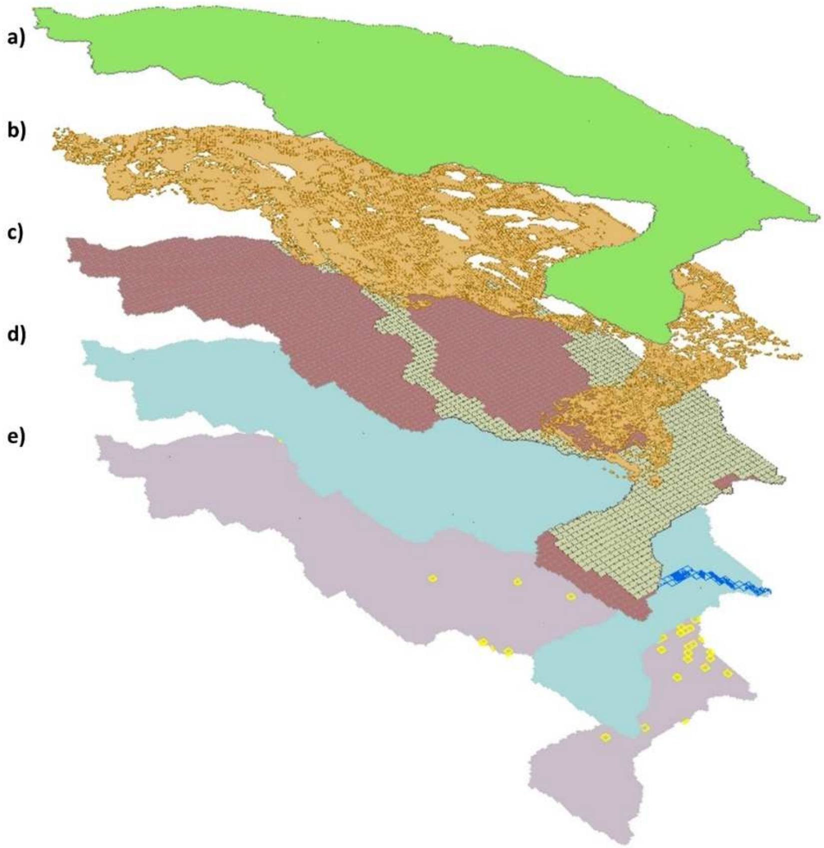

**Figure 4.3**. a) Subbasin 58 from SWAT model; b) HRUs within subbasin 58; c) MODFLOW grid cells (in coral) and alluvial aquifer active cells (in olive green) within subbasin 58; d) River cells within subbasin 58 (in royal blue); e) Pumping cells within subbasin 58 (in yellow).

### 4.2.3. Scenarios of Water Trading and Climate Change

In this study, we investigate the future of groundwater in the SPRB, as likely it will be an alternative irrigation water supply for the surface water that is transferred to municipalities through water trading. To do so, we impose water trading schemes during future decades by removing surface water irrigation from selected HRUs and replacing the removed water with groundwater extracted from the local alluvial aquifer. The amount of water transferred from the agricultural sector is based on reported trends from 1976 to 2010 for each county within the SPRB

(Implementation Plan, 2015), extrapolated to estimate annual volume of water transferred per county through the 21st century. The method of including water transfer and associated increase in groundwater pumping within the SWAT-MODFLOW model is as follows:

1) For each year between 2000 and 2100, select HRUs within each county until the estimated annual volume of transferred water is met.
2) Run the SWAT-MODFLOW model, with irrigation for the HRUs identified in step 1 turned off and the amount of removed water recorded and written to file. We assume that once an HRU has been targeted for dry-up, it will remain so, during the remainder of the century.
3) Run the simulation again, assigning groundwater pumping rates in MODFLOW's Well package that are equivalent in volume to the surface water removed from the HRUs in step 2. Based on the calculated volume of groundwater and average historical pumping rates in the SPRB, the number of required new wells are estimated (a total of 400 additional wells; see Figure 4.4).
4) Use results from step 3 to calculate the change in groundwater storage for each subbasin within the SPRB.

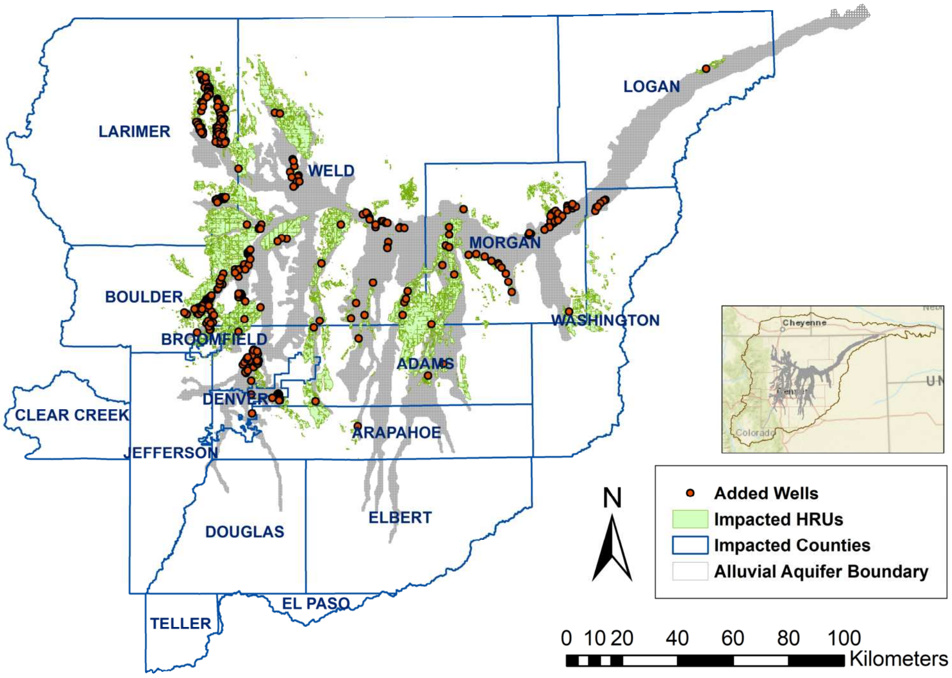

**Figure 4.4**. Impacted HRUs and Counties within Colorado portion of the SPRB, plus added wells.

The model is used in conjunction with the projected daily mean values of minimum and maximum surface air temperature as well as precipitation by the hot, dry, wet, and mild climate models listed in Table 4.2. The projected climate data are downloaded from the Multivariate Adaptive Constructed Analogs (MACA) dataset (Abatzoglou & Brown, 2012), a statistically downscaled climate model method that links GCM outputs to local meteorological variables across the contiguous United States. Through this method, the outputs of the twenty Coupled Model Inter-Comparison Project Phase 5 (CMIP5) GCMs are downscaled from their original resolution to either 4 or 6 kilometers for two future Representative Concentration Pathways (RCP4.5 and RCP8.5) scenarios from 2006 to 2100. Data prior to 2006 are considered the historical data and are the same for both RCPs. The terms hot, dry, wet, and mild projections are assigned to the climate models based on the analysis performed by (Joyce & Coulson, 2020) at the conterminous United States scale. As an example, 'IPSL-CM5A-MR' which is classified as a dry climate model, projects the lowest precipitation across the nation; and in terms of temperature, HadGEM2-ES365 ranks among those that project the higher temperature at the national scale and is characterized as a hot climate model.

**Table 4.2**. Climate models used in the water trading scenarios.

| **Core Model** | | **Emission Scenarios** | **Country** | **Agency** |
|---|---|---|---|---|
| **HOT** | HadGEM2-ES365 | RCP4.5, RCP8.5 | UK | Hardly Center<br>(Collins et al., 2008) |
| **DRY** | IPSL-CM5A-MR | RCP4.5, RCP8.5 | France | Institute Pierre Simon Laplace (Dufresne et al., 2013) |
| **WET** | CNRM-CM5 | RCP4.5, RCP8.5 | France | National Center of Meteorological Research (Voldoire et al., 2013) |
| **MILD** | NorESM1-M | RCP4.5, RCP8.5 | Norway | Norwegian Climate Center<br>(Bentsen et al., 2013) |

Based on the analysis performed by the authors on the groundwater availability impacted by different climate models across all RCPs, as reported in Aliyari et al. (2021), the wet (CNRM-CM5) and dry (IPSL-CM5A-MR) climate models are selected for use in this current study for assessment of water trading scenarios. Results of changes in groundwater storage in the SPRB during the 21st century as influenced by climate (Aliyari et al., 2021; see Figure 3.8) demonstrate as that the models used for this study, listed in Table 4.2, cover the majority of results and provide upper and lower boundaries to the influence of projected climate on groundwater storage in the SPRB alluvial aquifer system.

The data from the downscaled wet CNRM-CM5 and dry IPSL-CM5A-MR climate models are inserted into the weather input files of SWAT, and then the coupled SWAT- MODFLOW model is run from 2000 through 2100. Each simulation is assessed for groundwater hydraulic head, saturated thickness, groundwater storage, and crop yield.

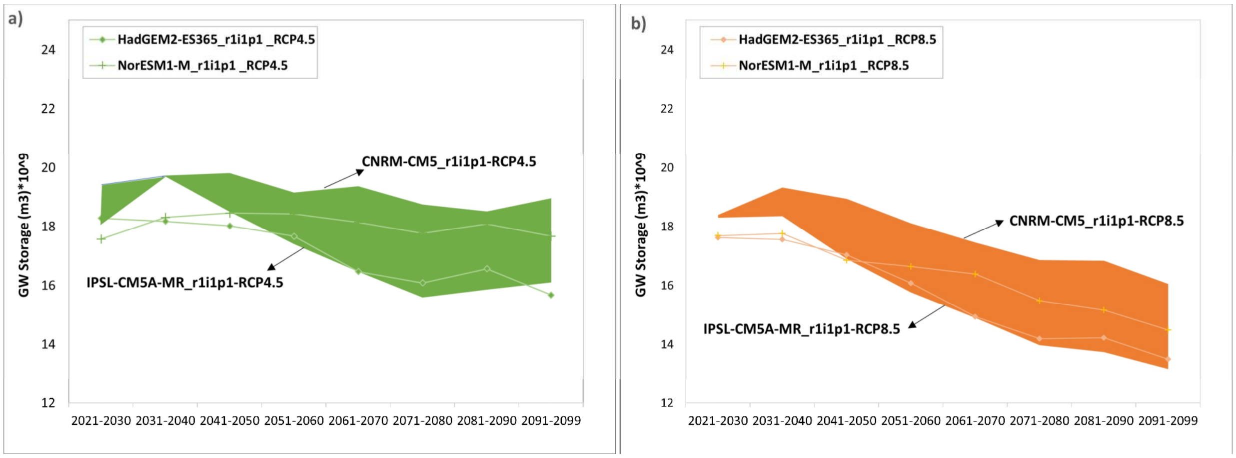

**Figure 4.5**. groundwater storage under various climate models and emission scenarios, a) RCP4.5 and b) RCP8.5, as is impacted only by climate change. Based on results reported in Aliyari et al. (2021).

## 4.3. RESULTS AND DISCUSSION

### 4.3.1. Climatic Variability Analysis Across the SPRB

The analysis of climate data indicates that in all climate models and across all emission scenarios, 3 to 5 °C increase in annual average temperature is projected, which agrees with previous regional studies in Colorado (Lukas et al., 2014). On the other hand, precipitation projection is highly related to the topography and distance from the mountains (Aliyari et al., 2021). Based on the observational values the total annual precipitation in a station with an altitude equal to 3,500 m is about 800 mm and decreases by 56% and reaches to 345 mm in a station with an altitude equal to 1,570 m.

Figure 4.6 presents the total average annual precipitation (PCP) across the entire basin from 2000 to 2100 for each of the climatic projection models and emission scenarios. Clearly, the projected values for precipitation are not unanimous across the climate models. Through the wettest projection (CNRM-CM5), precipitation increases across the entire basin; however, the driest climate model (IPSL-CM5A-MR) projects a reduction in average annual precipitation for the entire basin with the rates of 5% and 6.5% under the RCP4.5 and 8.5, respectively.

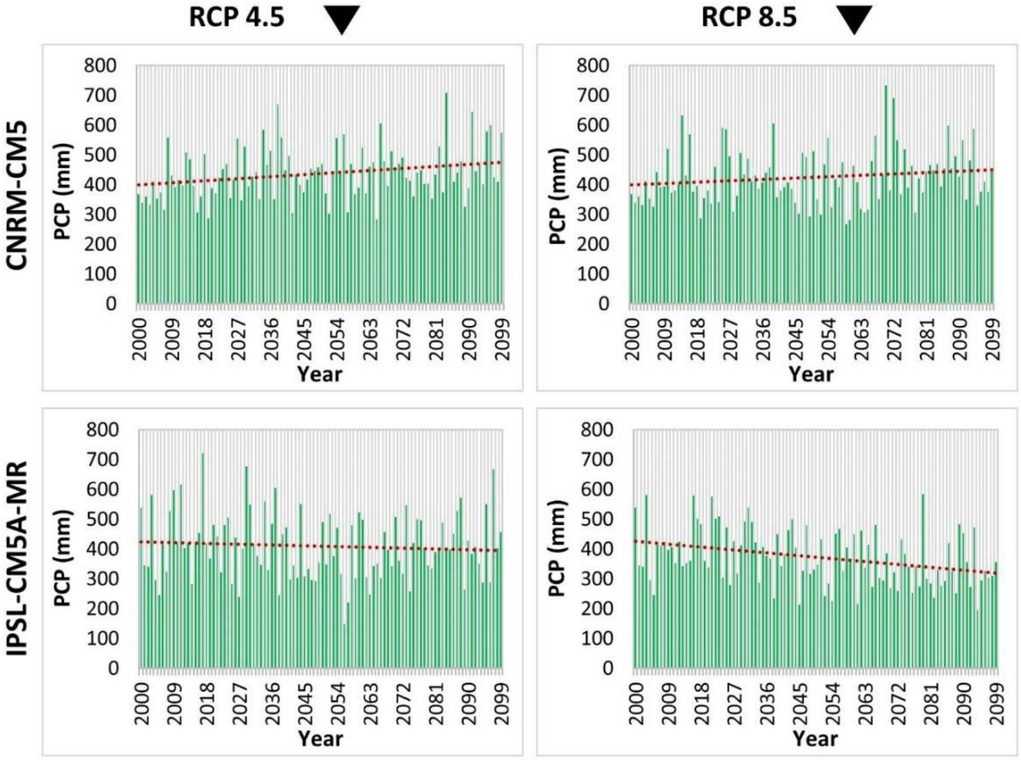

**Figure 4.6**. Total average annual precipitation (PCP; green bar) and precipitation trendline (dashed red) across the entire basin for wet and dry climate models and forcing scenarios, RCP4.5 & 8.5 through the end of the century.

### 4.3.2. Crop Yield Evaluation

Annual agricultural productivity (i.e., crop yield) is projected through the 21st century for the "climate impact only" scenario and the "climate and water trading impact" scenario. For the climate-only scenario, the crop yield reduction is remarkable under the driest projection, IPSL-CM5A-MR. The percent reduction compared to current crop yield values range from 26% to 57% under RCPs 4.5 and 8.5, respectively. On the other hand, the percent decline in the wettest climate model, CNRM-CM5-RCP8.5, is projected to be only 10%, and crop yield is projected to slightly increase under CNRM-CM5-RCP4.5. The change in crop yield is dependent on water availability and temperature (Aliyari et al., 2021).

For the 'climate change with water trading' scenario, a significant change in crop yield is not expected, compared to the "climate change only" scenario, since the surface water irrigation traded to urban areas is replaced by groundwater. Figure 4.7 presents annual crop yield for both scenarios, for dry and wet climate models under RCP4.5 and RCP8.5 through the end of the 21st century. The matching graphs with discrepancies less than 0.4% after 2040, indicate the successful application of groundwater irrigation to maintain crop yield capacity across the basin through the end of the 21st century.

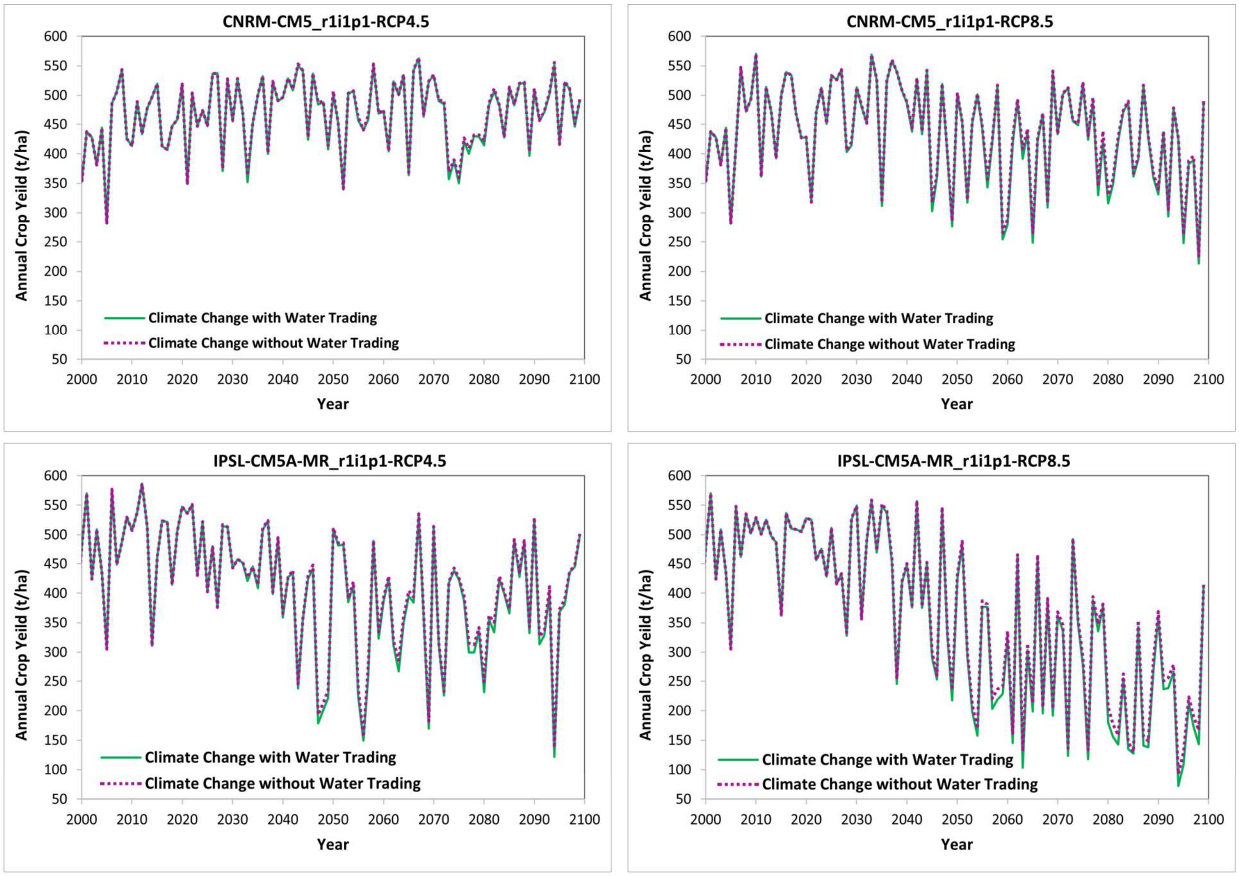

**Figure 4.7**. Annual crop yield comparison between scenarios of climate change with and without water trading under all climate models and emission scenarios.

### 4.3.3. Future Groundwater Distribution and Storage as Impacted by Climate Change and Land Dry-Up

In contract to crop yield changes, we expect significant changes in groundwater storage due to the additional pumping to compensate for the removal of traded surface water. Figure 4.8

presents the total average groundwater storage across the entire alluvial aquifer of the SPRB for each decade from 2021 through the end of the 21st century for scenarios of ‘climate change without water trading’ and ‘climate change with water trading’, separately. Total groundwater storage in the SPRB alluvial aquifer (see Figure 4.1c for spatial extent) is calculated by use of the saturated thickness and specific yield in each MODFLOW grid cell, in which the saturated thickness is equal to the vertical distance between the simulated groundwater head and the bedrock. In both scenarios, under each climate model projection, a rise in groundwater storage by the 2030s is following by a large decrease through the end of the century, due to changes in precipitation and resultant recharge. The exception is related to the wettest projection, CNRM-CM5-RCP4.5 that projects only a slight downward trend, with increases and decreases throughout the decades of the century.

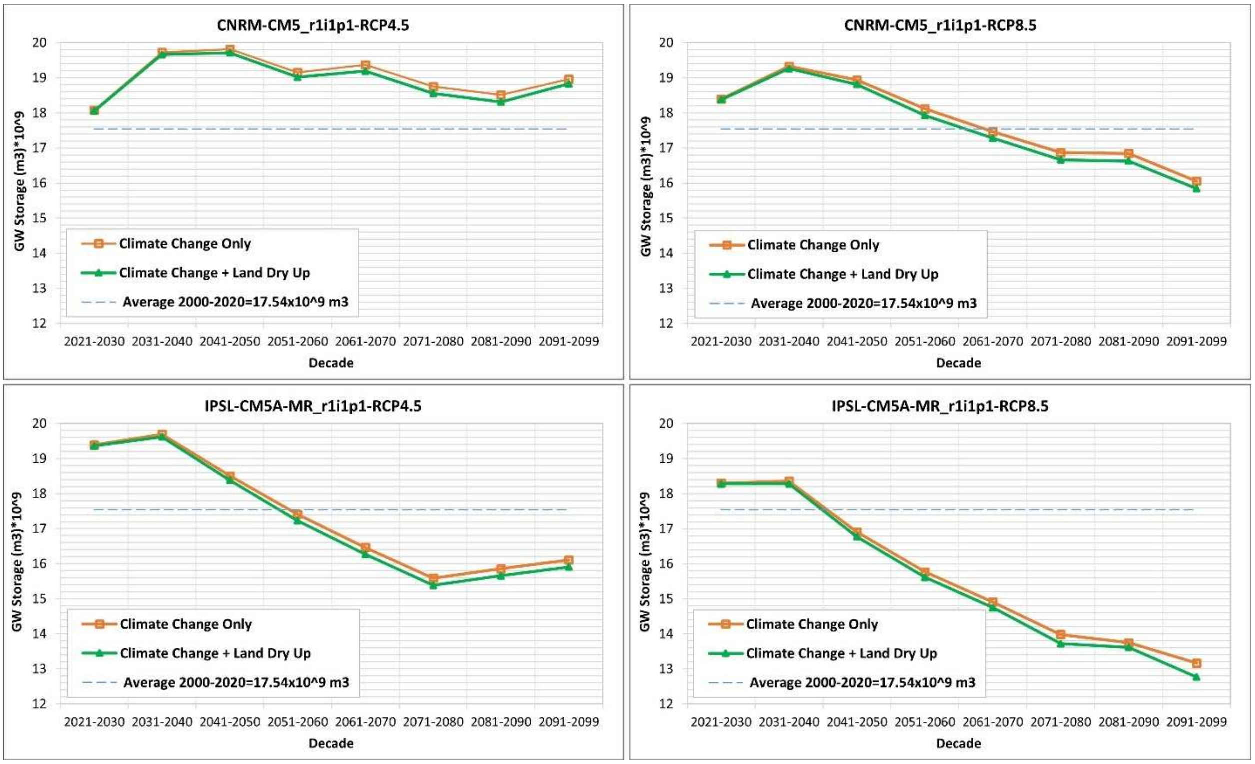

**Figure 4.8**. Decadal groundwater storage under downscaled GCM climate models and RCPs 4.5 & 8.5 through the end of the century for the scenarios of climate change with and without water trading, summed for the entire SPRB alluvial aquifer system.

In ‘climate change without water trading’ scenario, the greatest decline in groundwater storage from 2040 on is projected by the driest climate model, IPSL-CM5A-MR, under RCP8.5 by 25% reduction compared to the current (2000-2020) average groundwater storage (dotted blue lines in Figure 4.8). The decreasing rate for IPSL-CM5A-MR-RCP4.5 and CNRM-CM5-RCP8.5 under ‘climate change without water trading’ scenario by the end of the century is projected to be 8% and 9%, respectively. On the other hand, CNRM-CM5-RCP4.5 climate model projects 7% increase in groundwater storage by the end of the 21st century compared to the 2000-2020 period.

As expected, the water trading scenario results in a loss in groundwater storage, compared to the climate-only scenarios (green lines in Figure 4.8). The rate of change compared to the ‘climate change without water trading’ scenario is projected to be about -0.5% more across the entire basin by the end of the midcentury (2060) under all climate models and RCPs, with the change in storage as compared to the climate-only scenario increasing through the end of the 21st century. In comparison with ‘climate change without water trading’ scenario, groundwater storage is projected to experience an extra reduction of 1-1.2 % under the wettest climate models, CNRM-CM5, and 1.2-2.0% under the driest climate model, IPSL-CM5A-MR, by the end of the century.

Local assessment, however, demonstrate much higher rates of change in groundwater storage, particularly in areas of water trading. As an example, from 400 added pumping wells across the basin, 76 of them are placed in the SWAT subbasin 58 (see Figure 4.1a), in Larimer County (see Figure 4.4). The excess reduction rate in groundwater storage in subbasin 58 is tabulated in Table 4.3 for the RCP4.5 & RCP8.5 climate projections for the mid-century and end-of-century times. The percentages presented in this table indicate the extra reduction in the projected groundwater storage in ‘climate change with water trading’ scenario compared to the ‘climate change without water trading’ scenario across the subbasin 58. The values are averaged through RCP4.5s and RCP8.5s in both wet and dry climate models. These results demonstrate that, for a region that replaces removed surface water irrigation with groundwater, groundwater storage can decrease by up to 10% in addition to the loss in storage from climate change.

**Table 4.3**. Average percent reduction in groundwater storage under ‘climate change with water trading’ scenario compared to that of ‘climate change without water trading’, for RCP4.5s and RCP8.5s by midcentury and by the end of the century in subbasin 58.

| Percent Change by: | Average RCP 4.5s | Average RCP 8.5s |
|---|---|---|
| **Mid-Century** | 1.0 | 8.0 |
| **End of Century** | 6.0 | 10.0 |

To address the most affected regions across the basin, the percent decrease in groundwater storage, as compared to the ‘climate change without water trading’ scenario, is shown in Figure 4.9 for the entire alluvial aquifer system. The values are averaged across the two RCP4.5 (Figure 4.9a), and RCP8.5 (Figure 4.9b) projections in both wet and dry climate models through the end of the century. Groundwater storage decreases from 0 to 6% under the RCP4.5 projections in both wet and dry climate models, and from 0-11% for the RCP8.5 projections. Of course, in both climate scenarios, the upper bound in the percentage of decrease occurs in the regions where agriculture-to-urban water trading is active (see Figure 4.4 for locations). To summarize, when combined with the impact of climate change, the total average reduction in groundwater storage across the basin compared to the current (2000-2020) average groundwater storage is projected to be 10% under CNRM-CM5-RCP8.5 climate model and 9-27% under IPSL-CM5A-MR-RCP4.5 and RCP8.5, respectively.

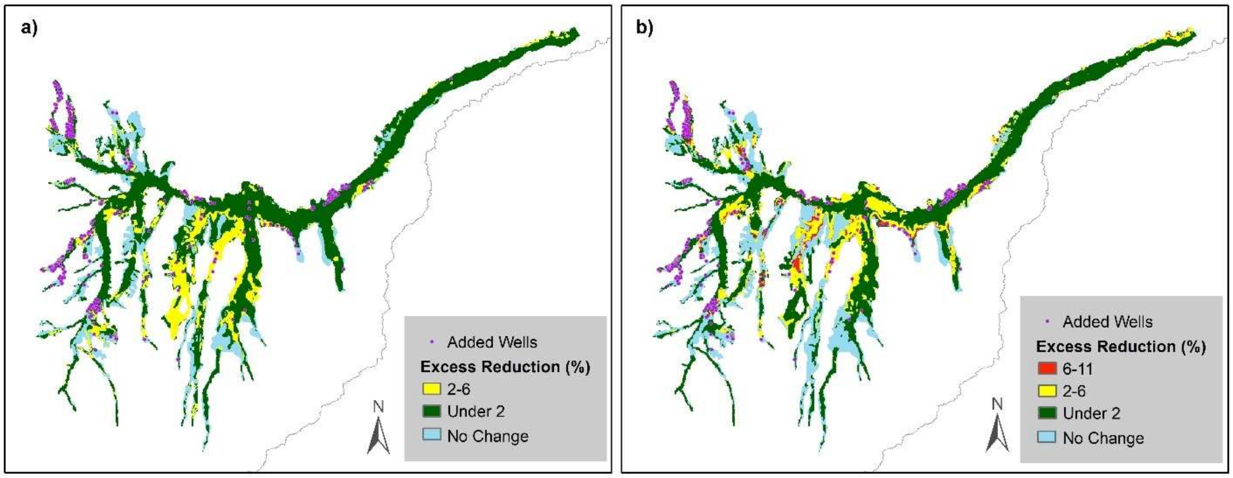

**Figure 4.9**. The spatial distribution of excess percent reduction in groundwater storage under the ‘climate change with water trading’ scenario compared to the 'climate change without water trading' scenario by the end of the century for all climate models under a) RCP4.5s and b) RCP8.5s across the entire basin.

From these results, we conclude that projected magnitudes of water trading in the SPRB basin through the 21st century will not significantly affect groundwater storage in the river basin beyond the impact of climate change. Declines of 10% in groundwater storage may affect local areas, but not the river basin at large. However, if actual future climate is drier and hotter than expected, which will result in declines in recharge and groundwater storage, then additional changes in storage due to water trading and groundwater pumping compensation should be considered more carefully. In addition, we do not include the effect of water quality in this study. Deep groundwater may have higher concentrations of dissolved solids, and therefore adding more pumping wells and extracting groundwater from deeper sections of the alluvial aquifer may result in salt accumulation in the soil profile, leading to decreased crop yield and deterioration of soil health. In addition, the construction of new pumping wells would need to be performed within the framework of local water right laws, i.e., such as the impact of additional groundwater pumping on streamflow depletion. Finally, we have not included the overall costs of drilling new groundwater wells to compensate for removed surface water irrigation. While this will not affect the hydrologic results of this study, an integrated hydro-economic analysis could provide useful information in understanding the overall costs and benefits of water trading with groundwater compensation.

## 4.4. CONCLUSIONS

This study examined the effects of agriculture-to-urban water trading on the availability of groundwater in the future, within the context of a changing climate. Here as a feasible solution to compensate for the surface water loss due to selling or leasing agricultural water rights to urban areas, groundwater resources are used to keep irrigated lands active and maintain crop production. The methodology consists of estimating groundwater storage under two different scenarios: i) 'climate change without water trading', and ii) 'climate change with water trading', using the coupled SWAT-MODFLOW model as a hydrologic simulator for the South Platte River Basin (SPRB), Colorado, USA, a mixed agro-urban river basin with an extensive history of agricultural water trading. The model is forced with two MACA downscaled, GSM climate models, each under two different climate emission scenarios, RCP4.5 and 8.5, with additional pumping wells instituted to compensate for the removal of surface water irrigation. Major results are as follow:

1) When considering only climate change, groundwater storage may decrease up to 25% by the end of the century;
2) Due to the inclusion of groundwater pumping to compensate for removal of surface water irrigation, crop yield does not vary from the "climate-only" scenario.
3) Water trading, with groundwater compensation, results in a basin-wide groundwater storage decrease of 2%, in addition to the loss in storage from climate change;
4) Areas of intensive water trading, with the additional of many pumping wells, can experience losses in groundwater storage of up to 10%, in addition to the loss in storage from climate change.

From these major results, we conclude that projected magnitudes of water trading in the SPRB basin through the 21st century will not significantly affect basin-wide groundwater storage beyond the impact of climate change. However, local losses of groundwater may be significant. Overall, the results of this study advance our understanding of the overall impact of water trading, within the context of climate change, on the alluvial aquifer system of a large river basin, for a system that feasibly lessens adverse impacts on the economy and food production. Further studies can explore in more detail the costs and benefits of such a system, by taking into account the total cost of installing and maintaining a new network of pumping wells in the areas of agriculture-to-urban water trading. While the area of focus in this study is the SPRB, the methodology described in this study can be employed in similar regions across the world.

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# Chapter 5. SUMMARY AND CONCLUSION

## 5.1. SUMMARY

Water resources in irrigated river basins in the western United States face competition from agricultural, municipal, industrial, and environmental users. Increasing populations can lead to transfer of water from irrigated agricultural to municipalities via agricultural dry-up or water leasing programs. Groundwater in rural areas is particularly vulnerable as transfer of surface water rights to urban areas will likely increase reliance on groundwater resources, leading to increased groundwater pumping. This study assesses the spatial vulnerability of groundwater to over-exploitation and climate change in the South Platte River Basin (SPRB) in Colorado. In this semi-arid river basin, which encompasses an area of 72,000 km$^2$ area, conjunctive use of surface water and groundwater is required, which often leads to groundwater depletion. Competition between urban and agricultural areas intensifies this exploitation as surface water rights are sold to growing municipalities.

In this study, the recently developed SWAT-MODFLOW coupled hydrologic model is modified for application to large managed river basins, with a specific application to the entire area of the SPRB. Specific modifications include the linkage of groundwater pumping to irrigation practices, and a change in the code to handle the large number of SWAT hydrologic response units (HRU) required for a large river basin with numerous land uses and soil types. SWAT handles land surface and soil zone processes, whereas MODFLOW handles groundwater flow and all sources and sinks (pumping, injection, bedrock inflow, canal seepage, recharge areas, groundwater/surface water interaction), with recharge and stream stage provided by SWAT. The model is tested against groundwater levels and stream discharge and is used to quantify available groundwater and surface water throughout SPRB for water resource management projects.

The model is used to quantify spatial groundwater vulnerability, surface water availability and crop yield trends in the basin under scenarios of climate change. Integrated management of surface water and groundwater is the key to achieve sustainable water resources and secure water availability, especially in arid and semi-arid regions of the world. With generally scarce surface water resources, groundwater often is the primary source of water supply in such regions, with significant groundwater-surface water (GW/SW) interactions often occurring in irrigated regions. Thus, in this study, possible future impacts imposed by climate change on surface water and groundwater exchange in a basin-scale complex semi-arid region is assessed as well. The developed updated version of SWAT-MODFLOW is forced with five different CMIP5 climate models downscaled by Multivariate Adaptive Constructed Analogs (MACA), each for two climate scenarios, RCP4.5, and RCP8.5, for 1980-2100. The projected crop yield, groundwater and surface water availability from 2000 through the end of the century are presented in 4 different time intervals along the South Platte River and its tributaries- current (2000-2020), near future (2021-2040), mid-century (2041-2070), and end of the century (2071-2100).

Lastly, using a coupled SWAT-MODFLOW model, this dissertation focuses on quantifying the combined impacts of agriculture-to-urban water trading (widely known as ‘buy and dry’) and climate change on groundwater availability in semi-arid river basins through the end of the 21st century, as groundwater pumping increases to satisfy irrigation water lost to the urban sector. The assessment of regional vulnerabilities will enable decision-makers to manage water resources in a sustainable fashion over the coming decades.

## 5.2. MAJOR FINDINGS

The major findings of this dissertation are summarized below:

The SWAT-MODFLOW code was modified for application to large-scale agro-urban river basins, with model use and performance demonstrated for the South Platte River Basin in northeastern Colorado, USA.

i) Updated SWAT-MODFLOW code can be used for large agro-urban river basins
ii) The model includes all major water transfer pathways for managed river basins
iii) The model is designed to handle water management schemes in large river basins, such as the conjunctive use of surface water and groundwater for irrigation.
iv) The presented model can be applied for management purposes, enabling the water resources managers to quantify spatial groundwater vulnerability in large complex managed basins.

To provide insight into possible future impacts imposed by climate change on water resources and crop yield in basin-scale complex semi-arid river basins, the SWAT-MODFLOW model is forced with five different CMIP5 climate models downscaled by MACA, each for two different climate emission scenarios, RCP4.5 and RCP8.5. The results of the analysis indicate that:

v) Water availability and agricultural production in SPRB are impacted by climate change.
vi) The worst climate condition happens when increases in temperature combines with decreases in precipitation.
vii) Climate change under the worst condition will reduce streamflow, groundwater storage, and crop yield.

viii) The worst-case climate model in the SPRB is IPSL-CM5A-MR-8.5, in which the basin experiences the combination of 2 climatically stressors, reduction in precipitation, and increase in temperature. Under this climate model, 1 °C elevation in temperature and 1.3% reduction in annual precipitation will result in 11% reduction in crop yield, 8.6% decline in average stream discharge, and 2 to 5% decrease in the groundwater storage.

Finally, this dissertation investigates the impact of agriculture-to-urban water trading on groundwater availability in a large agro-urban river basin within the context of a changing climate.

ix) Through the agriculture-to-urban water trading process, groundwater storage is reduced up to 2% basin-wide during the 21st century, beyond the impact of climate change which is up to 25% reduction by the end of the century.

x) Due to the inclusion of groundwater pumping to compensate for removal of surface water irrigation, crop yield does not vary from the "climate-only" scenario.

xi) In general, the projected magnitudes of water trading in the SPRB basin through the 21st century will not significantly affect basin-wide groundwater storage beyond the impact of climate change. However, local losses of groundwater may be significant.

xii) Areas of intensive water trading, with the additional of many pumping wells, can experience losses in groundwater storage of up to 10%, in addition to the loss in storage from climate change.

## 5.3. FUTURE RESEARCH

Surface water issues are immediate and visible and accordingly have been given more focus than groundwater systems; however, in arid and semi-arid regions of the world with generally scarce surface water resources, groundwater often is the primary water supply source. E.g., 60% of national groundwater withdrawals occur in the western United States. Groundwater in the western U.S. is a strategic water resource used for drinking, sanitation, and hygiene by nearly 10 million people. Groundwater is also critical to irrigated agriculture, especially in times of drought, and a thorough understanding of various stressors such as population pressure, climate change, groundwater abstraction (pumping), and land use and land cover alteration, on groundwater availability is critical. The studies show that the combination of stressors amplify the deterioration; however, few studies have scrutinized multiple stressors in their assessments (Aslam et al., 2018). In addition, due to the inherent uncertainties of climate models, the assessment of the effects of solely climate change on groundwater vulnerability remains uncertain as well. However, taking other stressors into account makes the groundwater vulnerability studies more robust. While in this dissertation, I have assessed the combined impact of land-use change due to the agriculture-to-urban water trading process and the climatic variations on groundwater storage, there is still a lack of considering multiple stressors combination on groundwater vulnerability. Moreover, as groundwater supply gap is associated with negative economic impacts and can be essentially crippling to the local economies, socio-economic studies are recommended for the future as well.

Besides defining a metric or index to quantify the groundwater vulnerability on a local scale will be a powerful and complementary tool in water resources planning and public awareness.

# REFERENCES

Aslam, R. A., Shrestha, S., & Pandey, V. P. (2018). Groundwater vulnerability to climate change: A review of the assessment methodology. *Science of the Total Environment*, 612, 853–875. https://doi.org/10.1016/j.scitotenv.2017.08.237