

DISSERTATION

INVESTIGATING THE IMPACT OF IRRIGATION AND WATER STORAGE  
PRACTICES ON HYDROLOGIC FLUXES UNDER CLIMATE CHANGE IN A HIGHLY  
MANAGED RIVER BASIN

Submitted by

Mohammed K. Almahawis

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2024

Doctoral Committee:

Advisor: Ryan T. Bailey

Neil S. Grigg

Joseph Scalia IV

William E. Sanford

Copyright by Mohammed K. Almahawis 2024

All Rights Reserved

## ABSTRACT

### INVESTIGATING THE IMPACT OF IRRIGATION AND WATER STORAGE PRACTICES ON HYDROLOGIC FLUXES UNDER CLIMATE CHANGE IN A HIGHLY MANAGED RIVER BASIN

Irrigation practices and sources can have significant impacts on water resources and the hydrologic fluxes that control these resources. To better manage water resources and future water supply, the influence of irrigation practices and management on these hydrologic fluxes should be quantified in time and space at varying scales, under potential irrigation management practices. To fulfill this objective, a surface-subsurface modeling approach was applied to simulate watershed-scale hydrologic processes in the Cache la Poudre River Basin, Colorado, USA (4,824 km<sup>2</sup>), in which both surface water irrigation and groundwater irrigation are prevalent. The model chosen for this study is the watershed model SWAT+, using the spatially distributed, physically based groundwater module *gflow*, in which unconfined groundwater storage, flows, and interaction with land surface features are simulated using a collection of grid cells that represent control volumes of the aquifer. Major groundwater inflows and outflows include pumping, recharge, groundwater-channel exchange, groundwater-lake

exchange, and tile drainage outflow. To investigate the impact of irrigation practices, detailed surface and groundwater irrigation routines and canal-aquifer interactions were added to the SWAT+ source code, requiring information of irrigation sources and irrigation canal locations throughout the river basin. Model calibration and testing was performed using monthly stream discharge and groundwater head. The calibrated model is used to quantify the impact of surface water and groundwater irrigation scenarios on water availability and hydrologic fluxes within the river basin. A total of 22 scenarios were conducted and grouped into five main groups: irrigation source, irrigation amount, irrigation type, canal bed thickness, and partial or full sealing of earthen irrigation canals. Using groundwater as the only irrigation source decreases groundwater discharge to streams (by 14%) due to lowering groundwater levels; converting flood irrigation to sprinkler irrigation throughout the basin decreases surface runoff by 22%; and sealing earthen canals leads to a lowering of groundwater levels, which decreases groundwater discharge to streams by 9%, leading to an overall decrease in streamflow in the Cache la Poudre River and changes to temporal patterns in streamflow. Overall, irrigation amount and type and canal sealing have a small impact on total groundwater storage, compared to changes in the percent of fields irrigated by groundwater pumping.

The potential impacts of climate change on water resources and hydrologic fluxes were analyzed in this study. The calibrated SWAT+*gwflow* model is run under five different CMIP5 climate models downscaled by MACA, each representing two different climate

emission scenarios, RCP4.5 and RCP8.5. Except for the CGCM3 (Warm) model, all climate models and emission scenarios predict an increase in the yearly average temperature. The projected variation in precipitation (that is, snow and rain) depends on the climate model used. However, the average annual precipitation across the entire basin is expected to increase by 6.1% under the RCP8.5 scenario for the NorESM1-M (Mild) model. On the other hand, the IPSL-CM5A-MR (Dry) model shows a maximum decrease rate of 6% from the average climate conditions under the RCP8.5 scenario. The analysis reveals that the IPSL-CM5A-MR-8.5 climate model in the CLP is the most severe, as it combines two climatic stressors: less precipitation and increased temperature. Runoff is observed to be reduced by 47.6%, groundwater recharge to drop by 11%, and a 0.5% reduction in groundwater storage under this climate scenario. Although the climate conditions in the past have been inconsistent, the transboundary water source that flows into the watershed has consistently maintained a stable discharge throughout the investigated historical period. This indicates the existence of regulated water management methods and agreements, irrespective of the impact of climate change.

The potential effects of constructing a new reservoir were also assessed in this study, specifically focusing on the influence on streamflow and hydrologic fluxes under changing climatic conditions. The calibrated SWAT+*gwflow* model was run using two different CMIP5 climate models downscaled by MACA, CNRM-CM5 (Wet) and IPSL-CM5A-MR (Dry) under RCP8.5 emission scenario. The analysis revealed that the CNRM-

CM5 (Wet) climate scenario had a higher average monthly diversion rate from the CLP river to the Glade Reservoir during operation months (2.1 m<sup>3</sup>/s) compared to the IPSL-CM5A-MR (Dry) scenario (1.6 m<sup>3</sup>/s). Both climate models show a consistent reduction in the average annual streamflow of the CLP river when the reservoir is present. The largest reduction in the average monthly streamflow in CLP river was observed under the IPSL-CM5A-MR (Dry) RCP8.5 with reservoir scenario for the month of June, showing a 78% decrease from the historical average streamflow. The reduction in streamflow, under the reservoir scenario, for both future climate models led to a 13% and 24% reduction in surface water irrigation for the wet and dry climate scenarios, respectively, compared to historical values.

Results are helpful for informed decision-making in agriculture water management and can lead to sustainable, efficient, and equitable use of water resources, helping to address the challenges posed by water scarcity and environmental conservation.

## DEDICATION

*I dedicate this dissertation to my dad, whose unwavering support and encouragement have been my greatest inspiration.*

## TABLE OF CONTENTS

ABSTRACT .....	ii
DEDICATION .....	vi
CHAPTER 1 - INTRODUCTION AND OBJECTIVES.....	1
1.1 Introduction .....	1
1.2 Dissertation objectives.....	4
References .....	5
CHAPTER 2 - Investigating the Impact of Irrigation Practices on Hydrologic Fluxes in a Highly Managed River Basin .....	11
2.1 Introduction .....	11
2.2 Materials and Methods .....	14
2.2.1 Study Area.....	14
2.2.2 SWAT+ model .....	17
2.2.3 <i>gwflow</i> module .....	19
2.2.4 Sensitivity Analysis, Calibration, and Testing .....	24
2.2.5 Quantifying the impact of irrigation practices on hydrologic fluxes .....	28
2.3 Results and Discussion.....	29
2.3.1 Hydrological Simulation and State Variables of the Baseline Simulation .....	29
2.3.2 Impact of Irrigation Scenarios on Hydrologic Fluxes.....	37
2.3.3 Groundwater Storage .....	42
2.4 Summary and Conclusions.....	43
References .....	45
CHAPTER 3 - Climate Change Impact on Hydrologic Fluxes Under Different Irrigation Scenarios in a Highly Managed Basin.....	52
3.1 Introduction .....	52
3.2 Materials and Methods .....	55

3.2.1 SWAT+ <i>gwflow</i> hydrologic simulation tool.....	55
3.2.2 Future Climate in CLP.....	56
3.2.3 Quantifying the impact of Climate Change on Transboundary Water Sources .....	57
3.2.4 Quantifying the impact of irrigation practices on hydrologic fluxes considering various climate patterns .....	60
3.3 Results and Discussion.....	60
3.3.1 Overview of future climate in the CLP .....	60
3.3.2 Impact of Future Climate Variation on Hydrologic Fluxes for the Base Scenario .....	62
3.3.3 Impact of Future Climate Variation on streamflow for the Base Scenario .....	66
3.3.4 Impact of Future Climate Variation on groundwater storage for the Base Scenario .....	68
3.3.5 Impact of Future Irrigation Scenarios on Hydrologic Fluxes in a Changing Climate.....	69
3.4 Study Limitations.....	73
3.5 Summary and Conclusion .....	73
References .....	76
 CHAPTER 4 - Assessing the Impact of Future Water Storage Practices on Water Availability in a Highly Managed River Basin .....	
4.1 Introduction .....	80
4.2 Materials and Methods .....	81
4.2.1 SWAT+ <i>gwflow</i> hydrologic simulation tool.....	81
4.2.2 Future Climate in CLP.....	82
4.2.3 Quantifying the impact of building a new reservoir on streamflow and hydrologic fluxes under climate extremes .....	83
4.3 Results and Discussion.....	84
4.3.1 Diversion to Glade Reservoir from Cache la Poudre River .....	84
4.3.2 Impact of building a new reservoir on streamflow under climate extremes ...	85

4.3.3 Impact of building a new reservoir on hydrologic fluxes under climate extremes.....	87
4.5 Summary and Conclusion .....	88
References .....	90
CHAPTER 5 – SUMMARY AND CONCLUSIONS .....	92
5.1 Summary and major findings.....	92
5.2 Future research directions .....	95
Appendix.....	96

# CHAPTER 1 - INTRODUCTION AND OBJECTIVES

## 1.1 Introduction

Irrigation accounts for 70% of freshwater consumption worldwide (Khokhar, 2017). Aridity is a challenge facing most of the irrigated arid/semi-arid watersheds in the current century (e.g., Cook et al., 2015). Therefore, there is a need to optimize use of water resources for irrigation, considering that 40% of the world's food is produced from irrigated lands (FAO, 2002). Improved irrigation efficiency may be achieved through the application of irrigation management (Saccon, 2018). Irrigation can have a strong impact on hydrologic fluxes in a managed river basin (Graf, 2006; Custodio, 2002). For example, irrigation may cause a decrease in streamflow due to diversion from the main river course to irrigation canals (e.g., Chen et al., 2006; Gao, 1991), and groundwater pumping can cause streamflow depletion (e.g., Barlow and Leake, 2012; Huang et al., 2018). In contrast, canal seepage can be a main source of recharge to alluvial aquifers, leading to, in some places, enhanced rates of groundwater discharge to streams due to increased groundwater levels (e.g., Hershey et al., 1964; Cao et al., 2002; Niemann et al., 2011). In general, the removal of water from either the stream network or unconfined aquifers for irrigation demand and the associated application of irrigation water to fields can have a significant impact on the storage and movement of water within a managed watershed.

The SWAT hydrologic model has been applied in thousands of studies. Samimi et al. (2020) reviewed over 3,000 published papers in SWAT applications to arid/semi-arid managed agricultural watersheds in the last two decades (2000-2020). A common SWAT application is to quantify the components of the water balance and study the impact of different watershed attributes (such as soil type and land use) on hydrologic processes under normal conditions (Brouziyne et al., 2018; Worqlul et al., 2018; Luan et al., 2018; Aouissi et al., 2016; Tarawneh et al., 2016). However, only a handful of studies have assessed the

impact of irrigation design and management on the watershed water balance (e.g., Schoumans et al., 2009; Devia et al., 2015; Francesconi, 2016). These studies, however, do not include the impact of groundwater storage and groundwater levels on watershed fluxes, as SWAT treats groundwater processes in a simplistic manner.

To provide a more realistic representation of groundwater storage and surface exchange in a watershed setting, the coupled SWAT-MODFLOW model (Bailey et al., 2016) has been applied to irrigated areas (Wei and Bailey, 2019; Gao et al., 2019; Dangol et al., 2022; Shaabani et al., 2023; Aliyari et al., 2019). Among these, Dangol et al. (2022) assessed the impact of irrigation on only land surface and soil fluxes (ET, streamflow, recharge), not considering head-dependent fluxes, and Wei and Bailey (2019) only assessed the impact of a decrease in irrigation on groundwater response. No study to our knowledge has systematically assessed the impact of irrigation practices on surface-subsurface hydrologic fluxes in a managed river basin setting. Due to the uncertain nature of a future state of climate and therefore the need for prediction, hydrologic models often are used to estimate the impact of climate change on water supply (e.g., Hagemann et al., 2013; Li and Fang, 2021).

Models can be used to differentiate the impact of climate change on water use for irrigation to provide a better understanding of the watershed behavior and proper management of resources. In the literature, several models were made for groundwater resource management from the perspective of irrigation management and climate change, either individually or simultaneously. These include the Catchment Hydrology Model (CATHY) (e.g., Sulis et al., 2011), MIKE SHE (e.g., Vansteenkiste et al., 2012), Parallel Flow model (ParFlow) (e.g., Ferguson et al., 2012), GSFLOW (e.g., Deen et al. 2023), HydroGeoSphere (e.g., Persaud et al., 2020), and SWAT-MODFLOW (e.g., Abbas et al., 2022; Liu et al., 2020; Aliyari et al., 2021).

Aliyari et al. (2021) examined the impact of climate change on water availability and crop productivity in the semi-arid South Platte River Basin in Colorado, USA. The research employs the coupled

SWAT-MODFLOW modeling code to simulate hydrologic conditions. It evaluated five distinct CMIP5 climate models, each representing two emission scenarios (RCP4.5 and RCP8.5), spanning the period from 1980 to 2100. The model incorporates surface runoff, soil lateral flow, groundwater flow, interactions between groundwater and surface water, irrigation, and agricultural output. The results revealed an increase of 3 to 5°C in temperature and varied precipitation changes influenced by topography.

Samimi et al. (2022) undertook a rigorous analysis of water availability for an irrigated agricultural watershed in the Rio Grande Basin in USA, using the Soil and Water Assessment Tool (SWAT) to investigate consequences under future climate conditions anticipated to 2099. A total number of 97 downscaled, bias corrected global climate models were chosen to represent wide range prospective dry and wet conditions compared to average historical flows in the river. The results show that reservoir storage is becoming less reliable for supporting irrigated agriculture, implying a greater reliance on groundwater. To the best of our knowledge, there was no study that used a holistic coupled surface and groundwater model to assess the impact of climate change on fluxes considering different irrigation practices. Therefore, in this study, we use a hydrologic modeling approach to quantify the impact of future climate on irrigation-related hydrologic fluxes in a semi-arid river basin.

Reservoir installation contributes to changes in streamflow and investigating the changes is crucial for ensuring social and economic stability, as well as for protecting the environment. A sudden drop in streamflow can severely affect aquatic life and irrigation, while a significant increase in runoff can cause floods that endanger lives and property. The cumulative hydrological impacts of reservoir installation are most estimated using runoff (Chai et al., 2019). There is general consensus that constructing reservoirs will lead to fewer flood peaks (Ayalew et al., 2017; Nathan and Lowe, 2012; Thompson, 2012) up to 45%, especially since some reservoirs are built as stormwater retention ponds (Del Giudice et al., 2014). Most of the research has focused on annual streamflow, with average annual reductions reported to range from 0.2% (Hughes and Mantel, 2010) to 36% (Meigh, 1995). It is useful for most water management agencies to

estimate the cumulative impact of reservoir installation on average annual runoff (Habets et al., 2018). To our knowledge, no study has utilized a holistic coupled model of surface and groundwater to evaluate the impacts of reservoir construction on hydrologic fluxes within the context of a changing climate.

## 1.2 Dissertation objectives

The general aim is to improve understanding of hydrological processes in a highly managed river basin. The specific objectives of this study are:

- Assessing the impact of irrigation practices on surface-subsurface hydrologic fluxes (Chapter 2).
- Evaluating the impact of climate change on fluxes considering different irrigation practices (Chapter 3).
- Estimating the impacts of reservoir construction on hydrologic fluxes within the context of a changing climate (Chapter 4).

These objectives were accomplished by applying the hydrologic model SWAT+ (Bieger et al., 2017) using the physically based spatially distributed *gwflow* module (Bailey et al., 2020; Bailey et al., 2023), to the Cache la Poudre River Basin (4,824 km<sup>2</sup>), located in northeast Colorado, USA, which contains a mixture of mountainous terrain, agricultural plains, and residential areas.

Chapter 2 has been published in *Agricultural Water Management: “Investigating the Impact of Irrigation Practices on Hydrologic Fluxes in a Highly Managed River Basin”* (Almahawis et. al, 2024).

## References

- Abbas, S. A., Xuan, Y., & Bailey, R. T. (2022). Assessing climate change impact on water resources in water demand scenarios using SWAT-MODFLOW-WEAP. *Hydrology*, 9(10), 164. <https://doi.org/10.3390/hydrology9100164>
- Aliyari, F., Bailey, R. T., & Arabi, M. (2021). Appraising climate change impacts on future water resources and agricultural productivity in agro-urban river basins. *Sci. Total Environ.*, 788, 147717. <https://doi.org/10.1016/j.scitotenv.2021.147717>
- Aliyari, F., Bailey, R. T., Tasdighi, A., Dozier, A., Arabi, M., & Zeiler, K. (2019). Coupled SWAT-MODFLOW model for large-scale mixed agro-urban river basins. *Environ. Model. SoftW.*, 115, 200-210. <https://doi.org/10.1016/j.envsoft.2019.02.014>
- Aouissi, J., Benabdallah, S., Chabaane, Z. L., & Cudennec, C. (2016). Evaluation of potential evapotranspiration assessment methods for hydrological modelling with SWAT – Application in data-scarce rural Tunisia. *Agric. Water Manag.*, 174, 39-51. <https://doi.org/10.1016/j.agwat.2016.03.004>
- Ayalew, T. B., Krajewski, W. F., Mantilla, R., Wright, D. B., & Small, S. J. (2017). Effect of spatially distributed small dams on flood frequency: Insights from the Soap Creek Watershed. *J. Hydrol. Eng.*, 22(7), 04017011. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001513](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001513)
- Bailey, R., Abbas, S., Arnold, J., White, M., Gao, J., and Čerkasova, N. (2023). Augmenting the national agroecosystem model with physically based spatially distributed groundwater modeling. *Environ. Model. SoftW.*, 160, 105589. <https://doi.org/10.1016/j.envsoft.2022.105589>
- Bailey, R., Bieger, K., Arnold, J., and Bosch, D. (2020). A new physically-based spatially-distributed groundwater flow module for SWAT+. *Hydrology*, 7(4), 75. <https://doi.org/10.3390/hydrology7040075>
- Bailey, R., Wible, T., Arabi, M., Records, R., and Ditty, J. (2016) Assessing regional-scale spatio-temporal patterns of groundwater–surface water interactions using a coupled SWAT-MODFLOW model. *Hydrol. Process.*, 30, 4420-4433. <https://doi.org/10.1002/hyp.10933>

- Barlow, P. M., & Leake, S. A. (2012). *Streamflow depletion by wells: understanding and managing the effects of groundwater pumping on streamflow* (Vol. 1376). Reston, VA: US Geological Survey.
- Brouziyne, Y., Abouabdillah, A., Bouabid, R., and Benaabidate, L. (2018). SWAT streamflow modeling for hydrological components' understanding within an agro-sylvo-pastoral watershed in Morocco. *J. Mater. Environ. Sci*, 9(1), 128-138. <https://doi.org/10.26872/jmes.2018.9.1.16>
- Cao, J., Xie, Y., Chen, Z., and Zhang, G. (2002). Preliminary research on the seepage and transportation of irrigation water in the plain of main stream region of Heihe river Gansu province. *Hydrogeology and Engineering Geology*, 4, 1-4.
- Chai, Y., Li, Y., Yang, Y. *et al.* (2019). Influence of Climate Variability and Reservoir Operation on Streamflow in the Yangtze River. *Sci. Rep.*, 9, 5060. <https://doi.org/10.1038/s41598-019-41583-6>
- Chen, Z., Nie, Z., Zhang, G., Wan, L., and Shen, J. (2006). Environmental isotopic study on the recharge and residence time of groundwater in the Heihe River Basin, northwestern China. *Hydrogeol J*, 14(8), 1635-1651. <https://doi.org/10.1007/s10040-006-0075-7>
- Cook, B.I., Ault, T.R., Smerdon, J.E., (2015). Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Sci. Adv.*, 1(1), e1400082. <https://doi.org/10.1126/sciadv.1400082>
- Custodio, E. (2002). Aquifer overexploitation: what does it mean?. *Hydrogeol J*, 10(2), 254-277. <https://doi.org/10.1007/s10040-002-0188-6>
- Dangol, S., Zhang, X., Liang, X. Z., and Miralles-Wilhelm, F. (2022). Agricultural Irrigation Effects on Hydrological Processes in the United States Northern High Plains Aquifer Simulated by the Coupled SWAT-MODFLOW System. *Water*, 14(12), 1938. <https://doi.org/10.3390/w14121938>
- Deen, T. A., Arain, M. A., Champagne, O., Chow-Fraser, P., & Martin-Hill, D. (2023). Impacts of climate change on streamflow in the McKenzie Creek watershed in the Great Lakes region. *Front. environ. sci.*, 11, 1171210. <https://doi.org/10.3389/fenvs.2023.1171210>

- Del Giudice, G., Rasulo, G., Siciliano, D., & Padulano, R. (2014). Combined effects of parallel and series detention basins for flood peak reduction. *Water Resour. Manag.*, 28(10), 3193-3205. <https://doi.org/10.1007/s11269-014-0668-1>
- Devia, G., Ganasri, B., and Dwarakish, G. (2015). A review on hydrological models. *Aquatic procedia*, 4, 1001-1007. <https://doi.org/10.1016/j.aqpro.2015.02.126>
- FAO (2002). Crops and Drops: Making the Best Use of Water for Agriculture. FAO, Rome (November 24, 2022). <https://www.fao.org/3/Y3918E/Y3918E00.htm>
- Ferguson, I. M., & Maxwell, R. M. (2012). Human impacts on terrestrial hydrology: climate change versus pumping and irrigation. *Environ. Res. Lett.*, 7(4), 044022. <https://doi.org/10.1088/1748-9326/7/4/044022>
- Francesconi, W., Srinivasan, R., Pérez-Miñana, E., Willcock, S. P., and Quintero, M. (2016). Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: A systematic review. *J. Hydrol.*, 535, 625-636. <https://doi.org/10.1016/j.jhydrol.2016.01.034>
- Gao, F., Feng, G., Han, M., Dash, P., Jenkins, J., and Liu, C. (2019). Assessment of surface water resources in the big sunflower river watershed using coupled SWAT–MODFLOW model. *Water*, 11(3), 528. <https://doi.org/10.3390/w11030528>
- Gao, Q. Z. (1991). Development and utilization of water resources in the Heihe River catchment. *Gansu Science and Technology Press*, Lanzhou, 205.
- Graf, W. L. (2006). Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology*, 79(3-4), 336-360. <https://doi.org/10.1016/j.geomorph.2006.06.022>
- Habets, F., Molénat, J., Carluet, N., Douez, O., & Leenhardt, D. (2018). The cumulative impacts of small reservoirs on hydrology: A review. *Sci. Total Environ.*, 643, 850-867. <https://doi.org/10.1016/j.scitotenv.2018.06.188>

- Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., *et al.* (2013). Climate change impact on available water resources obtained using multiple global climate and hydrology models. *Earth Syst. Dyn.*, 4(1), 129-144. <https://doi.org/10.5194/esd-4-129-2013>
- Hershey, L. A., and Schneider, P. A. (1964). Ground-water investigations in the lower Cache la Poudre River Basin, Colorado. US Government Printing Office.
- Huang, C. S., Yang, T., & Yeh, H. D. (2018). Review of analytical models to stream depletion induced by pumping: Guide to model selection. *Journal of Hydrology*, 561, 277-285. <https://doi.org/10.1016/j.jhydrol.2018.04.015>
- Hughes, D. A., & Mantel, S. K. (2010). Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. *Hydrological Sciences Journal*, 55(4), 578–592. <https://doi.org/10.1080/02626667.2010.484903>
- Khokhar, T. (2017). Chart: Globally, 70% of freshwater is used for agriculture. *World Bank Data Blog*. <https://blogs.worldbank.org/opendata/chart-globally-70-freshwater-used-agriculture>
- Li, C., & Fang, H. (2021). Assessment of climate change impacts on the streamflow for the Mun River in the Mekong Basin, Southeast Asia: Using SWAT model. *Catena*, 201, 105199. <https://doi.org/10.1016/j.catena.2021.105199>
- Liu, W., Bailey, R. T., Andersen, H. E., Jeppesen, E., Nielsen, A., Peng, K., *et al.* (2020). Quantifying the effects of climate change on hydrological regime and stream biota in a groundwater-dominated catchment: A modelling approach combining SWAT-MODFLOW with flow-biota empirical models. *Sci. Total Environ.*, 745, 140933. <https://doi.org/10.1016/j.scitotenv.2020.140933>
- Luan, X., Wu, P., Sun, S., Wang, Y., and Gao, X. (2018). Quantitative study of the crop production water footprint using the SWAT model. *Ecol. Indic.*, 89, 1-10. <https://doi.org/10.1016/j.ecolind.2018.01.046>

- Meigh, J. (1995, February). The impact of small farm reservoirs on urban water supplies in Botswana. In *Natural Resources Forum* (Vol. 19, No. 1, pp. 71-83). Oxford, UK: Blackwell Publishing Ltd. <https://doi.org/10.1111/j.1477-8947.1995.tb00594.x>
- Nathan, R., & Lowe, L. (2012). The hydrologic impacts of farm dams. *Australas. J. Water Resour.*, 16(1), 75-83. <https://doi.org/10.7158/13241583.2012.11465405>
- Niemann, J. D., Lehman, B. M., Gates, T. K., Hallberg, N. U., and Elhaddad, A. (2011). Impact of shallow groundwater on evapotranspiration losses from uncultivated land in an irrigated river valley. *J. Irrig. Drain. Eng.*, 137(8), 501-512. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000356](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000356)
- Persaud, E., Levison, J., MacRitchie, S., Berg, S. J., Erler, A. R., Parker, B., & Sudicky, E. (2020). Integrated modelling to assess climate change impacts on groundwater and surface water in the Great Lakes Basin using diverse climate forcing. *J. Hydrol.*, 584, 124682. <https://doi.org/10.1016/j.jhydrol.2020.124682>
- Saccon, P. (2018). Water for agriculture, irrigation management. *Applied soil ecology*, 123, 793-796. <https://doi.org/10.1016/j.apsoil.2017.10.037>
- Samimi, M., Mirchi, A., Moriasi, D., Ahn, S., Alian, S., Taghvaeian, S., and Sheng, Z. (2020). Modeling arid/semi-arid irrigated agricultural watersheds with SWAT: Applications, challenges, and solution strategies. *J. Hydrol.*, 590, 125418. <https://doi.org/10.1016/j.jhydrol.2020.125418>
- Schoumans, O., Silgram, M., Walvoort, D., Groenendijk, P., Bouraoui, F., Andersen, H., *et al.* (2009). Evaluation of the difference of eight model applications to assess diffuse annual nutrient losses from agricultural land. *J. Environ Monitor*, 11(3), 540-553. <https://doi.org/10.1039/B823240G>
- Shaabani, M. K., Abedi-Koupai, J., Eslamian, S. S., and Gohari, A. (2023). Simulation of the effects of climate change and reduce irrigation requirements on groundwater recharge using SWAT and MODFLOW models. *Model. Earth Syst. Environ.* 9, 1681–1693. <https://doi.org/10.1007/s40808-022-01580-7>
- Sulis, M., Paniconi, C., Rivard, C., Harvey, R., & Chaumont, D. (2011). Assessment of climate change impacts at the catchment scale with a detailed hydrological model of surface-subsurface interactions

and comparison with a land surface model. *Water Resour. Res.*, 47(1).

<https://doi.org/10.1029/2010WR009167>

Tarawneh, E., Bridge, J., and Macdonald, N. (2016). A pre-calibration approach to select optimum inputs for hydrological models in data-scarce regions. *Hydrol Earth Syst Sci.*, 20(10), 4391-4407.

<https://doi.org/10.5194/hess-20-4391-2016>

Thompson, J. C. (2012). *Impact and management of small farm dams in Hawke's Bay, New Zealand* (Doctoral dissertation, Open Access Te Herenga Waka-Victoria University of Wellington).

Vansteenkiste, T., Tavakoli, M., Ntegeka, V., Willems, P., De Smedt, F., & Batelaan, O. (2012). Climate change impact on river flows and catchment hydrology: a comparison of two spatially distributed models. *Hydrol. Process.*, 27(25), 3649-3662. <https://doi.org/10.1002/hyp.9480>

Wei, X., and Bailey, R. T. (2019). Assessment of system responses in intensively irrigated stream-aquifer systems using SWAT-MODFLOW. *Water*, 11(8), 1576. <https://doi.org/10.3390/w11081576>

Worqlul, A. W., Ayana, E. K., Yen, H., Jeong, J., MacAlister, C., Taylor, R., *et al.* (2018). Evaluating hydrologic responses to soil characteristics using SWAT model in a paired-watersheds in the Upper Blue Nile Basin. *Catena*, 163, 332-341. <https://doi.org/10.1016/j.catena.2017.12.040>

# CHAPTER 2 - Investigating the Impact of Irrigation Practices on Hydrologic Fluxes in a Highly Managed River Basin

## 2.1 Introduction

Irrigation accounts for 70% of freshwater consumption worldwide (Khokhar, 2017). Aridity is a challenge facing most of the irrigated arid/semi-arid watersheds in the current century (e.g., Cook et al., 2015). Therefore, there is a need to optimize use of water resources for irrigation, considering that 40% of the world's food is produced from irrigated lands (FAO, 2002). Improved irrigation efficiency may be achieved through the application of irrigation management (Saccon, 2018). Irrigation can have a strong impact on hydrologic fluxes in a managed river basin (Graf, 2006; Custodio, 2002). For example, irrigation may cause a decrease in streamflow due to diversion from the main river course to irrigation canals (e.g., Chen et al., 2006, Gao, 1991), and groundwater pumping can cause streamflow depletion (e.g., Barlow and Leake 2012, Huang et al., 2018). In contrast, canal seepage can be a main source of recharge to alluvial aquifers, leading to, in some places, enhanced rates of groundwater discharge to streams due to increased groundwater levels (e.g., Hershey et al., 1964, Cao et al., 2002, Niemann et al., 2011). In general, the removal of water from either the stream network or unconfined aquifers for irrigation demand and the associated application of irrigation water to fields can have a significant impact on the storage and movement of water within a managed watershed.

Hydrologic models are often used to enhance our understanding of hydrologic processes and watershed response in arid and semi-arid irrigated lands (Mirchi et al., 2010). Moreover, meaningful uses of watershed modeling require a practical representation of hydrologic fluxes, water management, and irrigation techniques (Arnold et al., 2015). Some of the frequently used models that assess hydrologic

processes and watershed response in agricultural regions are the Hydrological Simulation Program – Fortran, HSPF (Bicknell et al., 1997), the Agricultural NonPoint Source pollution model, AGNPS (Young et al., 1989), the Hydrologic Modeling System, HEC-HMS (Charley, 1995), the Soil and Water Integrated Model, SWIM (Krysanova et al., 2000), the KINematic runoff and EROsion model, KINEROS (Smith et al., 1995), and the Soil and Water Assessment Tool, SWAT (Arnold et al., 1998). SWAT, the most popular of these in terms of worldwide applications, is often used to assess water changes due to land use and agricultural management practices.

The SWAT hydrologic model has been applied in thousands of studies. Samimi et al. (2020) reviewed over 3,000 published papers in SWAT applications to arid/semi-arid managed agricultural watersheds in the last two decades (2000-2020). Those papers were selected if they: (i) were published in peer-reviewed scientific journals; (ii) applied SWAT in arid and/or semi-arid climates; (iii) explicitly mentioned a focus on the simulation of agricultural watersheds; and (iv) took irrigation into account. In the end, 102 papers that reported extensive discussions about irrigation modeling using SWAT were narrowed down. A common SWAT application is to quantify the components of the water balance and study the impact of different watershed attributes (such as soil type and land use) on hydrologic processes under normal conditions (Brouziyne et al., 2018, Worqlul et al., 2018, Luan et al., 2018, Aouissi et al., 2016, Tarawneh et al., 2016). However, only a handful of studies have assessed the impact of irrigation design and management on the watershed water balance (e.g., Schoumans et al., 2009, Devia et al., 2015, Francesconi, 2016). These studies, however, do not include the impact of groundwater storage and groundwater levels on watershed fluxes, as SWAT treats groundwater processes in a simplistic manner.

To provide a more realistic representation of groundwater storage and surface exchange in a watershed setting, the coupled SWAT-MODFLOW model (Bailey et al., 2016) has been applied to irrigated areas (Wei and Bailey, 2019; Gao et al., 2019; Dangol et al., 2022; Shaabani et al., 2023; Aliyari et al., 2019). Among these, Dangol et al. (2022) assessed the impact of irrigation on only land surface and soil fluxes (ET, streamflow,

recharge), not considering head-dependent fluxes, and Wei and Bailey (2019) only assessed the impact of a decrease in irrigation on groundwater response. No study to our knowledge has systematically assessed the impact of irrigation practices on surface-subsurface hydrologic fluxes in a managed river basin setting.

Our general aim is to improve understanding of hydrological processes in a managed, irrigated watershed. The specific objectives of this study are:

- (1) Identify model parameters that govern streamflow in a managed, irrigated watershed system;
- (2) Quantify historical, spatio-temporal hydrologic fluxes (surface-subsurface); and
- (3) Enhance understanding and quantify the impact of irrigation practices (canal diversions, canal seepage, applied irrigation, groundwater pumping) on basin hydrologic fluxes.

These objectives were accomplished by applying the hydrologic model SWAT+ (Bieger et al., 2017) using the physically based spatially distributed *gflow* module (Bailey et al., 2020; Bailey et al., 2023), to the Cache la Poudre River Basin (4,824 km<sup>2</sup>), located in northeast Colorado, USA, which contains a mixture of mountainous terrain, agricultural plains, and residential areas. To investigate the impact of irrigation practices, the SWAT+ modeling code was modified to include detailed, field-based surface water and groundwater irrigation practices as well as canal-groundwater exchange due to the extensive network of earthen canals. A global sensitivity analysis was first applied to the model using the Morris Method, followed by calibration and testing against monthly streamflow at multiple gage sites, and groundwater head, using the Parameter Estimation Software (PEST) program. The model is applied to the 2000-2015 period. Irrigation scenario categories investigated include source (surface water, groundwater), depth (mm) of irrigation events, type (drip, sprinkler, flood), canal bed thickness (cm), and canal sealing (i.e., canal bed conductivity).

## 2.2 Materials and Methods

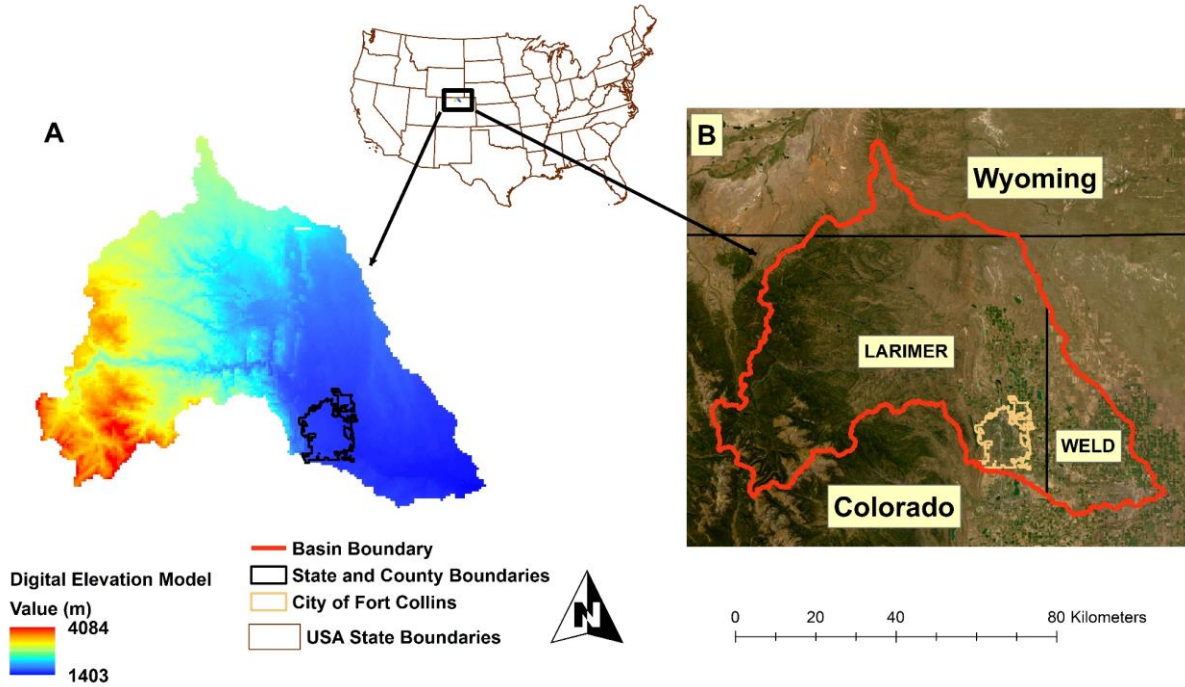
This section provides a description of the study area and the SWAT+ hydrologic model for the Cache la Poudre River Basin. It also demonstrates the adjustments to the SWAT+ code for simulating field-based irrigation practices and canal-groundwater exchange.

### 2.2.1 Study Area

The Cache la Poudre River Basin (CLP) is a mountainous watershed located in northern Colorado, with a small portion of the basin in southern Wyoming (Figure 2.1B) and is a headwater watershed within the Missouri River Basin. The CLP covers an area of 4,824 km<sup>2</sup> and ranges in elevation from 1,403 – 4,084 m (Figure 2.1A). Table 2.1 presents the characteristics of the watershed. A map showing watershed boundary, streams, the city of Fort Collins boundary (largest city in the basin), river gage stations, groundwater observation wells, weather station locations, SNOw TELemetry (SNOTEL) gages, and water bodies (lakes, reservoirs) is shown in Fig. 2.2. The CLP has a population of approximately 290,000, and the river serves as a source of water for both municipal and agricultural uses in the basin. A portion of the water used in the basin is supplied through the Colorado Big Thompson project, in which water is transferred from the western slope of the Rocky Mountains to reservoirs on the eastern slope. The movement of water in mountainous watersheds is crucial, as these regions often serve as a major freshwater supply for the drier lowland areas (Foy et al., 2015). The agricultural industry in Colorado had significant growth in the first twenty years of the 20th century, leading to an increased need for irrigated land along the Poudre River (Laflin, 2005).

The climate is categorized as semi-arid, with an average annual rainfall of 467 mm. Land use (Figure 2.3A) consists of forest (30%), pasture (26%), wetland (23%), and agricultural land (11%). Main crop types are corn and alfalfa (hay). Agricultural lands lie mainly in the eastern, low areas of the basin, whereas forests, wetlands, and pasture make up the western, mountainous area of the basin. Geologic units in the study area are mainly granite, gneiss, gravel, shale, and sandstone (Figure 2.3B), with alluvial material

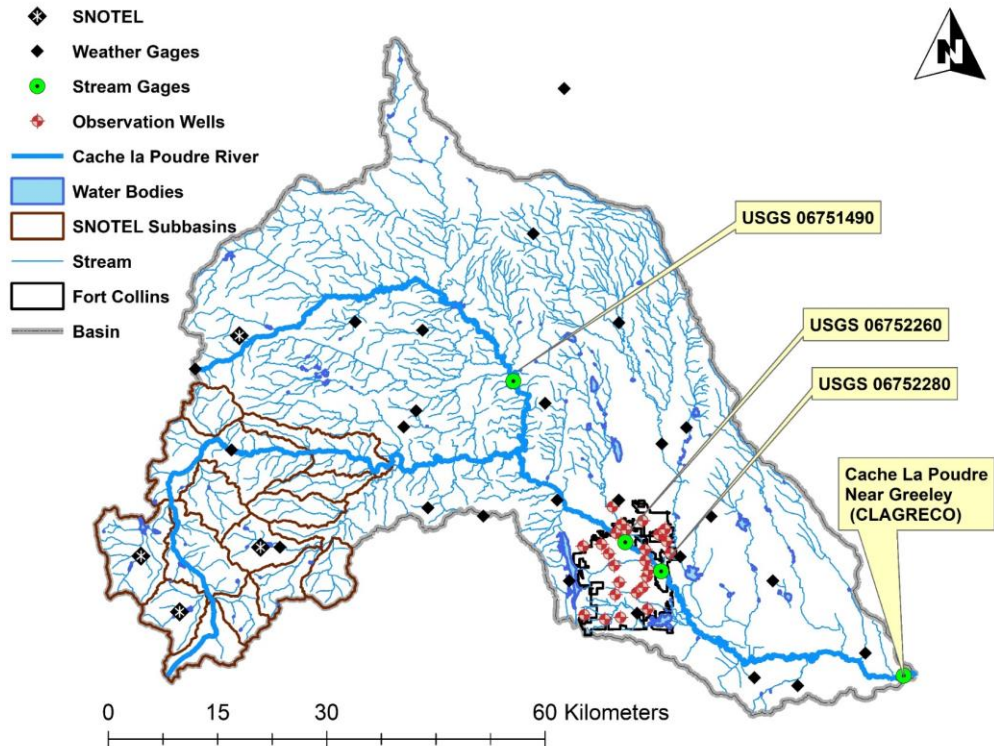
along the Cache la Poudre River and its tributaries. The vertical distance between the ground surface and bedrock, referred to as aquifer thickness, is shown in Figure 2.3C. The thicker sections of the aquifer lie in the eastern, low areas, and provide sufficient groundwater storage for irrigation.



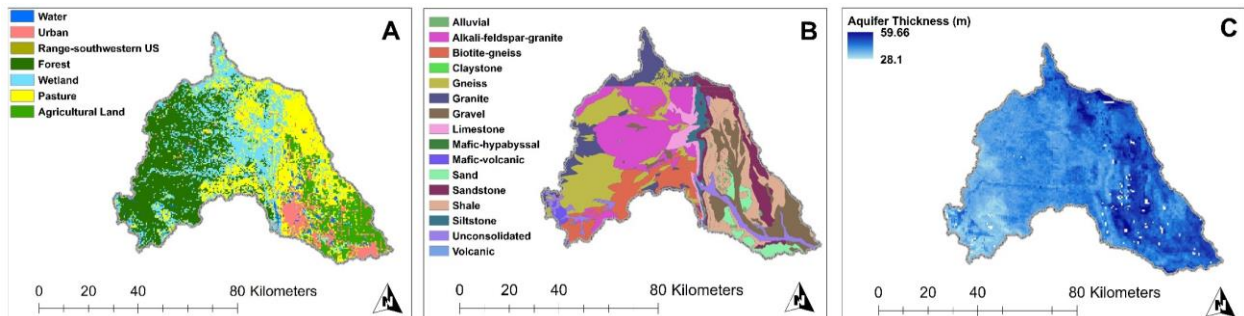
**Figure 2.1.** Maps of the location, state and county boundaries, and topography of the Cache la Poudre River basin.

**Table 2.1.** Characteristics of the Cache la Poudre River Basin, including spatial objects of the SWAT+ model.

State	HUC8	HUC2 Region	<sup>o</sup> C Mean temp.	<i>Mm</i> Annual rainfall	# HRU	# Channels	<i>gflow</i> grid	
							Rows	Cols
CO, WY	10190007	Missouri Region	7.2	467	4,023	1,859	187	226



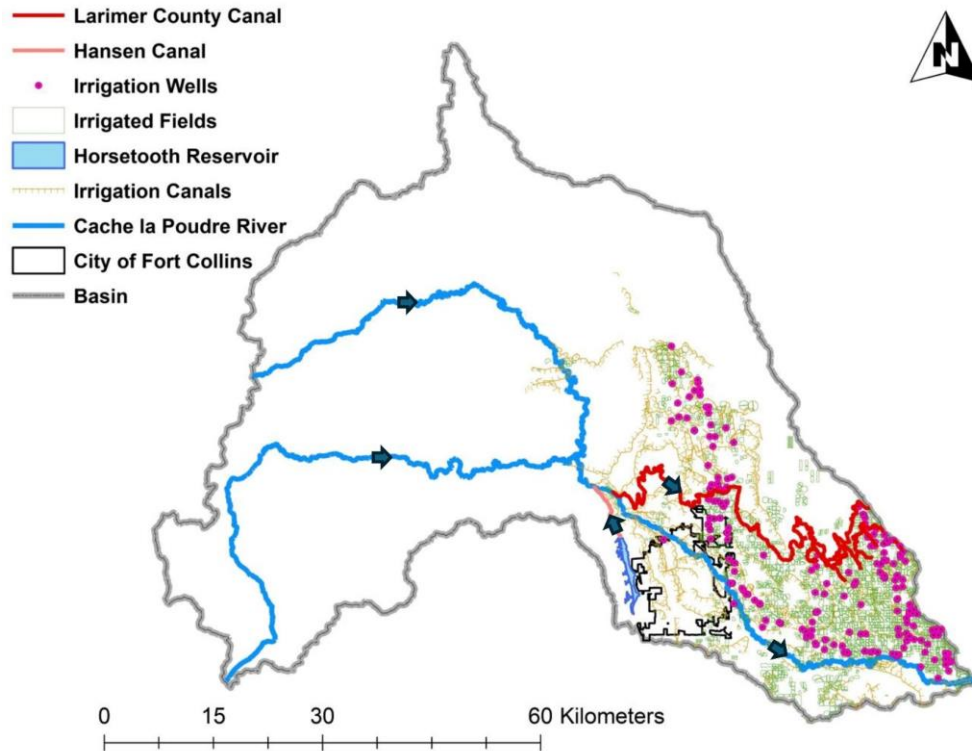
**Figure 2.2.** Main model details for the Cache la Poudre River Basin, revealing the location of streams, water bodies, city of Fort Collins boundary, river gages, observation wells, weather stations, SNOTEL gages (USDA-NRCS, 2023), and SNOTEL Subbasins.



**Figure 2.3.** Maps of (A) Land use; (B) Geologic Units; and (C) Aquifer Thickness for the study area (see Table 2 for dataset sources).

The irrigation system of the CLP is summarized in Figure 2.4. A network of 58 earthen irrigation canals (264 km total length) divert water from the Cache la Poudre River, and 213 pumping wells extract groundwater from the unconfined aquifer. A total of 2,083 fields are irrigated, of which 1,870 are canal fed

and 213 are groundwater fed (Colorado Division of Water Resources). The main type of irrigation is flooding with a total of 1,738 fields while the remaining fields use sprinklers.



**Figure 2.4.** Main irrigation details for the Cache la Poudre River watershed, revealing the location of irrigation wells, irrigated fields, irrigation canals, and city of Fort Collins boundary (See Table 2 for datasets sources).

### 2.2.2 SWAT+ model

The Soil and Water Assessment Tool, SWAT (Arnold et al., 1998), is a process-based model that simulates the storage and movement of water, nutrients, and sediment within a watershed system. It is a semi-distributed model that uses hydrologic response units (HRUs), unique combinations of land use, soil, and topography within a basin, to simulate water, nutrient, and sediment mass balances and their transport to underlying aquifers and nearby streams. In this study, the new version of SWAT was used, SWAT+ (Bieger et al., 2017), to provide more detailed and accurate connections between hydrologic objects in a watershed system. For example, SWAT is limited to one stream channel per sub-basin, whereas SWAT+

can simulate water, sediment, and nutrient movements in any number of channels within a basin. Specific hydrological features include stream channels, fields, aquifers, ponds, reservoirs, and wetlands, where water, sediment, and nutrient are transported between features on a daily time step. The basin is divided into routing units, which aggregate hydrographs from HRU objects across the landscape to channels (Bieger et al., 2017).

**Table 2.2.** Datasets used in the construction of the original SWAT+ models and the *gwflow* inputs.

	Dataset	Source	Resolution (m)
SWAT+ Construction	Field boundaries	Yan and Roy (2016)	
	Crop rotation	USDA-NASS, CDL	
	Topographic slope	USGS National Elevation Dataset (Gesch et al., 2018)	10
	Soil boundaries and properties	Gridded Soil Survey Geographic (Soil Survey Staff, 2014)	10
	Land use, Land cover	U.S. Geological Survey, National Land Cover Data	30
	Stream segments (NHD+)	Moore and Dewald (2016)	
	Lakes and reservoirs	Moore and Dewald (2016)	
	Weather	Global historical climatology network; PRISM SNOTEL	
	Water use	Dieter et al. (2018)	
	Canal Diversions	Colorado's Decision Support Systems	
	Discharge from facilities	Skinner and Maupin (2019)	
<i>gwflow</i> module	Geologic units	Horton et al. (2017)	Vector Polygons
	Tile drainage	Valayamkunnath et al. (2020)	30
	Aquifer thickness	Shangguan et al. (2017)	250

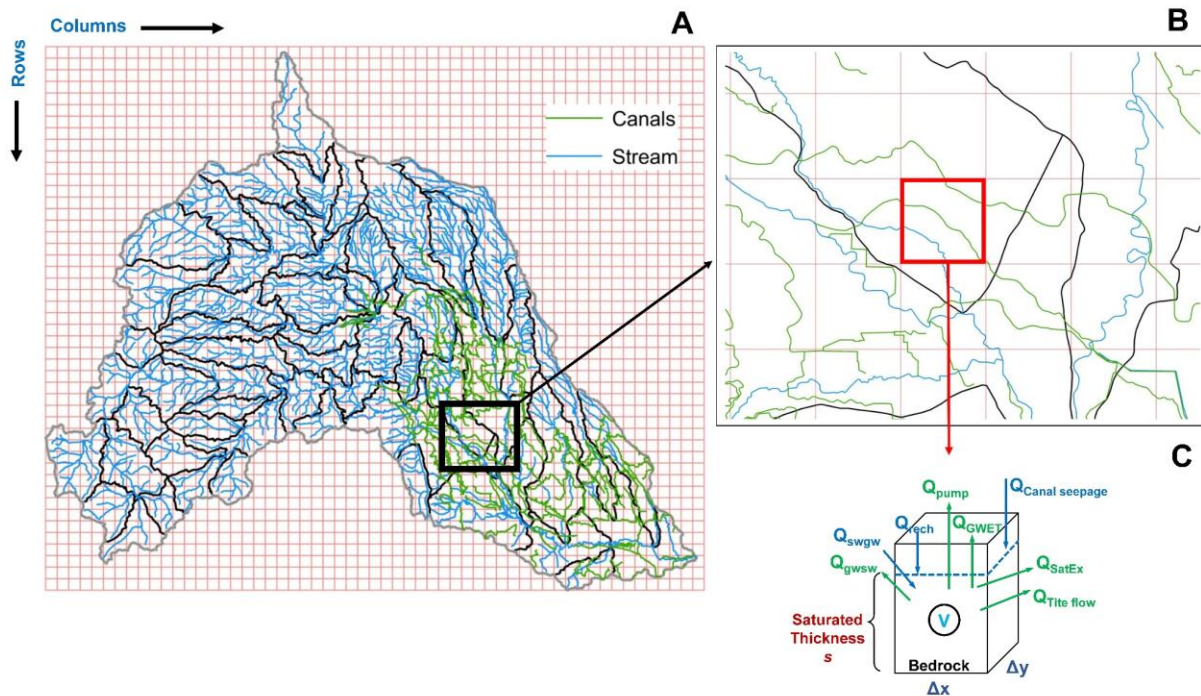
The SWAT+ model for the CLP is constructed using the datasets listed in Table 2.2. This model is part of the National Agroecosystem Model (NAM) (Arnold et al., 2021; White et al., 2022), for which a separate SWAT+ model is constructed for each of the 2,121 8-digit watersheds that comprise the continental United States river drainage system. Subbasins are delineated by 12-digit catchments, stream channels and lakes/reservoirs are delineated using the NHD+ network, and cultivated fields are delineated using the national dataset of Yan and Roy (2016). Each field is a unique HRU. Applying these datasets and the NAM framework to the CLP resulted in 4,023 HRUs and 1,859 stream channels. Global Historical Climatology Network (GHCN) and Parameter-elevation Regressions on Independent Slopes Model (PRISM) data are used as an input for daily weather (precipitation, temperature) (White et al., 2022), but then corrected for

mountainous subbasins using measured precipitation data from SNOTEL observation network (accessed May 2023) (see Figure 2.2 for the four observation sites). Hansen canal delivers water to Cache la Poudre River from Colorado River through Horsetooth Reservoir as seen in Figure 2.4 and was included in the model as a transboundary source. Moreover, Larimer County canal was included in the model as a negative point source that is taking water from the river for multiple uses such as water supply and storage.

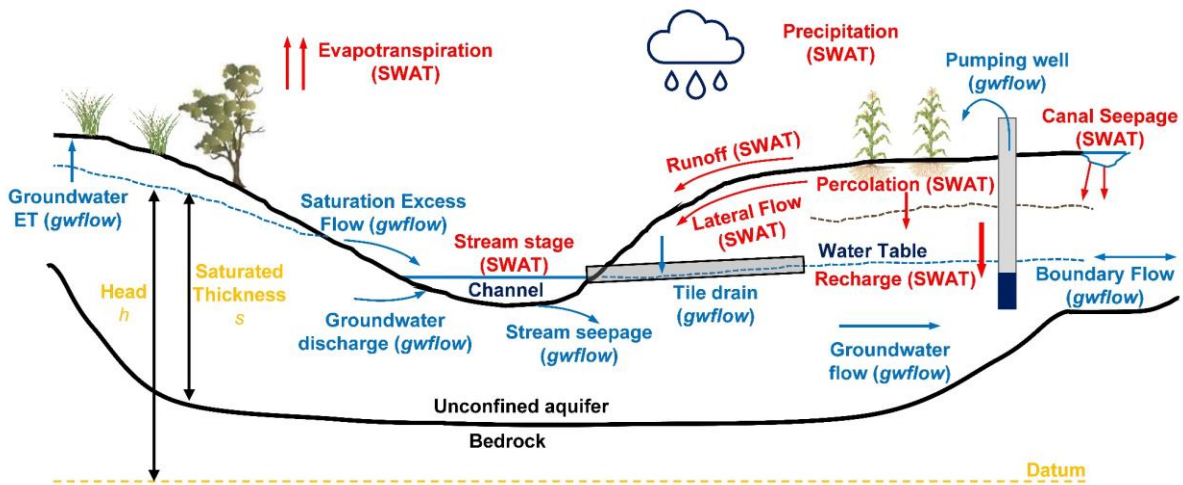
### **2.2.3 *gwflow* module**

#### *2.2.3.1 Introduction to the gwflow module*

Similar to the original SWAT model, the SWAT+ groundwater module simulates groundwater storage and interaction with land surface features in a simplistic manner, including homogeneous aquifer characteristics; groundwater discharge into rivers based on steady flow conditions and user-defined thresholds rather than slope or head; and lack of groundwater flow between adjacent aquifer units. To improve groundwater simulation in a watershed setting, Bailey et al. (2020) developed the *gwflow* subroutine for SWAT+. This subroutine simulates the lateral movement of groundwater through an unconfined single-layer aquifer using a series of spatially connected cells. Figure 2.5 shows an example grid for the CLP, showing the *gwflow* grid of cells, and a schematic of the water balance that is applied to each control volume (cell) of aquifer. Inflows into each aquifer cell can include recharge, lateral flow from surrounding cells, stream seepage, and lake seepage; outflows can include groundwater ET, lateral flow to surrounding cells, pumping for agriculture and municipalities, transfer to the soil profile (upflux), saturation excess flow in locations where the water table intersects the ground surface, and discharge to streams, lakes, and tile drains. Each cell also has a value of hydraulic conductivity ( $K$ ; m/day) and specific yield ( $S_y$ ). Figure 2.6 shows the transfer of water from each hydrologic object in the watershed system. Blue arrows represent fluxes that are simulated by the original SWAT+ code, whereas red arrows represent fluxes simulated by the *gwflow* subroutine.



**Figure 2.5.** Spatial layout and calculation approach of the *gwflow* module, showing (A) grid cells, subbasins (black outlines), and stream channels (blue lines) for a generic watershed; (B) close-up of grid and channels, showing the water balance calculations for each individual grid cells; and (C) control volume schematic of an individual grid cell, showing groundwater volume  $V$  and all groundwater inputs and outputs.



**Figure 2.6.** Schematics showing hydrologic pathways within the integrated SWAT+ model with the *gwflow* routines. Blue arrows represent fluxes that are simulated by the *gwflow* module.

For each daily time step of the SWAT+ simulation, the *gwflo*w module is called as a subroutine to compute sources and sinks and update groundwater storage and groundwater head for each grid cell. The module uses an explicit, forward-in-time numerical method to loop through the grid cells, updating groundwater storage  $V$  for each cell storage and flux values from the previous day (see Figure 2.5B, 2.5C):

$$\frac{\Delta V_{i,j}^{n+1}}{\Delta t} = sources_{i,j}^n - sinks_{i,j}^n \pm lateral\ flow_{i,j}^n \quad (2.1)$$

where  $n+1$  represents the current time (day),  $n$  represents the previous day, and  $i$  and  $j$  represent the row and column indices, respectively, of each cell. Equation (1) can be expanded to:

$$V_{i,j}^{n+1} = V_{i,j}^n + (sources_{i,j}^n - sinks_{i,j}^n \pm lateral\ flow_{i,j}^n)(t^{n+1} - t^n) \quad (2.2)$$

Groundwater sources, sinks, and lateral flow are volumetric fluxes ( $m^3/day$ ) of groundwater, computed as:

$$sources = Q_{rech} + Q_{sw \rightarrow gw} + Q_{lake \rightarrow gw} \quad (2.3)$$

$$sinks = Q_{gwet} + Q_{gw \rightarrow sw} + Q_{satex} + Q_{pump} + Q_{gw \rightarrow lake} + Q_{tile} + Q_{soil} \quad (2.4)$$

$$lateral\ flow = \pm Q_{north} \pm Q_{south} \pm Q_{west} \pm Q_{east} \quad (2.5)$$

where *rech*, *sw → gw*, *lake → gw*, *gwet*, *gw → sw*, *satex*, *pump*, *gw → lake*, *tile*, and *soil* represent recharge, stream seepage to the aquifer, lake seepage to the aquifer, groundwater evapotranspiration (ET), groundwater discharge to streams, saturation excess flow when the water table intersects the ground surface, groundwater pumping, groundwater discharge to lakes, groundwater discharge to tile drains, and groundwater transfer to the soil profile, respectively (see Figure 2.5C).  $Q_{north}$ ,  $Q_{south}$ ,  $Q_{west}$ , and  $Q_{east}$  represent lateral groundwater fluxes into/out of the four sides of the grid cell, which provides the spatial connectivity of the aquifer system. The resulting groundwater volume  $V$  for each grid cell is used to update the saturated thickness  $s$  and groundwater head  $h$  for each cell, using  $S_y$  and the surface area of the cell. As the method

is explicit in nature, i.e., all values of  $V$  and  $h$  at the current time step  $n+1$  are calculated using values from the previous time step  $n$ , initial  $V$  and  $h$  must be specified for each cell for the first day of the simulation.

#### 2.2.3.2 Implementation for the CLP SWAT+ model

For the CLP, the watershed is discretized using 500 m cells, resulting in a  $187 \times 226$  grid (42,262 cells), of which 20,118 are active (i.e., within the watershed boundary). The datasets utilized to populate the values of  $S_y$ ,  $K$ , aquifer thickness, and initial groundwater head  $h$  are listed in Table 2.2 and include geologic units for initial values of  $S_y$  and  $K$ ; tile drainage locations, used to identify grid cells for which tile drainage outflow can be calculated if the water table is higher than the specified drain elevation; and aquifer thickness. The initial head for each cell was determined by spatially interpolating across observation wells (Figure 2.2) using values from the years 2000 to 2006.

#### 2.2.3.3 Modifications to the SWAT+ code for this study

As the focus of our study is the impact of irrigation practices on hydrologic processes and fluxes, the detailed irrigation system (canal diversion points, earthen irrigation canals, groundwater pumping wells) (see Figure 2.4) were included into the SWAT+ model.

To simulate detailed irrigation, the SWAT+ code was modified to read in and then implement irrigation source type (canal, aquifer), irrigation source (specific stream channel, pumping well), irrigation efficiency, and irrigation runoff ratio for each irrigated field in the model domain, with the latter two defining the irrigation type (sprinkler, flood). When irrigation is triggered within the simulation for a given irrigated field, this information is used to determine irrigation amount (mm), the source of the irrigation water (canal, which removes water from a specified channel; or aquifer, which removes groundwater from the underlying *gwflow* grid cells), and runoff fractions. Information to populate these input data, such as irrigation source and irrigation type, was obtained from the Colorado Division of Water Resources (<https://cdss.colorado.gov/gis-data/division-1-south-platte>).

As canal seepage can be a significant source of groundwater recharge, particularly in the CLP with the vast network of irrigation canals, the *gwflow* subroutine was modified in this study to calculate canal-groundwater exchange for any cells that intersect the line of an irrigation canal. The exchange rate  $Q_{canal}$  ( $m^3/day$ ) is calculated with Darcy's Law, using canal bed thickness  $bed_{thick}$  (m), canal bed hydraulic conductivity  $K_{bed}$  (m/day), the length of the canal in the cell  $l$  (m), the canal width  $w$  (m), and the difference between groundwater head  $h$  (m) and canal *stage* (m):

$$Q_{canal} = (w \cdot l) \cdot K_{canal} \cdot \left( \frac{diff}{bed_{thick}} \right) \quad (2.6)$$

where *diff* depends on the elevations of canal stage and water table, using the following three conditions:

$h < stage:$	$diff = stage - bed \ elevation$
$h$ between <i>bed elevation</i> and <i>stage</i> :	$diff = stage - h$
$h > stage:$	$diff = h - stage$

The first two conditions simulate canal seepage to the aquifer, as groundwater head  $h$  is less than the canal stage; the third condition simulates groundwater discharge from the aquifer to the canal, as  $h$  is greater than canal stage. The exchange rate  $Q_{canal}$  is included in the water balance storage equation (Equation 2.2).

The following inputs were used for this study:

- Canal bed thickness  $bed_{thick}$  (m): assumed to be equal to 0.5 m, based on local canal conditions. This could be used as a calibration parameter.
- Canal bed hydraulic conductivity  $K_{bed}$  (m/day): we used the NRCS SSURGO data based on soil type, to provide a value of saturated soil hydraulic conductivity.
- The length of the canal in the cell  $l$  (m): we intersected the *gwflow* grid with the shape file of the irrigation canals, to determine the length of the canal in each grid cell.
- The canal width  $w$  (m): we assumed to be equal to 5 m, based on local canal conditions.

- The difference between groundwater head  $h$  (m): this difference is calculated during the model simulation; the canal stage is provided by the ground surface elevation for the grid cell, whereas the groundwater head is simulated and updated for each day of the simulation, using the *gflow* methodology.
- Canal stage (m): we assumed this value to be equal to 1 m, based on local canal conditions. This value is often used in hydrologic modeling studies in Colorado.

## 2.2.4 Sensitivity Analysis, Calibration, and Testing

### 2.2.4.1 Sensitivity Analysis

Before model calibration, global sensitivity analysis (GSA) was performed to identify the model parameters that have the strongest influence on streamflow. The Morris method was used, sometimes referred to as the Elementary Effects Test, to establish the relative sensitivity of model parameters (Morris, 1991). The methodology used in this work is based on the one-at-a-time (OAT) technique, whereby each parameter  $x_i$  is successively modified with a size of  $\Delta_i$ . The procedure yields a trajectory that encompasses the whole of the parameter space. Within the framework of a model defined by a specific set of parameters denoted as  $p$ , a trajectory may be understood as a sequential arrangement of  $p$  values, with each value corresponding to one of the parameters. Each trajectory produces an estimate of the elementary effect for every parameter. The elementary effect is defined as the ratio of the change in model output to the change in the corresponding parameter. Equation (2.7) demonstrates the calculation of a singular elementary effect concerning to the  $i^{th}$  parameter.

$$EE_i = \frac{f(x_1, \dots, x_i + \Delta_i, \dots, x_p) - f(x)}{\Delta_i} \quad (2.7)$$

where "EE<sub>*i*</sub>" represents the elementary effect value of the  $i^{th}$  model parameter, and  $x_1, \dots, x_i$  are the values of the model parameters, the Morris screening approach often utilizes two computational measurements, namely the mean and the standard deviation of the elementary effect. These measurements are used to

assess the sensitivity and statistical significance of parameters. Campolongo et al. (2007) proposed a modification to this methodology, whereby the conventional average " $\mu$ " is substituted with a modified absolute average " $\mu^*$ ". This revision aims to resolve concerns associated with the polarity of positive and negative values while handling " $EE_i$ ". The procedure for determining the absolute mean and standard deviation may be stated as follows:

$$\mu_i^* = \frac{1}{n} \sum_{j=1}^n |EE_i(j)| \quad (2.8)$$

$$\sigma_i = \sqrt{\frac{1}{n-1} \sum_{j=1}^n \left[ EE_i(j) - \frac{1}{n} \sum_{j=1}^n EE_i(j) \right]^2} \quad (2.9)$$

where  $\mu_i^*$  is the absolute mean elementary effect value of the  $i^{th}$  model parameter,  $n$  is the number of model parameter samples,  $EE_i(j)$  is the elementary effect value estimated from the  $i^{th}$  model parameter and the  $j^{th}$  sample, and  $\sigma_i$  is the standard deviation of the elementary effect value of the  $i^{th}$  parameter.

For this study, the 'pestpp-sen' tool within the PEST++ framework was used (White et al., 2020) to perform the Morris method. Table 2.4 lists the parameters included in the Morris method, and Table 2.5 presents the range for each parameter. A total of 32 parameters were selected, with targeted attention on surface runoff, canal seepage processes, lateral flow, groundwater flow, potential and actual evapotranspiration, channel flow processes, snow melt processes, soil water processes, and time of concentration (Table 2.4). The quantity of classes (Table 2.5, column 2) denotes the count of distinct zones or categories assigned to each parameter. Within the pestpp-sen tool, measured streamflow response at four USGS gauge locations the Cache la Poudre River (see Figure 2.2) was set as the calibration target. The model was run for the 2009-2015 period.

**Table 2.4.** The selected parameters for the use in model calibration and sensitivity analysis of the SWAT+ *gwflow* model of the study watershed.

Parameters	Parameter description	Hydrologic Processes
CN2 #	SCS runoff curve number for moisture condition II	Surface runoff processes
slp #	Average slope steepness in HRU (m/m)	Lateral flow processes
esco #	Soil evaporation compensation factor	Potential and actual evapotranspiration processes
epco #	Plant uptake compensation factor	
can_max #	Maximum canopy storage (mm H <sub>2</sub> O)	
rech_del	Recharge delay (days)	Groundwater flow processes
syaqu #	Aquifer specific yield for a specific zone for i <sup>th</sup> zone	
kaqu #	Aquifer hydraulic conductivity for a specific zone (m/day) for i <sup>th</sup> zone	
bed_thick	Streambed thickness (m)	
bed_k	Streambed hydraulic conductivity (m/day)	
bed_depth	River depth (m)	
tile_k	Hydraulic conductivity of the drain perimeter (m/day)	
tile_area	Area of groundwater inflow (m <sup>2</sup> ) to tile	
tile_depth	Depth of tiles below ground surface (m)	
ftmp	Snowfall temperature (°C)	
tmplag	Snowpack temperature lag factor	
mmin	Melt factor for snow on December 21 (mm H <sub>2</sub> O/°C– day)	
mmax	Melt factor for snow on June 21 (mm H <sub>2</sub> O/°C– day)	
mtmp	Snowmelt base temperature (°C)	
snowd	Minimum snow water content (mm H <sub>2</sub> O)	
cov50	Fraction of COVMX	
ch_n	Manning's n for the channels	Channel flow processes
ch_k	Effective hydraulic conductivity of the channels (mm/h)	
canal_d	Canal depth (m)	Canal seepage processes
canal_w	Canal width (m)	
canal_bt	Canal bed thickness (m)	
canal_bk #	Canal bed hydraulic conductivity (m/day)	
ovn #	Manning's "n" value for overland flow	Time of concentration processes
slp_len #	Average slope length for erosion (m)	
surq_lag	Surface runoff lag time (days)	
awc #	Available water capacity of the soil layer (mm H <sub>2</sub> O/mm soil) for i <sup>th</sup> layer	Soil water processes
perco #	Percolation coefficient	

#: indicates there are multiple categories for the parameter; for example, there are CN2 values for multiple land use types used during calibration and sensitivity analysis.

#### 2.2.4.2 Model Calibration and Testing

After the Morris application, model calibration was performed by targeting the parameters with the strongest influence on streamflow. Calibration was performed using PEST (Doherty, 2020) for the 2009-2015 period using measured monthly streamflow at the three USGS gauge stations (Figure 2.2; USGS 06751490, USGS, 06752260, and USGS 06752280). The period of 2009-2015 was chosen to include the wet period. The testing period was 2002-2008, with a two-year (2000-2001) warm-up period. The stream gage

at the watershed outlet (see Figure 2.2) is reserved for testing. The model is further tested for measured groundwater head during 2002-2015. Streamflow is evaluated using the Nash-Sutcliffe efficiency index NSE (Nash and Sutcliffe, 1970), the percentage deviation PBIAS, and the Kling-Gupta efficiency (KGE).

**Table 2.5.** Selected parameters range for the sensitivity analysis and model calibration for the SWAT+ *gworkflow* model.

Parameter	No. of classes	Parameter range
rech_del	–	1 to 30
kaqu #	10	0.10 to 10 (relative change)
syaqu #	10	0.05 to 0.35
bed_k	–	0.000005 to 0.1000
bed_thick	–	0.10 to 1.50
bed_depth	–	1.0 to 5.0
tile_depth	–	1.0 to 2.0
tile_area	–	10 to 100
tile_k	–	0.08 to 8.70
CN2	3	0.70 to 1.70 (relative change)
esco	–	0.00 to 1.00
epco	–	0.00 to 1.00
can_max	–	0.00 to 100
surq_lag	–	0.05 to 24.00
slp_len #	6	10.00 to 150.00
ovn #	3	0.01 to 1.00
ch_n	–	0.01 to 0.30
ch_k	–	0.01 to 500
slp #	3	0.00 to 1.00
perco	2	0.00 to 1.00
awc #	6	0.00 to 1.00
ftmp	–	–5.0 to 5.0
mtmp	–	–5.0 to 5.0
mmax	–	1.4 to 6.9
mmin	–	1.4 to 6.9
mmplag	–	0.01 to 1.01
mnowd	–	0.5 to 1.0
cov50	–	0.1 to 1.0
canal_w	–	1.00 to 6.00
canal_d	–	0.50 to 1.50
canal_bt	–	0.10 to 0.70
canal_bk #	5	0.00 to 15

The main challenge faced in calibrating the model was obtaining the high amount of peak flow in the wet period (i.e., 2009-2015). Snow parameters have a direct and significant impact on timing and peak streamflow in snowmelt-dominated watersheds and were a focus during the calibration process. We initially calibrated the dry period of 2000-2008; however, while capturing the streamflow response during the dry period, the model underpredicted the peak flows during the wet period of 2009-2015 (see Supplementary Section). However, as the CLP River Basin is semi-arid, with water fully allocated to

municipal and irrigation water rights, correctly simulating peak flows during the wet period when the majority of water yield for the basin occurs is vital, and therefore we elected to calibrate the model for the 2009-2015 period.

Results from the tested model are used to quantify historical spatio-temporal hydrologic fluxes within the CLP River Basin. These fluxes include surface runoff to streams, evapotranspiration, soil lateral flow to streams, recharge to the water table, groundwater-stream exchange, groundwater saturation excess flow, groundwater-lake exchange, and groundwater pumping. With the inclusion of detailed irrigation applications and canal seepage into the modeling code. Also, applied irrigation and canal seepage were quantified.

### **2.2.5 Quantifying the impact of irrigation practices on hydrologic fluxes**

The model was used to investigate the impact of irrigation practices on hydrologic fluxes within the CLP Basin. Alteration to hydrologic fluxes can occur because of irrigation techniques, and comprehending the consequences of different irrigation scenarios on hydrologic fluxes is crucial for sustainable water resources management. In this paper, applied irrigation (pumping and surface irrigation) refers to the amount of water that is allowed to infiltrate the soil. Therefore, with higher irrigation efficiency, more of the irrigation water will infiltrate the soil rather than running off the field. The actual volume of water provided to the field—and thus removed from either the channel or the aquifer, depending on the irrigation source—is calculated as the product of the amount and the field area. Therefore, five main scenario groups were considered in this study (Table 2.6):

- (1) irrigation source, with irrigation occurring all from either surface water (i.e., diversions from the Cache la Poudre River) or from groundwater (i.e., pumping from the underlying aquifer, within the vicinity of the field);
- (2) amount of applied irrigation (20 mm to 100 mm);
- (3) irrigation type: drip, sprinkler, flooding, using various efficiencies;

- (4) canal bed thickness (cm), which affects the exchange rate between canals and the aquifer; and
- (5) canal bed sealing, from 20% sealed to fully sealed.

The latter two scenarios are included to explore the effect of canal seepage on groundwater processes, as groundwater head resulting from canal recharge likely affects the volumetric flow rate of groundwater discharging to streams.

**Table 2.6.** Irrigation scenario groups for SWAT+*gwflow* simulations.

Scenario Group	Parameter	Values
Irrigation Sources	Surface Water	All Surface Water
	Ground Water	All Ground Water
Irrigation Amount	Amount (mm)	0, 30, 40, 60, 70, 80, 90, 100
Irrigation Type	Drip	High Efficiency (0.9)
	Sprinkler	Medium Efficiency (0.75)
	Flooding	Low Efficiency (0.6)
Canal Bed Thickness	Thickness (cm)	10, 20, 30, 40
Canal Bed Sealing	Fully Sealed	100% Sealed
	Partially Sealed	80%, 60%, 40%, 20% Sealed

## 2.3 Results and Discussion

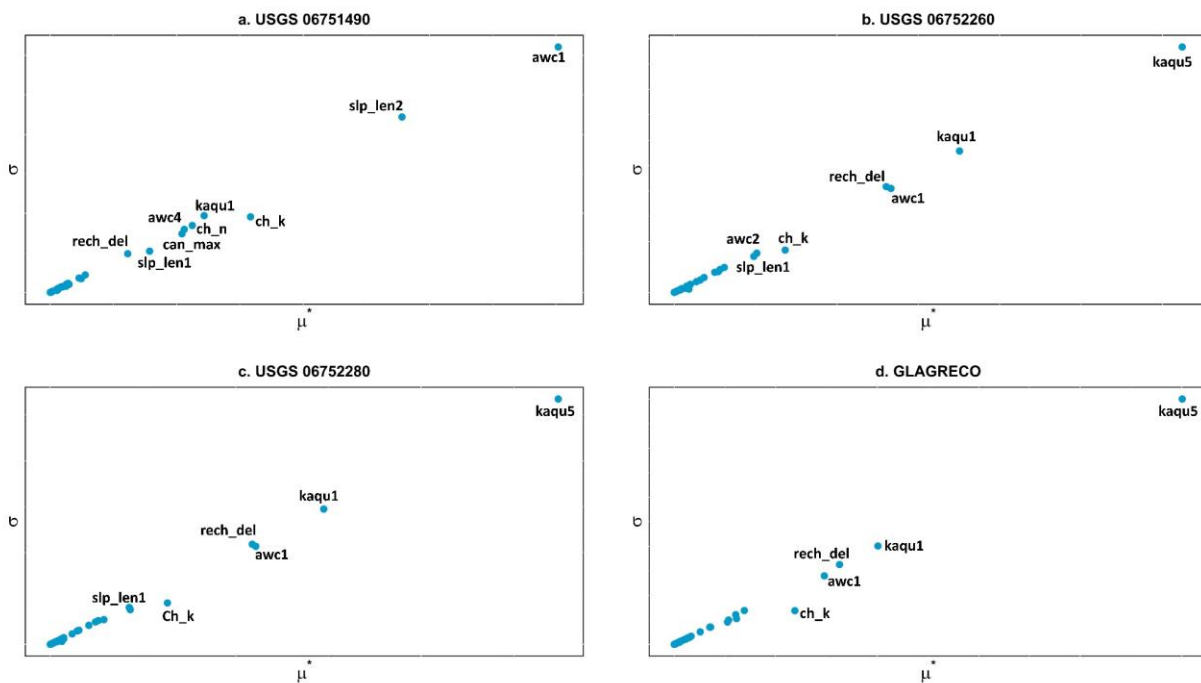
### 2.3.1 Hydrological Simulation and State Variables of the Baseline Simulation

#### 2.3.1.1 Sensitivity Analysis

Results from the Morris method (Figure 2.7) indicate the following, for each of the four USGS gage sites along the Cache la Poudre River:

**Gage (USGS 06751490):** streamflow is governed by available water capacity (*awc1*), channel hydraulic conductivity (*ch\_k*), aquifer *K* (*kaqu1*), slope length (*slp\_len2*), recharge delay (*rech\_del*), riverbed thickness (*bed\_thick*), river depth (*bed\_depth*), channel Manning’s *n* value (*ch\_n*), and maximum canopy storage (*can\_max*) (Figure 2.7A). This gage is situated in a topographically elevated area where several sensitive parameters have been identified, including available water capacity and hydraulic conductivity. The sensitivity to parameters such as Manning’s *n* value and maximum canopy storage implies that this particular gage exhibits intricate surface water processes, including vegetation and channel flow dynamics.

**Gage (USGS 06752260), Gage (USGS 06752280), and GLAGRECO:** streamflow generation is governed by available water capacity (awc1), the hydraulic conductivity of the channel (ch\_k), aquifer K (kaqua5 and kaqua1), and the recharge delay (rech\_del) (see Figure 2.7B: Gage (USGS 06752260); Figure 2.7C: Gage (USGS 06752280); Figure 2.7D (GLAGRECO)). All gages are in areas characterized by the presence of extensively irrigated agricultural fields, where irrigation is facilitated via the use of both surface water and groundwater resources. The model's responsiveness to characteristics such as available water capacity and K suggests a strong sensitivity to the soil and aquifer's capability for water storage and transmission, as a portion of irrigation water recharges the aquifer and then flows back to the stream network as groundwater discharge.

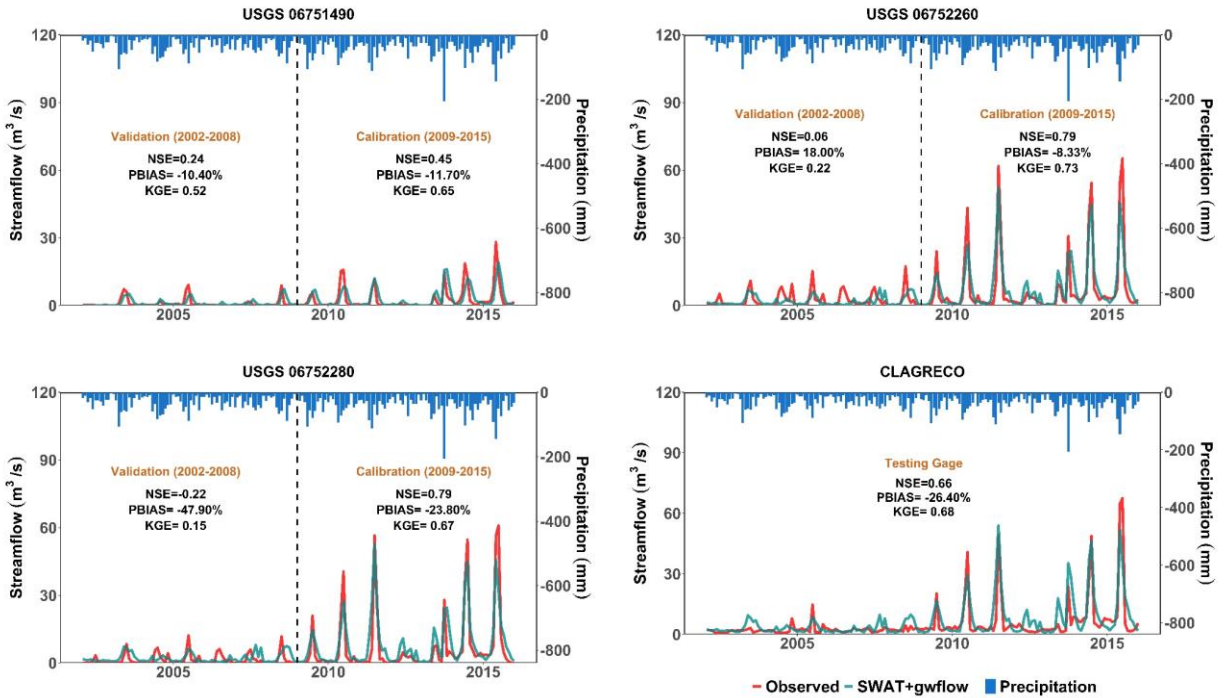


**Figure 2.7.** Parameters sensitivity analysis based on the Morris screening approach for streamflow response for four river gage locations. Only the most sensitive parameters are labelled.  $\sigma$  shows the degree of nonlinearity or factor interaction, and  $\mu^*$  is the sensitivity measure.

### 2.3.1.2 Streamflow Hydrographs and Water Balance

Evaluation of model results reveals that the model has good performance in terms of statistical indicators such as NSE, PBIAS, and KGE (Figure 2.8). The downstream of the basin is highly irrigated and the most downstream gages in the Fort Collins area (USGS 06752260 and USGS 06752280) show good performance with NSE of 0.79 for the calibration period (wet period). GLAGRECO is the testing gage that was not included in the calibration process and has a NSE of 0.66, indicating a good model performance.

From an analysis of watershed-wide hydrologic fluxes (Table 2.7), 88% of precipitation (412 mm / 468 mm) is lost from the basin through ET, typical of semi-arid regions. This agrees with the estimated average annual hydrologic fluxes and fractions provided by Reitz et al. (2017). For the CLP river basin, ET fraction is above 80%, with lower values occurring in the mountainous regions and higher values in the downstream plains area. Water yield (i.e., streamflow generation) is 54.4 mm, comprised of surface runoff (12.4 mm; 22.1%), soil lateral flow (15 mm; 26.8%), tile flow (0.6 mm; 1.1%), groundwater discharge (28 mm; 50%), minus stream seepage (1.6 mm), resulting in a baseflow fraction of 0.52 if only groundwater is included, and 80% if baseflow includes both groundwater and soil lateral flow. Applied irrigation is 11 mm for canal (surface water) and 5 mm for groundwater, with pumping and canal seepage approximately equal in magnitude. Recharge from both precipitation and irrigation totals 24 mm. As seen in Figure 2.8, by comparing the hydrographs from upstream gauge (USGS 06751490) to the outlet (CLAGRECO), more baseflow occurs in the downstream, irrigated portions of the region, as a higher water table from irrigation induces groundwater return flows to the Cache la Poudre River and its tributaries.



**Figure 2.8.** Measured and simulated monthly streamflow for SWAT+*gflow* models for the USGS stream gaging sites within the CLP watershed. Performance statistics (NSE, PBIAS, KGE) are shown for each gage site.

To provide more details regarding hydrologic fluxes, the daily hydrologic fluxes from 2009 to 2012 are shown in Figure 2.9. The left plot displays average fluxes for the entire watershed, while the right plot shows average fluxes exclusive to the aquifer system. Watershed inputs, such as boundary inflow and precipitation, are represented by positive values, while the outputs, including tile drainage, runoff, surface evapotranspiration, groundwater saturation excess flow, and lateral flow, are represented by negative numbers. Canal seepage fluxes represent a loss from the surface water system and as a result it is shown as an inflow for the groundwater system in the plot to the right. This loss can reduce the amount of water available for irrigation but increases groundwater saturation excess flow, due to the local rising of the water table. Groundwater pumping and canal seepage occur only during the growing season (late spring to early fall). Recharge occurs mainly during these same months, due to the application of irrigation and precipitation events. Recharge entering the aquifer is mirrored by groundwater leaving the aquifer via groundwater saturation excess flow, as areas near streams also have high water tables.

**Table 2.7.** Average annual hydrologic fluxes (mm).

	Flux (mm)	Cache la Poudre
<b>Input</b>	Precipitation	467.5
	Boundary Outflow	0.4
<b>Watershed Output</b>	ET	411.7
	Surface Runoff	12.4
	Saturation Excess Flow	33.6
	Groundwater discharge	0.5
	Stream seepage	1.6
	Soil Lateral Flow	15.0
	Tile flow	0.6
<b>Internal Flows</b>	Recharge	30.1
	Pumping Irrigation	4.5
	Surface Water Irrigation	11.1
	Canal seepage	5.4
	GW-Lake Outflow	0.9
<b>Fractions</b>	Water Yield <sup>a</sup>	54.4
	ET Fraction <sup>b</sup>	0.88
	Baseflow Fraction <sup>c</sup>	0.52
	Yield Fraction <sup>d</sup>	0.12
	Recharge Fraction <sup>e</sup>	0.05

a: Water Yield = Surface Runoff + Lateral Flow + Groundwater discharge – Stream seepage + Saturation Excess Flow + Tile flow

b: ET / Precipitation

c: Net groundwater inflow to streams (Sat Excess Flow+ Tile flow+ Groundwater discharge –Stream Seepage) / Water Yield

d: Water Yield / Precipitation

e: Recharge / Precipitation

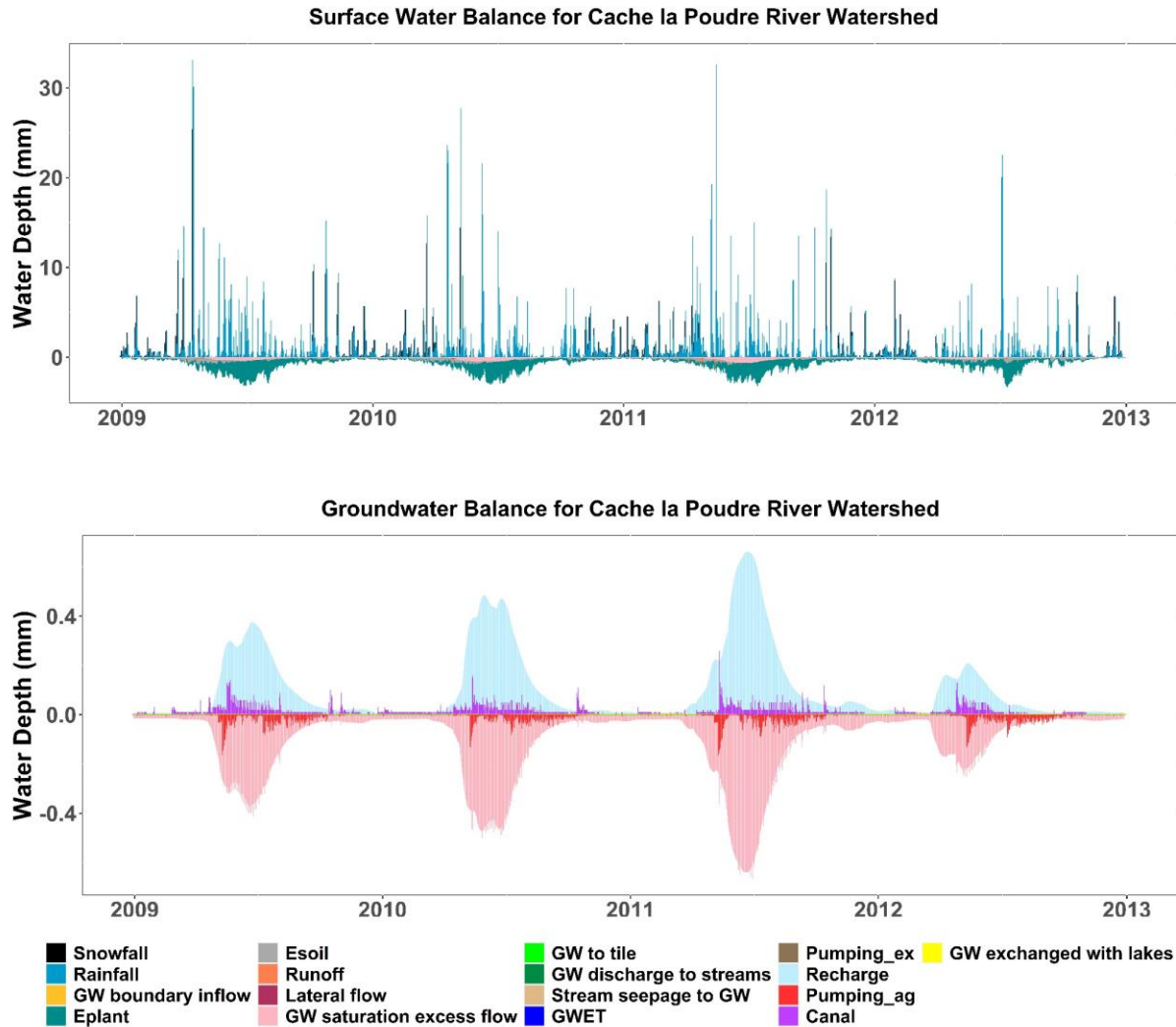
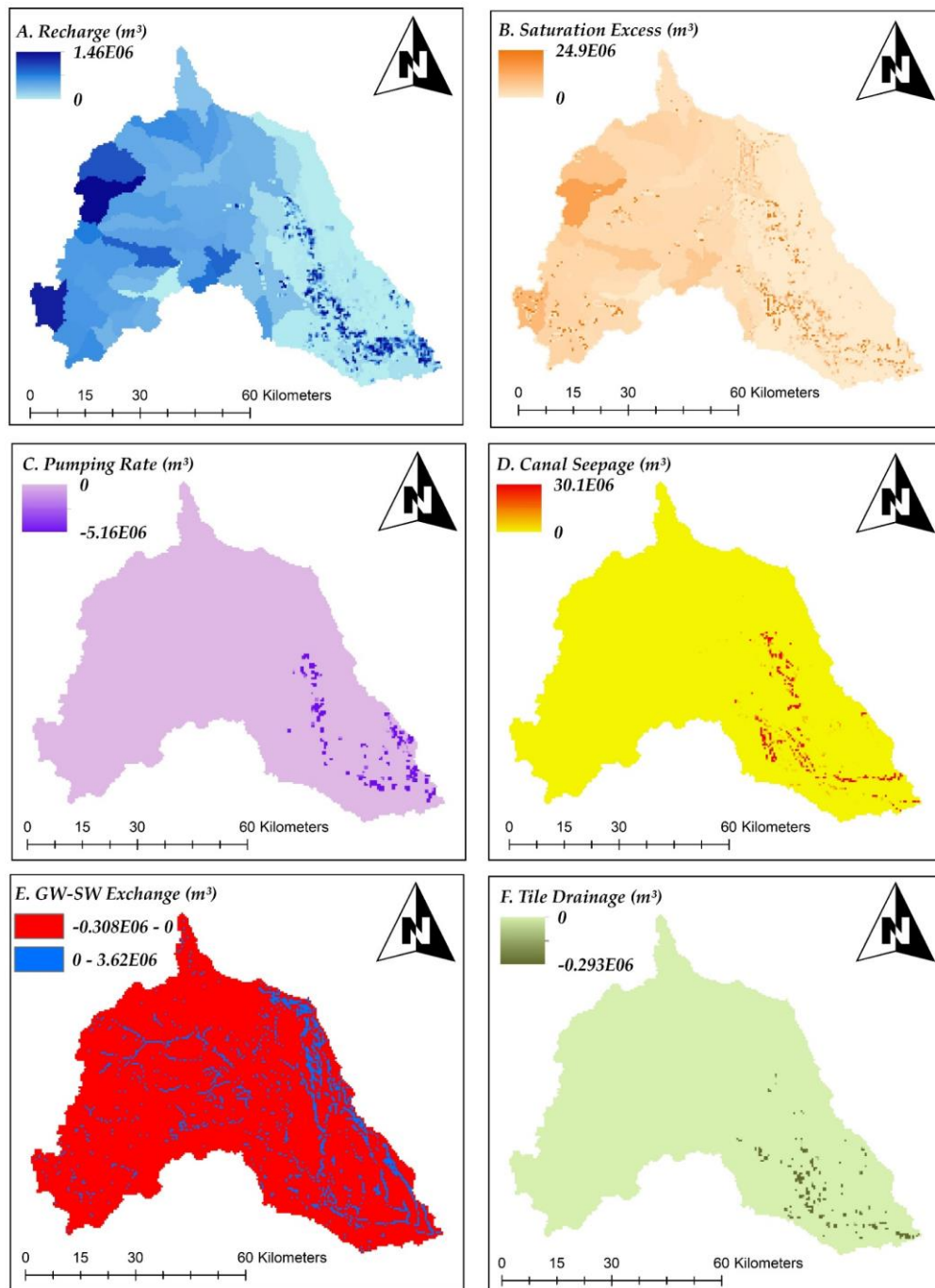


Figure 2.9. Daily surface water fluxes (mm) and groundwater fluxes (mm) for the period of 2009–2012.

Zones of stress within the aquifer system and regions of primary inputs into the stream channel system are shown on raster (cell-by-cell) maps (Figure 2.10) of total groundwater sink/source flow fluxes for the entire simulation period (2000-2015). They are used to illustrate spatial fluxes of recharge (Fig. 2.10A), groundwater saturation excess flow (Fig. 2.10B), groundwater pumping (Fig. 2.10C), canal seepage (Fig. 2.10D), groundwater (GW)-surface water (SW) exchange through the streambed (Fig. 2.10E), and tile drainage (Fig. 2.10F). Recharge occurs where sources of water are available such as snowmelt, streams and rivers, and irrigation. Recharge in the mountain subbasins is averaged over the extent of each subbasin,

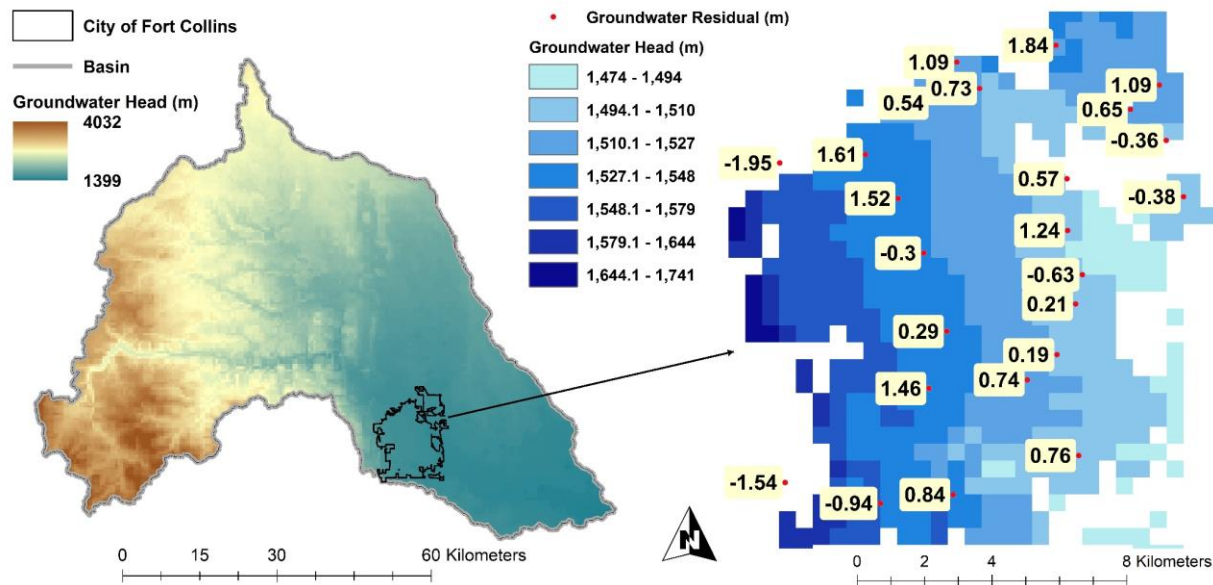
due to the lack of field boundaries. Saturation excess flow occurs in areas characterized by high groundwater levels when the soil is already saturated. Groundwater pumping occurs in areas of irrigation. Canal seepage occurs along the canals when groundwater level is lower than the canal bed. Groundwater-channel exchange takes place where surface water comes into direct contact with the underlying aquifer along riverbanks. Tile drainage removes excess water from the soil profile which ensures a stable and regulated environment for plant growth. These results demonstrate that the model is simulating specific groundwater inflows/outflows in the correct locations throughout the basin.



**Figure 2.10.** Maps of total groundwater fluxes ( $m^3$ ) for the entire watershed for the whole simulation period (2000-2015).

### 2.3.1.3 Groundwater Head

Simulated groundwater head (Figure 2.11) mimics the basin topography. For model testing, the available data of depth to groundwater table in 25 different locations in and around the city of Fort Collins (Figure 2.11) shows a good model performance ( $< 2$  m difference in groundwater head) between simulated and measured groundwater head (Almahawis, 2018) throughout the entire model simulation (2002-2015). The localized head map in Figure 11 indicates groundwater flow from east to west, towards the Cache la Poudre River, indicative of groundwater discharge and baseflow patterns in the region.



**Figure 2.11.** Maps of groundwater head (m) for the entire watershed and locations of measured groundwater residuals (m) for the simulation period (2002-2015)

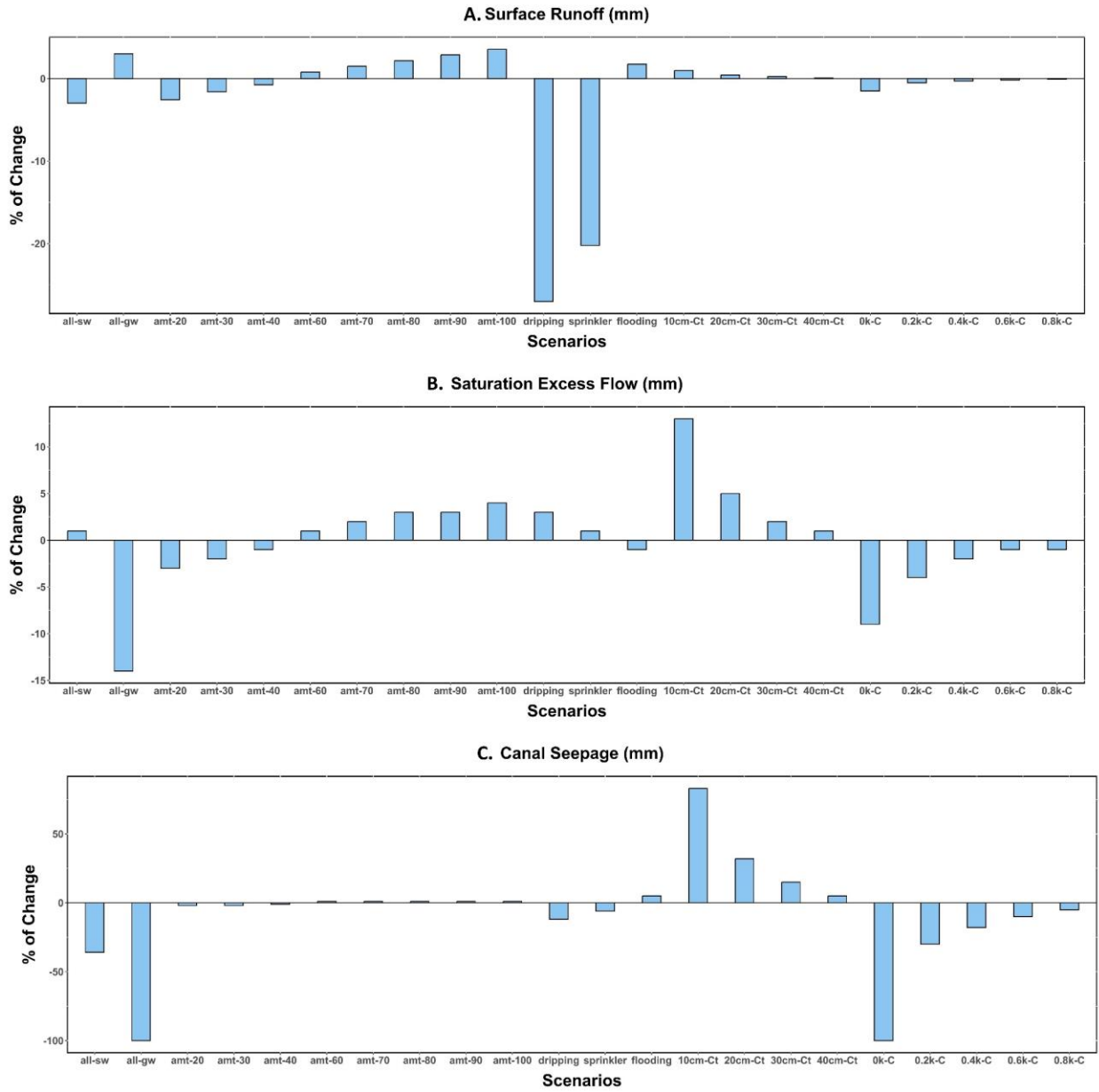
### 2.3.2 Impact of Irrigation Scenarios on Hydrologic Fluxes

The “base” scenario presented in this section refers to the calibrated and tested model simulation, as presented in Section 2.3.1. The base scenario has the following features: 50 mm irrigation amount, both surface and groundwater sources, sprinkler and flooding types of irrigation, and earthen canal conductivity based on soil type. Hydrologic fluxes are influenced by irrigation practices (Figure 2.12; Table 2.8). The use of groundwater as the only source for irrigation led to a 4% increase in surface runoff as seen in Figure

2.12A because there is more water available for irrigation in this scenario. The generation of runoff varies across different irrigation practices, such as sprinkler irrigation or drip irrigation where a 26% reduction is observed when using drip irrigation to minimize water losses. The augmentation of surface runoff has the potential to impact water inflow into streams and rivers. Soil lateral flow remained constant among all irrigation scenarios. The impact of irrigation scenarios on saturation excess flow depends on numerous factors, including the source of irrigation, the amount, the type of irrigation, canal bed thickness, and canal bed conductivity as seen in Figure 2.12B. As more water is used for irrigation, which in turn increases recharge volumes to the aquifer, more groundwater discharge to streams occurs due to higher groundwater levels in relation to stream stage. Canal sealing leads to a decrease in canal seepage recharge to the aquifer, resulting in a lowering of the regional water table (Figure 2.12C) and a subsequent decrease in groundwater discharge to streams (9% decrease, from 33.6 mm/yr in the baseline to 30.7 mm/yr in the full sealing scenario).

Wei and Bailey (2019) investigated the impact of reducing the amount of water used for irrigation in the Lower Arkansas River Valley using coupled SWAT-MODFLOW without including canal seepage. Their findings revealed that decreasing the amount of water used for irrigation results in a decrease in surface runoff and groundwater recharge. These findings are consistent with the results of this study. On the other hand, Ahmadzadeha et al. (2016) examined the effects of transitioning from a surface to a pressurized irrigation system using the base SWAT model without utilizing a physically based spatially distributed groundwater model, such as MODFLOW or *gwflo*w as done in this study. Based on their findings, transitioning from surface irrigation to pressured irrigation reduces the water needed for irrigation and hence decreases groundwater recharge. Additionally, Leng et al. (2017) found that the substantial volumes of water applied to the surface using flood irrigation can contribute to additional runoff, surpassing the amount simulated by drip and sprinkler watering techniques. In both studies, the higher the efficiency the lower the amount of water is needed for irrigation; however, in our simulation,

the same amount of water is used for irrigation regardless of the irrigation type. Farmers continue to use their full water allotment (a common practice in Colorado to avoid losing water rights). This explains why groundwater recharge increases and surface runoff decreases when using a more efficient irrigation technique.

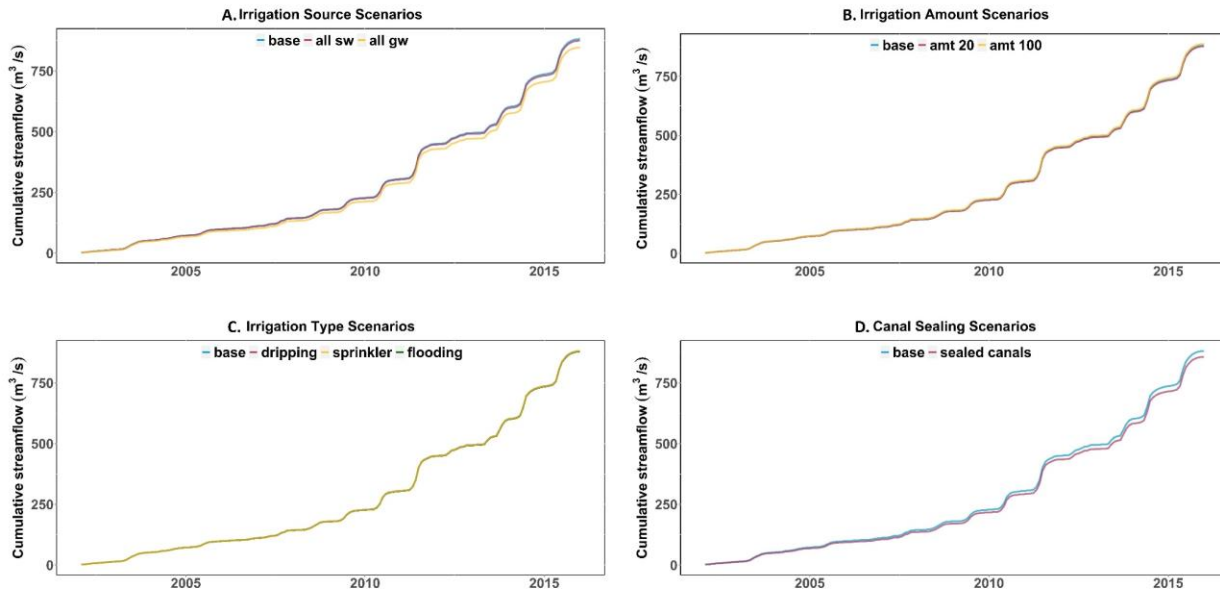


**Figure 2.12.** Basin annual average percent of change from the base scenario for (A) Surface Runoff; (B) Saturation Excess Flow; and (C) Canal Seepage.

**Table 2.8.** Average annual hydrologic fluxes (mm) for each scenario.

Hydrologic Flux (mm/yr)								
Scenario	Surface Runoff	Soil Lateral Flow	Groundwater Recharge	Saturation Excess Flow	Pumping	Tile Drainage	Canal Seepage	Surface Water Irrigation
Base	12.4	15.0	30.1	33.6	4.5	0.6	5.4	11.1
<b>Irrigation Source:</b>								
All Surface water	12.1	15.0	29.8	34.0	0.0	0.7	3.4	14.0
All Groundwater	12.9	15.0	31.3	29.0	17.8	0.2	0.0	0.0
<b>Irrigation Amount (mm):</b>								
20	12.1	15.0	28.7	32.8	4.0	0.6	5.3	10.0
30	12.2	15.0	29.2	33.0	4.2	0.6	5.3	10.4
40	12.3	15.0	29.6	33.3	4.4	0.6	5.3	10.8
60	12.5	15.0	30.6	33.9	4.7	0.6	5.4	11.4
70	12.6	15.0	31.0	34.2	4.8	0.6	5.4	11.7
80	12.7	15.0	31.4	34.5	4.9	0.6	5.5	12.0
90	12.8	15.0	31.8	34.7	5.0	0.6	5.4	12.3
100	12.9	15.0	32.2	35.0	5.2	0.6	5.4	12.6
<b>Irrigation Type:</b>								
Drip	9.1	15.0	31.7	34.8	3.5	0.7	4.8	13.9
Sprinkler	9.9	15.0	30.7	34.0	4.0	0.6	5.1	12.1
Flooding	12.7	15.0	29.4	33.1	5.0	0.6	5.7	9.4
<b>Canal Bed Thickness (cm):</b>								
10	12.6	15.0	30.2	38.1	4.6	0.6	9.8	11.7
20	12.5	15.0	30.2	35.3	4.6	0.6	7.1	11.3
30	12.5	15.0	30.1	34.4	4.5	0.6	6.2	11.2
40	12.5	15.0	30.1	33.9	4.5	0.6	5.7	11.1
<b>Canal Sealing:</b>								
Sealed Canals	12.3	15.0	29.9	30.7	3.9	0.4	0.0	10.8
80% Sealing	12.4	15.0	30.0	32.4	4.4	0.6	3.8	10.9
60% Sealing	12.4	15.0	30.1	32.8	4.5	0.6	4.4	10.9
40% Sealing	12.4	15.0	30.1	33.1	4.5	0.6	4.8	11.0
20% Sealing	12.4	15.0	30.1	33.4	4.5	0.6	5.1	11.1

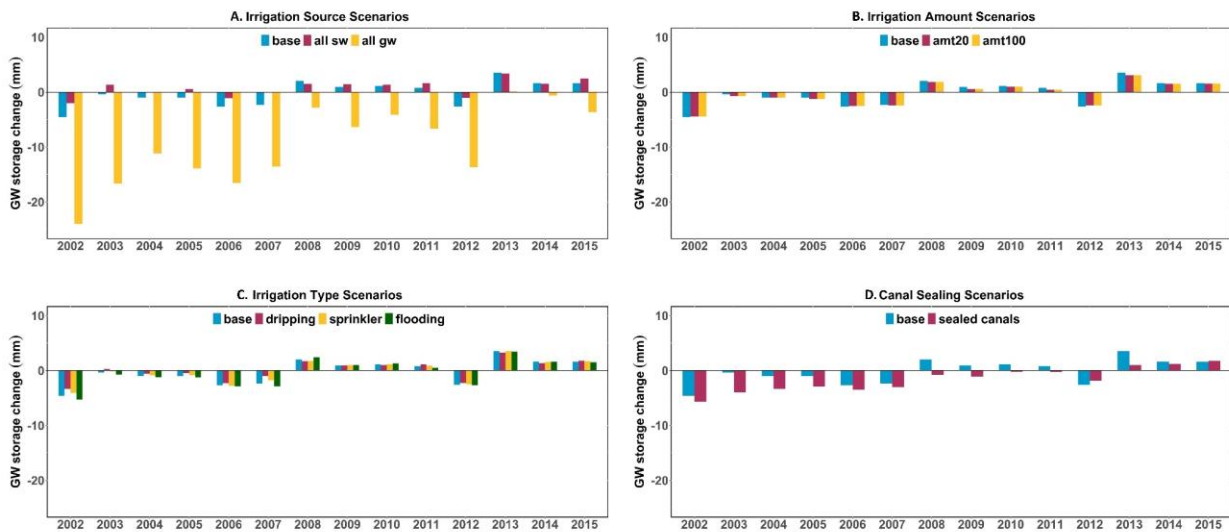
The source of water used for irrigation has notable effects on the streamflow. The recharge of aquifers is typically enhanced by surface water, whereas streams can receive discharge from groundwater. The excessive extraction of groundwater leads to a 2.5% reduction in streamflow as seen in Figure 2.13A. The amount of irrigation water applied has a noticeable impact on streamflow as seen in Figure 2.13B. A 3% increase in streamflow is seen when doubling the applied water depth for irrigation events (base vs 100 mm); however, the type of irrigation used has no impact on streamflow as per Figure 2.13C. Canal seepage can be a major source of recharge to the aquifer, which can increase groundwater head and thereby increase the amount of groundwater discharged to the stream. If the canals are sealed, then groundwater levels and associated groundwater discharge rates to the river decrease, resulting in an overall decrease of 6% in streamflow (Figure 2.13D).



**Figure 2.13.** Cumulative streamflow for four different scenario groups (A) Irrigation Source; (B) Irrigation Amount; (C) Irrigation Type; and (D) Canal Sealing at the USGS 06752280 gage.

### 2.3.3 Groundwater Storage

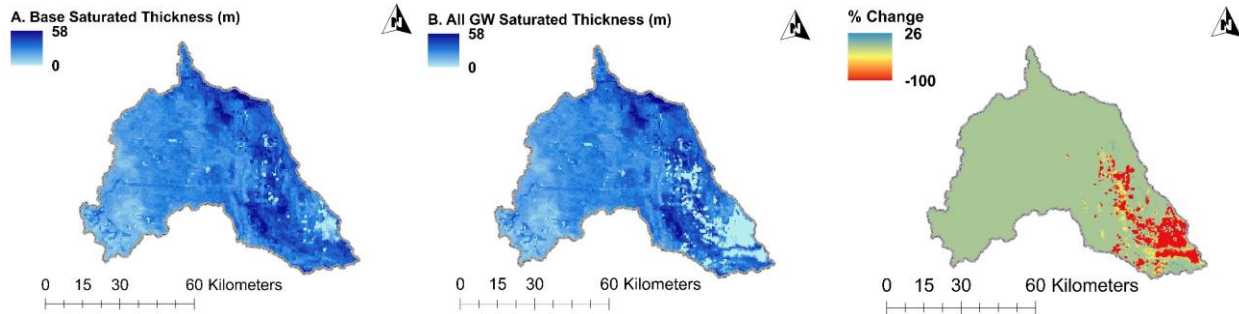
The assessment of groundwater storage is crucial for ensuring sustainable water management, adapting to climate change, and enhancing the well-being of people who depend on groundwater as a major water source, as is the case in CLP. Figure 2.14 presents the overall change in the amount of water stored in the shallow aquifer in the study region throughout the whole modeling period (2002-2015) for the most significant scenarios. As expected, the irrigation source has the largest impact on the storage when groundwater is used as the only source for irrigation as seen in Fig 2.14A, due to increased groundwater pumping. For example, the decrease in groundwater storage was 16 mm when groundwater was used as the only source for the year 2003. In contrast, a 1 mm increase in storage was seen when surface water was used as the only source of irrigation for the same year. Irrigation amount, irrigation type, and canal sealing have a less significant impact on groundwater storage.



**Figure 2.14.** Watershed average annual groundwater storage changes from the base scenario for (A) Irrigation Source; (B) Irrigation Amount; (C) Irrigation Type; and (D) Canal Sealing.

Figure 2.15 shows the decrease in the aquifer saturated thickness (m) when groundwater is used as the only source for irrigation for the whole period of simulation. Some areas have extreme decreases in groundwater head (45 m), particularly in areas of intensive crop production and hence groundwater

pumping. The unconfined aquifer system has been depleted in the same areas due to extensive pumping as seen in Figure 2.15C.



**Figure 2.15.** Maps of saturated thickness for the (A) base scenario; (B) groundwater as an only source for irrigation; and (C) the percent change in the aquifer thickness for the whole period of simulation.

## 2.4 Summary and Conclusions

In this chapter, a thorough methodology was employed to model hydrologic processes at the watershed scale in the Cache la Poudre River Basin, which is classified as a HUC8 watershed. The study employed a new groundwater modeling routine called the *gwflow* module, which is integrated within the SWAT+ watershed modeling system. This routine is characterized by its spatial distribution and physical basis. The daily water balance in the unconfined aquifer is calculated by employing a collection of connected grid cells, with each cell representing a volume of the unconfined aquifer. To explore the effect of irrigation practices, the SWAT+ modeling code was modified to include detailed, field-based surface water and groundwater irrigation practices as well as canal-groundwater exchange due to the extensive network of earthen canals.

The process of model calibration was conducted utilizing the PEST software, taking into consideration the observed data of stream flow and groundwater head. Cell-by-cell raster maps were utilized to validate the accuracy of hydrologic fluxes in a watershed by representing various groundwater fluxes such as canal seepage, recharge, saturation excess flow, tile drainage, pumping, and groundwater-surface water exchange. The model was subsequently employed to assess the quantitative effects of several irrigation

scenarios including surface water and groundwater on water availability and hydrologic fluxes within the river basin. A total set of 22 scenarios was carried out, encompassing five distinct categories: irrigation source, irrigation amount, irrigation type, canal bed thickness, and partial or full sealing of irrigation canals.

The following conclusions are drawn from the results:

1. Quantifying the impact of surface water and groundwater irrigation scenarios on water availability and hydrologic fluxes is important for water management. Irrigation source, irrigation amount, and irrigation type are essential for minimizing negative impacts and maximizing the benefits of irrigation practices.
2. The source of irrigation plays the biggest role among all factors impacting hydrologic fluxes.
3. The canal seepage was included in the SWAT+*gwflow* modeling code and the resulting canal seepage fluxes had an impact on the overall comprehensive hydrologic fluxes, a loss from the surface water system and an increased groundwater discharge. The inclusion of canal seepage in hydrologic models is crucial for enhancing the precision of hydrological simulations and plays a vital role in facilitating efficient water resource management and planning.
4. The findings from the Morris analysis demonstrate the significance of certain model parameters in governing the hydrological mechanisms at individual gage sites. The findings of this study provide valuable insights into the distinctive characteristics of the watershed, including the prevalence of snowmelt in mountainous parts and the impact of irrigation methods on streamflow in places with intensive agricultural irrigation. Gaining insight into these sensitivities has significant value in enhancing the precision of the distributed hydrologic model and in facilitating well-informed decision-making pertaining to water resource management within the watershed.

## References

- Ahmadzadeh, H., Morid, S., Delavar, M., & Srinivasan, R. (2016). Using the SWAT model to assess the impacts of changing irrigation from surface to pressurized systems on water productivity and water saving in the Zarrineh Rud catchment. *Agric. Water Manag.*, 175, 15-28. <https://doi.org/10.1016/j.agwat.2015.10.026>
- Aliyari, F., Bailey, R. T., Tasdighi, A., Dozier, A., Arabi, M., & Zeiler, K. (2019). Coupled SWAT-MODFLOW model for large-scale mixed agro-urban river basins. *Environ. Model. SoftW.*, 115, 200-210. <https://doi.org/10.1016/j.envsoft.2019.02.014>
- Almahawis, M. (2018). *Assessing Groundwater Storage and Groundwater Level Fluctuations in the Area of Fort Collins, Colorado* (Master Thesis, Colorado State University).
- Aouissi, J., Benabdallah, S., Chabaane, Z. L., & Cudennec, C. (2016). Evaluation of potential evapotranspiration assessment methods for hydrological modelling with SWAT – Application in data-scarce rural Tunisia. *Agric. Water Manag.*, 174, 39-51. <https://doi.org/10.1016/j.agwat.2016.03.004>
- Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: model development 1. *J. Am. Water Resour. As.*, 34(1), 73-89. <https://doi.org/10.1111/j.1752-1688.1998.tb05961.x>
- Arnold, J.G., White, M.J., Allen, P.M., Gassman, P.W. and Bieger, K., (2021). Conceptual framework of connectivity for a national agroecosystem model based on transport processes and management practices. *J. Am. Water Resour. As.*, 57(1), pp.154-169. <https://doi.org/10.1111/1752-1688.12890>
- Arnold, J.G., Youssef, M.A., Yen, H., White, M.J., Sheshukov, A.Y., Sadeghi, A.M., Moriasi, D.N., Steiner, J.L., Amatya, D.M., Skaggs, R.W., Haney, E.B., Jeong, J., Arabi, M., Gowda, P.H., (2015). Hydrological processes and model representation: impact of soft data on calibration. *Trans. ASABE*, 58, 1637–1660. <https://doi.org/10.13031/trans.58.10726>

- Bailey, R., Abbas, S., Arnold, J., White, M., Gao, J., and Čerkasova, N. (2023). Augmenting the national agroecosystem model with physically based spatially distributed groundwater modeling. *Environ. Model. SoftW.*, 160, 105589. <https://doi.org/10.1016/j.envsoft.2022.105589>
- Bailey, R., Bieger, K., Arnold, J., and Bosch, D. (2020). A new physically-based spatially-distributed groundwater flow module for SWAT+. *Hydrology*, 7(4), 75. <https://doi.org/10.3390/hydrology7040075>
- Bailey, R., Wible, T., Arabi, M., Records, R., and Ditty, J. (2016) Assessing regional-scale spatio-temporal patterns of groundwater–surface water interactions using a coupled SWAT-MODFLOW model. *Hydrol. Process.*, 30, 4420-4433. <https://doi.org/10.1002/hyp.10933>
- Barlow, P. M., & Leake, S. A. (2012). *Streamflow depletion by wells: understanding and managing the effects of groundwater pumping on streamflow* (Vol. 1376). Reston, VA: US Geological Survey.
- Bicknell, B., Imhoff, J., Kittle Jr, J., Donigian Jr, A., and Johanson, R. (1997). Hydrological simulation program—FORTRAN user’s manual for version 11. Environmental Protection Agency Report No. EPA/600/R-97/080. US Environmental Protection Agency, Athens, Ga.
- Bieger, K., Arnold, J., Rathjens, H., White, M., Bosch, D., Allen, P., *et al.* (2017). Introduction to SWAT+, a completely restructured version of the soil and water assessment tool. *J. Am. Water Resour. As.*, 53(1), 115-130. <https://doi.org/10.1111/1752-1688.12482>
- Brouziyne, Y., Abouabdillah, A., Bouabid, R., and Benaabidate, L. (2018). SWAT streamflow modeling for hydrological components’ understanding within an agro-sylvo-pastoral watershed in Morocco. *J. Mater. Environ. Sci*, 9(1), 128-138. <https://doi.org/10.26872/jmes.2018.9.1.16>
- Cao, J., Xie, Y., Chen, Z., and Zhang, G. (2002). Preliminary research on the seepage and transportation of irrigation water in the plain of main stream region of Heihe river Gansu province. *Hydrogeology and Engineering Geology*, 4, 1-4.
- Charley, W. (1995). The hydrologic modeling system (HEC-HMS): Design and development issues (No. 149). US Army Corps of Engineers, Hydrologic Engineering Center.

- Chen, Z., Nie, Z., Zhang, G., Wan, L., and Shen, J. (2006). Environmental isotopic study on the recharge and residence time of groundwater in the Heihe River Basin, northwestern China. *Hydrogeol J*, 14(8), 1635-1651. <https://doi.org/10.1007/s10040-006-0075-7>
- Cook, B.I., Ault, T.R., Smerdon, J.E., (2015). Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Sci. Adv.*, 1(1), e1400082. <https://doi.org/10.1126/sciadv.1400082>
- Custodio, E. (2002). Aquifer overexploitation: what does it mean?. *Hydrogeol J*, 10(2), 254-277. <https://doi.org/10.1007/s10040-002-0188-6>
- Dangol, S., Zhang, X., Liang, X. Z., and Miralles-Wilhelm, F. (2022). Agricultural Irrigation Effects on Hydrological Processes in the United States Northern High Plains Aquifer Simulated by the Coupled SWAT-MODFLOW System. *Water*, 14(12), 1938. <https://doi.org/10.3390/w14121938>
- Devia, G., Ganasri, B., and Dwarakish, G. (2015). A review on hydrological models. *Aquatic procedia*, 4, 1001-1007. <https://doi.org/10.1016/j.aqpro.2015.02.126>
- Dieter, C. A., M. A. Maupin, R. R. Caldwell, M. A. Harris, T. I. Ivahnenko, J. K. Lovelace, N. L. Barber and K. S. Linsey (2018). Estimated use of water in the United States in 2015. In: Circular. Report 1441, Reston, VA, p. 76.
- Doherty, J. (2020). PEST, Model-independent Parameter Estimation: User Manual (seventh ed.). *Watermark Numerical Computing, Brisbane, Australia*, 3338, 3349.
- FAO (2002). Crops and Drops: Making the Best Use of Water for Agriculture. FAO, Rome (November 24, 2022). <https://www.fao.org/3/Y3918E/Y3918E00.htm>
- Foy, C., Arabi, M., Yen, H., Gironás, J., & Bailey, R. T. (2015). Multisite assessment of hydrologic processes in snow-dominated mountainous river basins in Colorado using a watershed model. *Journal of Hydrologic Engineering*, 20(10), 04015017.

- Francesconi, W., Srinivasan, R., Pérez-Miñana, E., Willcock, S. P., and Quintero, M. (2016). Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: A systematic review. *J. Hydrol.*, 535, 625-636. <https://doi.org/10.1016/j.jhydrol.2016.01.034>
- Gao, F., Feng, G., Han, M., Dash, P., Jenkins, J., and Liu, C. (2019). Assessment of surface water resources in the big sunflower river watershed using coupled SWAT–MODFLOW model. *Water*, 11(3), 528. <https://doi.org/10.3390/w11030528>
- Gao, Q. Z. (1991). Development and utilization of water resources in the Heihe River catchment. Gansu Science and Technology Press, Lanzhou, 205.
- Gesch, D. B., Evans, G. A., Oimoen, M. J., & Arundel, S. (2018). The national elevation dataset (pp. 83–110). American society for photogrammetry and remote sensing.
- Graf, W. L. (2006). Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology*, 79(3-4), 336-360. <https://doi.org/10.1016/j.geomorph.2006.06.022>
- Hershey, L. A., and Schneider, P. A. (1964). Ground-water investigations in the lower Cache la Poudre River Basin, Colorado. US Government Printing Office.
- Horton, J.D., Juan, C.A.S, and Stoesser, D.B. (2017). The State Geologic Map Compilation (SGMC) Geodatabase of the conterminous United States: US Geological Survey data release. US Geol. Surv. <https://doi.org/10.3133/ds1052>
- Huang, C. S., Yang, T., & Yeh, H. D. (2018). Review of analytical models to stream depletion induced by pumping: Guide to model selection. *Journal of Hydrology*, 561, 277-285.
- Khokhar, T. (2017). Chart: Globally, 70% of freshwater is used for agriculture. *World Bank Data Blog*. <https://blogs.worldbank.org/opendata/chart-globally-70-freshwater-used-agriculture>
- Krysanova, V, Wechsung, F, Arnold, J, Srinivasan, R, and Williams, J. (2000). *SWIM (Soil and Water Integrated Model)*. Germany.

- Laflin, R., 2005. *Irrigation, Settlement, and Change on the Cache la Poudre River*. Special Report Number 15, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado, 172 pp.
- Leng, G., Leung, L. R., & Huang, M. (2017). Significant impacts of irrigation water sources and methods on modeling irrigation effects in the ACME L and Model. *J. Adv. Model. Earth Syst.*, 9(3), 1665-1683. <https://doi.org/10.1002/2016MS000885>
- Luan, X., Wu, P., Sun, S., Wang, Y., and Gao, X. (2018). Quantitative study of the crop production water footprint using the SWAT model. *Ecol. Indic.*, 89, 1-10. <https://doi.org/10.1016/j.ecolind.2018.01.046>
- Mirchi, A., Watkins Jr, D., and Madani, K., (2010). Modeling for Watershed Planning, Management, and Decision Making. *Watersheds: Management, Restoration and Environmental Impact*. Nova Science Publishers, Hauppauge, NY, USA.
- Moore, R. B., and T. G. Dewald, 2016. The Road to NHDPlus - Advancements in Digital Stream Networks and Associated Catchments. *J. Am. Water Resour. As.*, 52, 890-900. <https://doi.org/10.1111/1752-1688.12389>
- Niemann, J. D., Lehman, B. M., Gates, T. K., Hallberg, N. U., and Elhaddad, A. (2011). Impact of shallow groundwater on evapotranspiration losses from uncultivated land in an irrigated river valley. *J. Irrig. Drain. Eng.*, 137(8), 501-512. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000356](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000356)
- Reitz, M., Sanford, W.E., Senay, G.B. and Cazenias, J., (2017). Annual estimates of recharge, quick-flow runoff, and evapotranspiration for the contiguous US using empirical regression equations. *J Am Water Resour As*, 53(4), pp.961-983. <https://doi.org/10.1111/1752-1688.12546>
- Saccon, P. (2018). Water for agriculture, irrigation management. *Applied soil ecology*, 123, 793-796. <https://doi.org/10.1016/j.apsoil.2017.10.037>

- Samimi, M., Mirchi, A., Moriasi, D., Ahn, S., Alian, S., Taghvaeian, S., and Sheng, Z. (2020). Modeling arid/semi-arid irrigated agricultural watersheds with SWAT: Applications, challenges, and solution strategies. *J. Hydrol.*, 590, 125418. <https://doi.org/10.1016/j.jhydrol.2020.125418>
- Schoumans, O., Silgram, M., Walvoort, D., Groenendijk, P., Bouraoui, F., Andersen, H., *et al.* (2009). Evaluation of the difference of eight model applications to assess diffuse annual nutrient losses from agricultural land. *J. Environ Monitor*, 11(3), 540-553. <https://doi.org/10.1039/B823240G>
- Shaabani, M. K., Abedi-Koupai, J., Eslamian, S. S., and Gohari, A. (2023). Simulation of the effects of climate change and reduce irrigation requirements on groundwater recharge using SWAT and MODFLOW models. *Model. Earth Syst. Environ.* 9, 1681–1693. <https://doi.org/10.1007/s40808-022-01580-7>
- Shangguan, W., Hengl, T., Mendes de Jesus, J., Yuan, H. and Dai, Y. (2016). Mapping the global depth to bedrock for land surface modeling. *J. Adv. Model. Earth Syst.*, 9(1), pp.65-88. <https://doi.org/10.1002/2016MS000686>
- Skinner, K.D. and Maupin, M.A. (2019). Point-source nutrient loads to streams of the conterminous United States, 2012 (No. 1101). US Geological Survey. <https://doi.org/10.3133/ds1101>
- Smith, R. E., Goodrich, D. C., Woolhiser, D. A., and Unkrich, C. L. (1995). KINEROS-a kinematic runoff and erosion model. *Computer models of watershed hydrology.*, 697-732.
- Soil Survey Staff (2014). Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. edited by United States Department of Agriculture.
- Tarawneh, E., Bridge, J., and Macdonald, N. (2016). A pre-calibration approach to select optimum inputs for hydrological models in data-scarce regions. *Hydrol Earth Syst Sci.*, 20(10), 4391-4407. <https://doi.org/10.5194/hess-20-4391-2016>
- United States Department of Agriculture, Natural Resources Conservation Service USDA-NRCS. (2023). SNOTEL Data: Snowpack and Precipitation Update. Retrieved from <https://nwcc-apps.sc.egov.usda.gov/imap/>

- Valayamkunnath, P., Barlage, M., Chen, F., Gochis, D.J. and Franz, K.J., (2020). Mapping of 30-meter resolution tile-drained croplands using a geospatial modeling approach. *Scientific data*, 7(1), pp.1-10. <https://doi.org/10.1038/s41597-020-00596-x>
- Wei, X., and Bailey, R. T. (2019). Assessment of system responses in intensively irrigated stream–aquifer systems using SWAT-MODFLOW. *Water*, 11(8), 1576. <https://doi.org/10.3390/w11081576>
- White, J., Hunt, R., Fienen, M., and Doherty, J. (2020). Approaches to Highly Parameterized Inversion: PEST++ Version 5, a Software Suite for Parameter Estimation, Uncertainty Analysis, Management Optimization and Sensitivity Analysis: U.S. Geological Survey Techniques and Methods 7C26, 52 p., <https://doi.org/10.3133/tm7C26>
- White, M. J., Arnold, J. G., Bieger, K., Allen, P. M., Gao, J., Čerkasova, N., *et al.* (2022). Development of a Field Scale SWAT+ Modeling Framework for the Contiguous U.S. *J. Am. Water Resour. Assoc.*, 58(6), 1545-1560. <https://doi.org/10.1111/1752-1688.13056>
- Worqlul, A. W., Ayana, E. K., Yen, H., Jeong, J., MacAlister, C., Taylor, R., *et al.* (2018). Evaluating hydrologic responses to soil characteristics using SWAT model in a paired-watersheds in the Upper Blue Nile Basin. *Catena*, 163, 332-341. <https://doi.org/10.1016/j.catena.2017.12.040>
- Yan, L., and Roy, D. (2016). Conterminous United States crop field size quantification from multi-temporal Landsat data, *Remote Sens. Environ.*, 172, pp. 67-86. <https://doi.org/10.1016/j.rse.2015.10.034>
- Young, R. A., Onstad, C. A., Bosch, D. D., & Anderson, W. P. (1989). AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *J Soil Water Conserv.*, 44(2), 168-173.

## CHAPTER 3 - Climate Change Impact on Hydrologic Fluxes Under Different Irrigation Scenarios in a Highly Managed Basin

### 3.1 Introduction

Understanding the movement of water in an irrigated, highly-managed landscape is essential for effective water resources planning and management (Singh, 2024). Hydrologic pathways include irrigation diversions into canals, field runoff, infiltration, crop evapotranspiration, recharge to the aquifer, groundwater flow, groundwater discharge to streams, subsurface tile drainage outflow to streams, and streamflow. The volumetric flow rate along these pathways changes in space and time, based on weather patterns, water management, and local water rights. These changes can be intensified over time due to changing climate (temperature, rainfall, windspeed), particularly for semi-arid and arid regions. Water management strategies should include an estimate of how a changing climate will affect water movement and fluxes in irrigated river basins.

Due to the uncertain nature of a future state of climate and therefore the need for prediction, hydrologic models often are used to estimate the impact of climate change on water supply (e.g., Hagemann et al., 2013; Li and Fang, 2021). Models can be used to differentiate the impact of climate change on water use for irrigation to provide a better understanding of the watershed behavior and proper management of resources. In the literature, several models were made for groundwater resource management from the perspective of irrigation management and climate change, either individually or simultaneously. These include the Catchment Hydrology Model (CATHY) (e.g., Sulis et al., 2011), MIKE SHE (e.g., Vansteenkiste et al., 2012), Parallel Flow model (ParFlow) (e.g., Ferguson et al., 2012), GSFLOW (e.g., Deen et al. 2023), HydroGeoSphere (e.g., Persaud et al., 2020), and SWAT-MODFLOW (e.g., Abbas et al., 2022; Liu et al., 2020; Aliyari et al., 2021).

Aliyari et al. (2021) examined the impact of climate change on water availability and crop productivity in the semi-arid South Platte River Basin in Colorado, USA. The research employs the coupled SWAT-MODFLOW modeling code to simulate hydrologic conditions. It evaluated five distinct CMIP5 climate models, each representing two emission scenarios (RCP4.5 and RCP8.5), spanning the period from 1980 to 2100. The model incorporates surface runoff, soil lateral flow, groundwater flow, interactions between groundwater and surface water, irrigation, and agricultural output. The results revealed an increase of 3 to 5°C in temperature and varied precipitation changes influenced by topography. These findings show that a large river basin's water and food supplies are significantly impacted by climate change, highlighting the immediate need to put conservation practices into place.

Samimi et al. (2022) undertook a rigorous analysis of water availability for an irrigated agricultural watershed in the Rio Grande Basin in USA, using the Soil and Water Assessment Tool (SWAT) to investigate consequences under future climate conditions anticipated to 2099. A total number of 97 downscaled, bias corrected global climate models were chosen to represent wide range prospective dry and wet conditions compared to average historical flows in the river. The results show that reservoir storage is becoming less reliable for supporting irrigated agriculture, implying a greater reliance on groundwater. This trend may require the consumption of saline groundwater sources as the basin's fresh groundwater supplies decrease outstanding to expected hotter and drier weather, paired with current land and water management practices.

Ou et al. (2018) used a regression model to evaluate the influence of climate change on irrigation and the accessibility of groundwater in the US High Plains aquifer. The study specifically concentrated on the Nebraska-Colorado-Kansas region within the Republican River Basin. A groundwater flow model using MODFLOW is constructed to simulate the effects of different climate forcings on groundwater. The downscaled global climate models from 32 model outputs, to predict changes in irrigation requirements

by considering expected fluctuations in temperature and precipitation. The study quantifies variations in precipitation recharge and modifies irrigation-recharge rates accordingly. The results show that heightened groundwater pumping is likely to worsen the decline in groundwater levels, particularly in areas that are already experiencing a decrease due to irrigation.

Orkodjo et al. (2022) performed a thorough evaluation of the effects of climate change on water availability in the Omo-Gibe Basin, with a specific focus on the consequences for irrigation and hydroelectric power production. The study employed the SWAT and WEAP models to forecast substantial declines in streamflow and water availability across three future timeframes, aggravated by increasing temperatures in both RCP4.5 and RCP8.5 scenarios. The research emphasizes the possibility of a rise in water shortage, especially during the crucial hot and dry season. It also emphasizes the importance of implementing strong water management methods to reduce the negative impacts of climate change.

To the best of our knowledge, there was no study that used a holistic coupled surface and groundwater model to assess the impact of climate change on fluxes considering different irrigation practices. Therefore, in this study, we use a hydrologic modeling approach to quantify the impact of future climate on irrigation-related hydrologic fluxes in a semi-arid river basin. We use the Cache la Poudre Basin (Colorado, USA) as a demonstration case. The selected model is SWAT+ (Bieger et al., 2017), with the *gwflow* module used for simulating groundwater storage, groundwater flow, and groundwater interaction with land surface and surface water features. The model has been calibrated and tested against streamflow and groundwater levels (Almahawis et al., 2024), and will now be used for assessing climate change impacts.

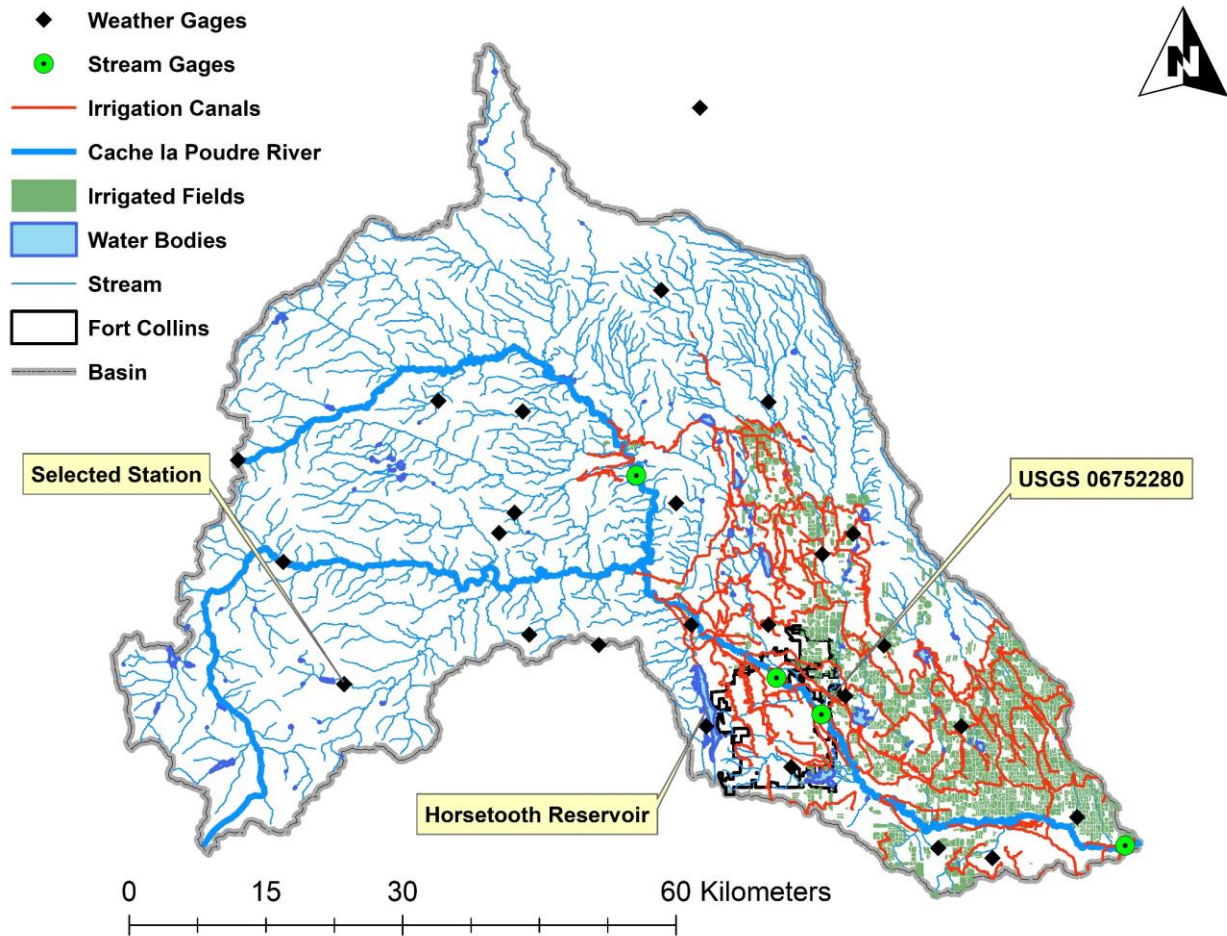
The impacts of potential future agricultural water management practices require intense investigation to understand their effectiveness and possible unintended outcomes. This study incorporated a thorough examination of irrigation practices and canal seepage under different climate models. This comprehensive investigation examined multiple irrigation practices, encompassing the source, type, and amount of

irrigation water utilized. In addition, various land use scenarios were examined using different climate models. This technique provided a thorough understanding of the effects of various irrigation practices and climate conditions on water availability.

## **3.2 Materials and Methods**

### **3.2.1 SWAT+*gflow* hydrologic simulation tool**

This chapter utilizes the modeling system of SWAT+*gflow*, as discussed in Chapter 2, to assess the effects of climate extremes on hydrologic fluxes in the Cache la Poudre River basin. An enhanced version of SWAT+*gflow*, calibrated and tested against historical groundwater levels and monthly streamflow at several stream gages along the Cache la Poudre River, was presented by Almahawis et al. (2024). The model includes detailed irrigation (e.g., irrigation source, irrigation type, etc.) as well as canal seepage, both essential parts of the hydrologic system of the river basin.



**Figure 3.1.** Model details for the Cache la Poudre River Basin, revealing the location of streams, water bodies, weather stations, river gages, city of Fort Collins, irrigated fields, and irrigation canals.

### 3.2.2 Future Climate in CLP

The tested SWAT+*gwflow* model for the CLP is used in this study with projected climate data to quantify the impact of climate extremes on hydrologic fluxes from 2024 to 2059. Global Climate Models (GCMs) are primary tools for predicting precipitation and temperature. However, their application in local areas is limited by their coarse spatial resolution (Larocque et al., 2019). The Multivariate Adaptive Constructed Analogs (MACA) method, developed by Abatzoglou and Brown (2012), is a statistically downscaled climate model technique used for the contiguous United States and is important in areas characterized by

significant spatial climatic variability (Larocque et al., 2019), such as the CLP. It establishes a connection between GCM outputs and local meteorological variables. This approach increases the resolution of the outputs from the twenty Coupled Model Inter-Comparison Project Phase 5 (CMIP5) GCMs to either 4 or 6 km for two future Representative Concentration Pathways (RCP4.5 and RCP8.5) scenarios spanning the years 2006 to 2100.

The RCPs describe the possible future levels of greenhouse gas and CO<sub>2</sub> emissions. The classification of these scenarios is based on the intended level of radiative forcing by the year 2100. The RCP4.5 scenario is viewed as moderate and optimistic, while the RCP8.5 scenario is considered pessimistic (Hayhoe et al., 2017). Five different GCM models were used in this study as presented in Table 3.1. To account for future variations, RCP 4.5 and RCP 8.5 for each model were included in the analysis. The climate models chosen are commonly used GCMs that represent a range of temperature and precipitation projections. These include the least warm, hottest, driest, wettest, and a moderate projection that represents the average variability in temperature and precipitation projected by all other models at a regional scale. These same models were applied to a hydrologic modeling study of the South Platte River Basin by Aliyari et al. (2021).

**Table 3.1.** GCM models used in this study

GCM	Description	Country	Agency
CNRM-CM5	Wet	France	National Center of Meteorological Research (Voldoire et al., 2013)
IPSL-CM5A-MR	Dry	France	Institute Pierre Simon Laplace (Dufresne et al., 2013)
HadGEM2-ES365	Hot	United Kingdom	Hadley Center (Collins et al., 2008)
MRI-CGCM3	Warm	Japan	Meteorological Research Institute (Yukimoto et al., 2012)
NorESM1-M	Mild	Norway	Norwegian Climate Center (Bentsen et al., 2013)

### 3.2.3 Quantifying the impact of Climate Change on Transboundary Water Sources

The city of Fort Collins, the main urban area within the CLP river basin, receives municipal water from the CLP and Horsetooth Reservoir, with the latter located just west of Fort Collins, Colorado (see Figure 3.1). Almost all the water in Horsetooth Reservoir is sourced from the Colorado-Big Thompson Project, which

is delivered through the Hansen Feeder Canal (City of Fort Collins Utilities, 2010). The diversion record from the canal to the reservoir will be investigated to assess the impact of climate change in the originating watershed (the Upper Colorado Headwaters watershed) on the amount of water delivered, the original water is from the west slope collection system (Northern Water, 2022).

Despite the variability in historical climate conditions (see Figure 3.2), the transboundary water source feeding into the watershed has remained at a remarkably constant discharge over the historical period analyzed as seen in Figure 3.2. Also, The R-squared value between the discharge to Horsetooth Reservoir and the Upper Colorado Headwaters watershed (source of Horsetooth Reservoir water, through the Colorado Big Thompson project) weather data, precipitation and temperature, is very low (close to 0) as shown in Figure 3.3, indicating that there is no significant correlation between them. This indicates the presence of regulated water management practices and agreements regardless of climate change. As a result, average historical Hansen Canal flow rates from Horsetooth Reservoir to Cache la Poudre River were used for future simulations.

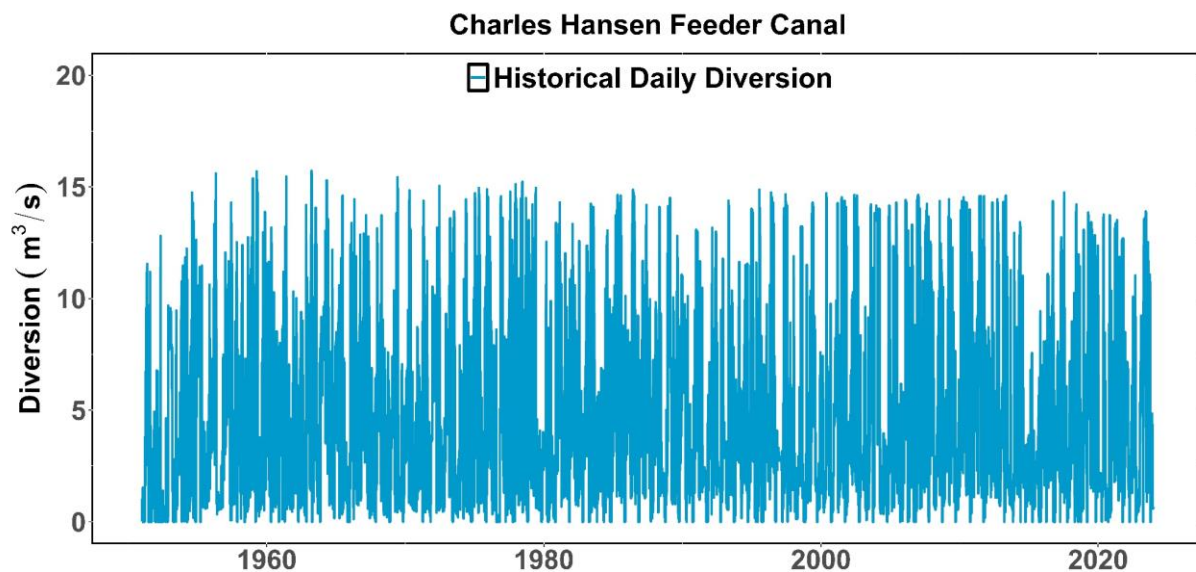
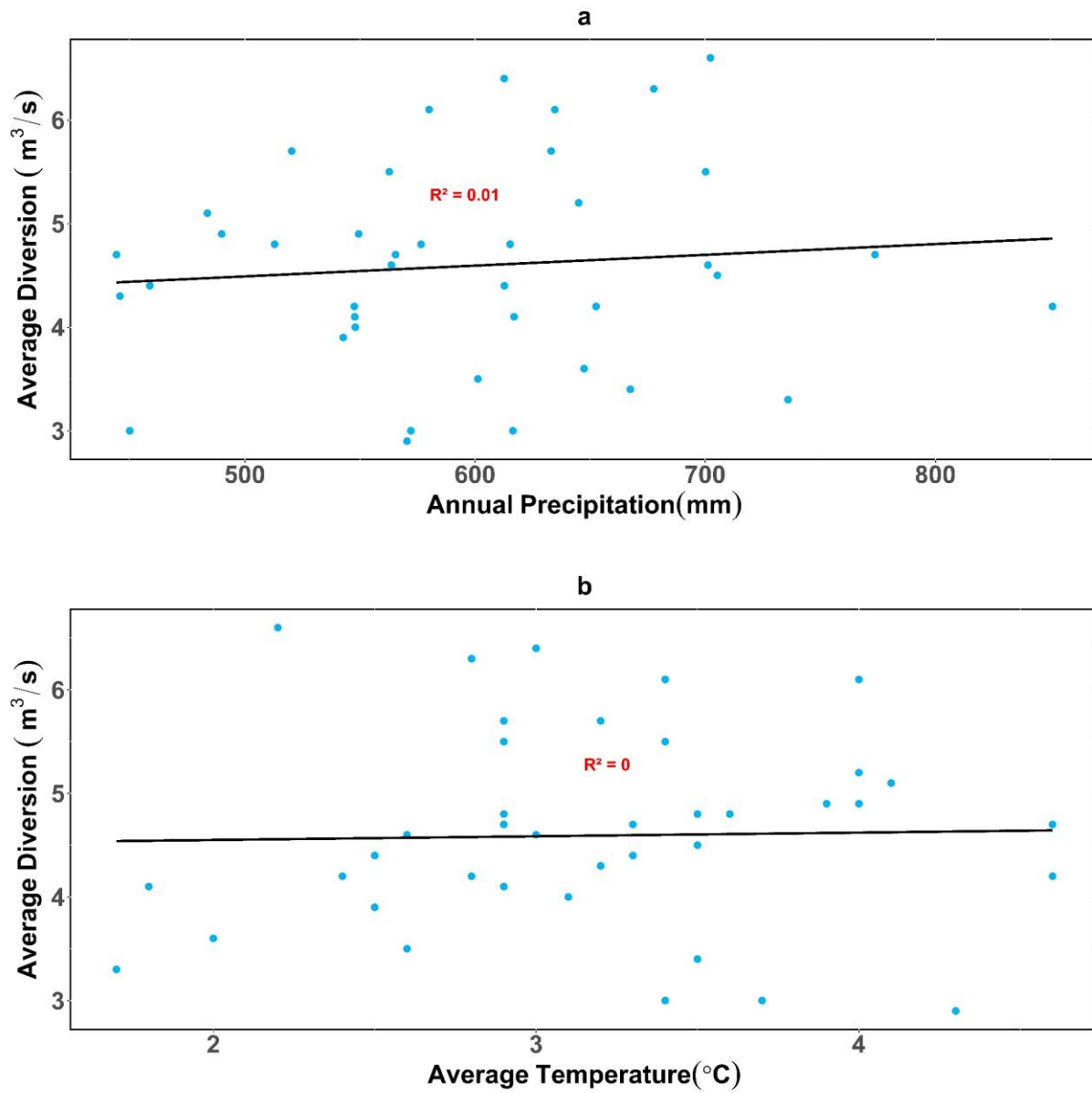


Figure 3.2. Diversion records for the Horsetooth reservoir through Charles Hansen Feeder Canal.



**Figure 3.3.** Relationship between the average annual canal diversion ( $m^3/s$ ) of the Charles Hansen Canal to Horsetooth and (a) the average annual precipitation (mm) at the Upper Colorado Headwaters watershed and (b) the average annual temperature ( $^{\circ}C$ ) at the Upper Colorado Headwaters watershed.

### **3.2.4 Quantifying the impact of irrigation practices on hydrologic fluxes considering various climate patterns**

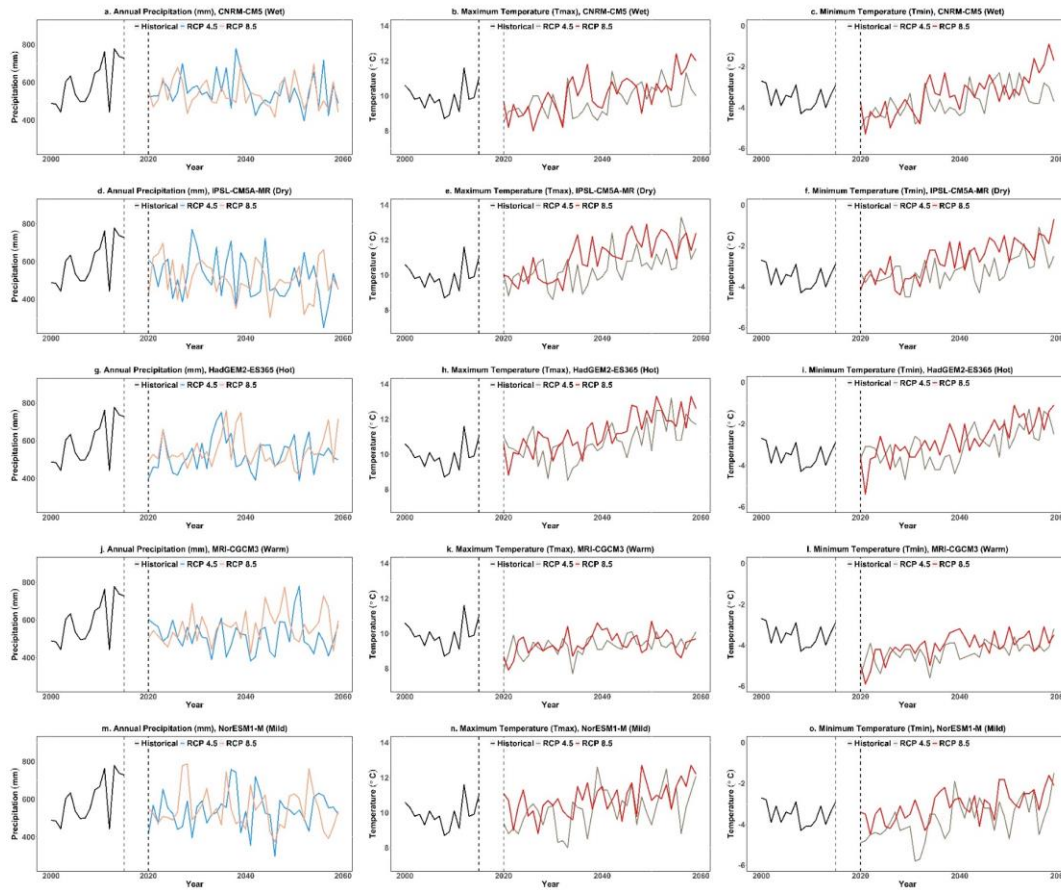
The SWAT+*gwflow* model was used to investigate the impact of irrigation practices on hydrologic fluxes within the CLP Basin, under a variety of future climates. Changes to hydrologic fluxes can arise because of alteration in irrigation, and understanding the implications of various irrigation scenarios on hydrologic flow is essential for the sustainable management of water resources. In this chapter, the following scenarios are considered:

1. Irrigation practices continue to be the same as during historical periods, base scenario as described in chapter 2.
2. Surface water irrigation is the only method of irrigation.
3. Groundwater irrigation is the only method of irrigation.
4. Conversion from irrigated land to dry land (i.e., water transfer from agricultural to urban areas).
5. The amount of water applied for irrigation has doubled (100 mm).

## **3.3 Results and Discussion**

### **3.3.1 Overview of future climate in the CLP**

The effects of climate change on the overall amount of annual precipitation and the average maximum/minimum temperatures for each year are illustrated in Fig 3.4. Figure 3.4 displays the precipitation patterns, maximum and minimum temperatures for several climate models and scenarios (RCP 4.5 and RCP 8.5), together with historical data (2000-2015). The data is specific to a chosen weather station, as shown in Fig. 3.1. The station was chosen from a mountainous region and is used in the model for 10 different subbasins.



**Figure 3.4.** Historical and projected total average annual precipitation (left column), historical and projected average maximum temperature (middle column), and historical and projected average minimum temperature (right column) for the five GCMs for a selected weather station (see Figure 3.1).

An increase in precipitation rate is seen in the CNRM-CM5 (Wet) and NorESM1-M (Mild) models, as shown in Figure 3.4a and Figure 3.4m, respectively. The maximum increasing rate from the climate normal (467.5 mm) is equal to 6.1% under the RCP8.5 scenario for the NorESM1-M (Mild) model. The findings align with the earlier research conducted in Colorado (Christensen et al., 2004). In contrast, the IPSL-CM5A-MR (Dry) model shows a maximum decreasing rate of 7.2% from the climate normal under the RCP8.5 scenario as shown in Table 3.2.

All climate models, regardless of emission scenarios, forecast a rise in the average annual temperature except for CGCM3 (Warm) model. This finding is consistent with prior research conducted in this area (Lukas et al., 2014; Aliyari et al., 2021). Temperatures are expected to rise steadily over the next 45 years. As predicted and based on the charts in Fig. 3.4 and Table 3.4, temperature rises are larger in the RCP8.5 scenarios for all GCMs. The HadGEM2-ES365 (Hot), RCP8.5 model shows the maximum increase in average annual temperature (2 °C) in the CLP from the climate normal temperate ( $T_{max}= 11.3\text{ }^{\circ}\text{C}$  and  $T_{min}= -2.7\text{ }^{\circ}\text{C}$ ) by the year 2059.

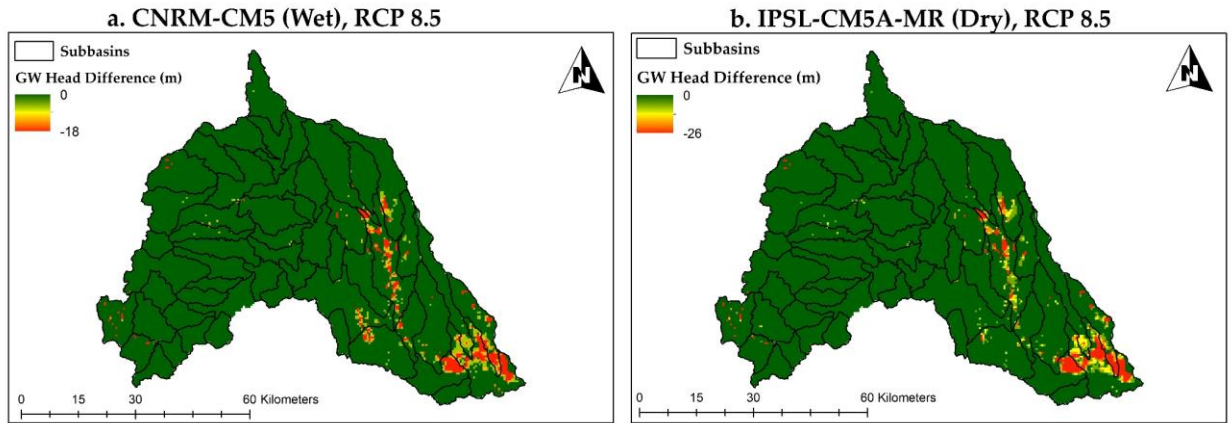
**Table 3.2.** Change from annual average historical climate (Precipitation = 467.5 mm,  $T_{max}= 9.9\text{ }^{\circ}\text{C}$ ,  $T_{min}= -3.5^{\circ}\text{C}$ ).

Climate Scenario	Precipitation (mm)	Maximum Temperature (°C)	Minimum Temperature (°C)
CNRM-CM5 (Wet)			
RCP 4.5	+20.3	-0.2	+0.2
RCP 8.5	+7.5	+0.2	-0.2
IPSL-CM5A-MR (Dry)			
RCP 4.5	-23.2	+0.5	+0.3
RCP 8.5	-33.7	+1.1	+0.9
HadGEM2-ES365 (Hot)			
RCP 4.5	-5	+0.8	+0.4
RCP 8.5	+10.2	+1.4	+0.8
MRI-CGCM3 (Warm)			
RCP 4.5	-28.6	-0.6	-0.9
RCP 8.5	+28.3	-0.5	-0.5
NorESM1-M (Mild)			
RCP 4.5	+16.4	+0.3	-0.3
RCP 8.5	+4.2	+0.9	+0.4

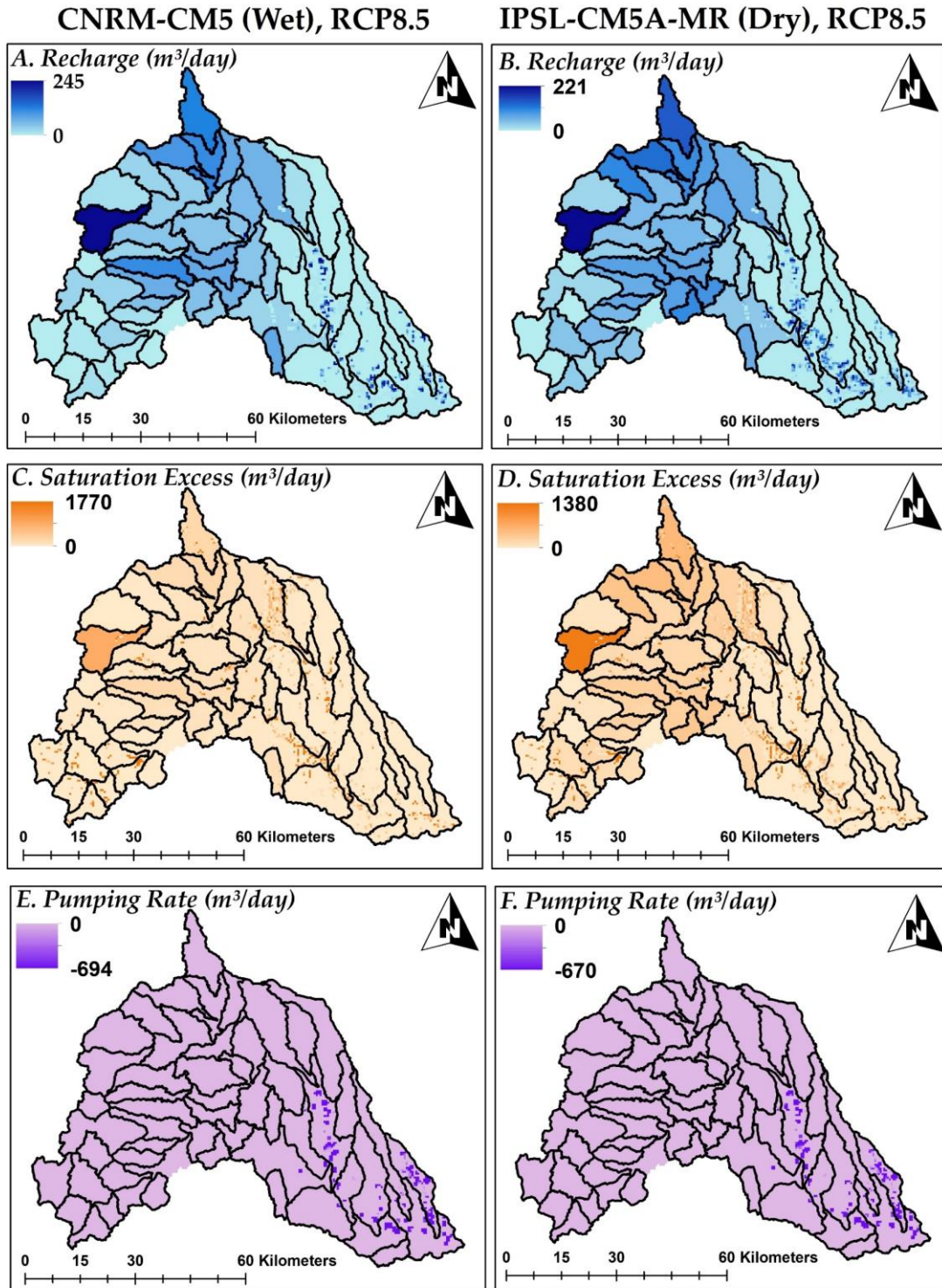
### 3.3.2 Impact of Future Climate Variation on Hydrologic Fluxes for the Base Scenario

The "base" scenario discussed in this section refers to the model simulation that has been calibrated and tested, as outlined in Chapter 2. The base scenario has the following characteristics: The irrigation amount

is 50 mm, and it is sourced from both surface and groundwater sources. The irrigation methods used include sprinkler and flooding. The conductivity of the earthen canal is determined based on the soil type. Changes in the climate affect hydrologic fluxes (Table 3.3). Runoff generation differs among several climate scenarios, such as IPSL-CM5A-MR (Dry) or NorESM1-M (Mild), with a 48% decrease observed under the IPSL-CM5A-MR (Dry) RCP 8.5 scenario. A general decrease in surface runoff and soil lateral flow among all scenarios is seen as well as increased surface ET due to increasing temperature as seen in Table 3.3. Groundwater recharge and saturation excess flow varies for each climate model where generally increased amount of precipitation results in increased recharge to water table and saturation excess flow as shown in Figure 3.6 and Table 3.3. The maximum increase in groundwater recharge and saturation excess flow was observed under the CNRM-CM5 (Wet), RCP 8.5 scenario, at 26% and 23%, respectively. Saturation excess flow decreases during the dry simulations, due to a decrease in the water table (10% decrease under IPSL-CM5A-MR (Dry), RCP 8.5 scenario). Figure 3.5.a shows a drop in the groundwater table despite an overall increase in groundwater recharge (9%), as seen in Table 3.3, due to increased surface ET (+5%). A larger decrease in the groundwater table is observed in Figure 3.5.b for the dry scenario, attributed to decreased recharge (11%) and a higher pumping rate, as shown in Table 3.3 and Figure 3.6. The amount of water applied for irrigation decreased among all scenarios due to increased temperature and surface ET and as a result decreased surface runoff and water table.



**Figure 3.5.** The drop in groundwater head for (a) CNRM-CM5, RCP8.5 (Wet) scenario and (b) IPSL-CM5A-MR, RCP8.5 (Dry) from historical levels.



**Figure 3.6.** Maps of groundwater flux rates ( $m^3/day$ ) for the entire watershed over the simulation period (2024-2059) under the CNRM-CM5, RCP8.5 (Wet) scenario and the IPSL-CM5A-MR, RCP8.5 (Dry) scenario.

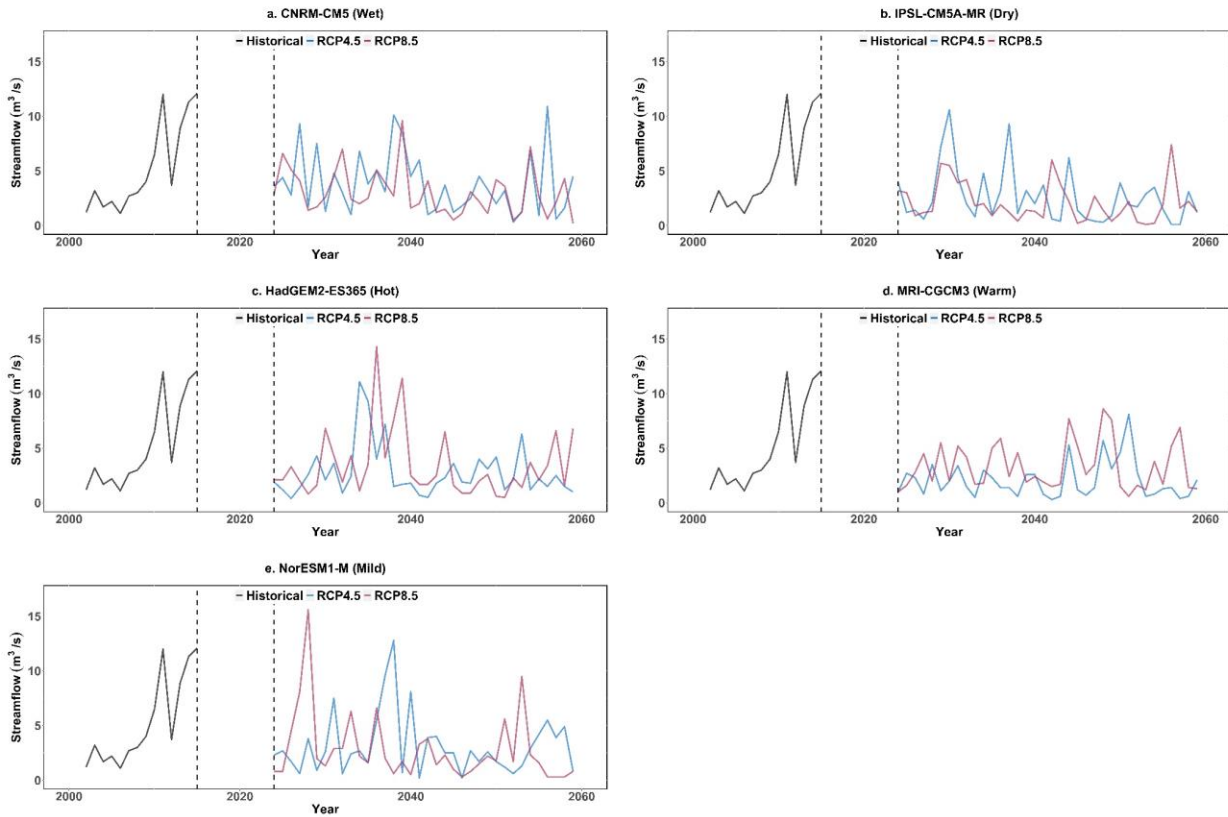
**Table 3.3.** Average annual hydrologic fluxes (mm) for historical and future climates for the base scenario.

Hydrologic Flux (mm/yr)										
Climate Scenario	Rainfall	Snowmelt	Surface Runoff	Soil Lateral Flow	GW Recharge	Saturation Excess Flow	Pumping	Surface ET	Canal Seepage	Surface Water Irrigation
Historical	322.1	145.4	12.4	15.0	30.1	33.6	4.5	411.7	5.4	11.1
CNRM-CM5 (Wet)										
RCP 4.5	388.3 (+21%)	99.5 (-32%)	9.0 (-27%)	12.3 (-18%)	37.8 (+26%)	41.2 (+23%)	4.3 (-4%)	437.2 (+6%)	4.9 (-9%)	10.9 (-2%)
RCP 8.5	387.9 (+20%)	87.2 (-40%)	7.9 (-36%)	10.5 (-30%)	32.7 (+9%)	36.4 (+8%)	4.4 (-2%)	434.3 (+5%)	4.7 (-13%)	10.7 (-4%)
IPSL-CM5A-MR (Dry)										
RCP 4.5	339.6 (+5%)	104.7 (-28%)	7.2 (-42%)	9.3 (-38%)	28.2 (-6%)	31.8 (-5%)	4.5 (0%)	409.2 (-1%)	4.5 (-17%)	9.3 (-16%)
RCP 8.5	347.6 (+8%)	86.2 (-41%)	6.5 (-48%)	8.0 (-47%)	26.8 (-11%)	30.2 (-10%)	4.4 (-2%)	402.1 (-2%)	4.3 (-20%)	9.2 (-17%)
HadGEM2-ES365 (Hot)										
RCP 4.5	361.0 (+12%)	101.5 (-30%)	7.9 (-36%)	10.1 (-33%)	31.5 (+5%)	35.1 (+4%)	4.4 (-2%)	424.1 (+3%)	4.7 (-13%)	10.8 (-3%)
RCP 8.5	371.4 (+15%)	106.3 (-27%)	9.2 (-26%)	11.2 (-25%)	33.8 (+12%)	37.3 (+11%)	4.5 (0%)	433.4 (+5%)	4.8 (-11%)	11.0 (-1%)
MRI-CGCM3 (Warm)										
RCP 4.5	341.0 (+6%)	97.9 (-33%)	6.7 (-46%)	8.2 (-45%)	24.8 (-18%)	28.3 (-16%)	4.3 (-4%)	409.6 (-1%)	4.4 (-19%)	9.7 (-13%)
RCP 8.5	384.4 (+19%)	111.4 (-23%)	8.6 (-31%)	11.6 (-23%)	33.9 (+13%)	37.4 (+11%)	4.3 (-4%)	450.3 (+9%)	4.9 (-9%)	11.2 (+1%)
NorESM1-M (Mild)										
RCP 4.5	393.1 (22%)	90.8 (-38%)	8.7 (-30%)	10.4 (-31%)	32.4 (+8%)	35.8 (+7%)	4.3 (-4%)	441.1 (+7%)	4.7 (-13%)	10.2 (-8%)
RCP 8.5	386.3 (+20%)	85.4 (-41%)	8.1 (-35%)	9.9 (-34%)	30.4 (+1%)	33.9 (+1%)	4.3 (-4%)	431.7 (+5%)	4.4 (-19%)	9.8 (-11%)

### 3.3.3 Impact of Future Climate Variation on streamflow for the Base Scenario

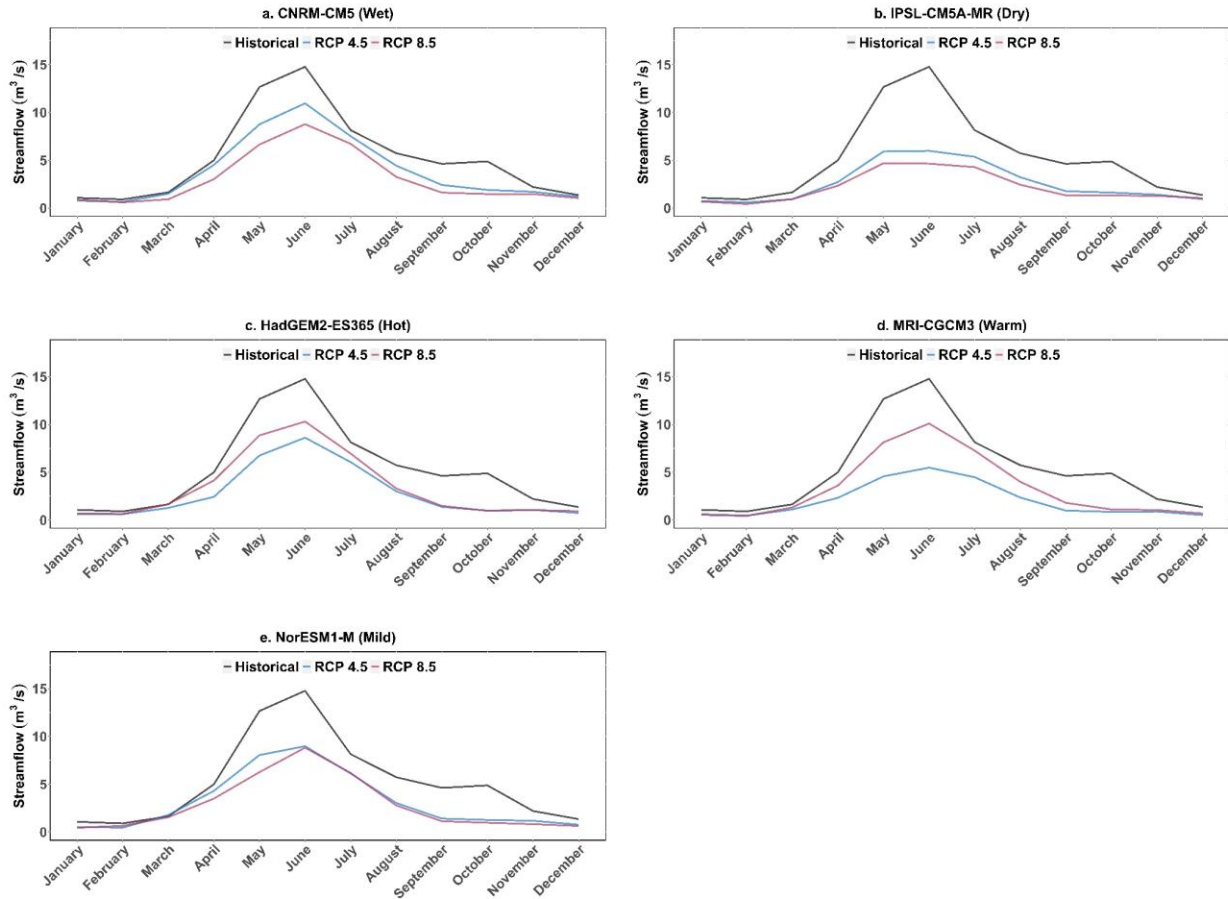
The average annual stream discharge for the historical and projected climate by all climate models under both RCP scenarios (RCP 4.5 and RCP 8.5) for the USGS 06752280 gage station (see Figure 3.1) is presented in Fig 3.7. A general decrease in streamflow is observed under all climate models by the mid of the century which agrees with old studies done in the same area (Aliyari et al., 2021). The decrease in stream discharge

is a result of increased temperature and surface ET as presented in Table 3.3. However, higher stream discharge is seen in Figure 3.7.a and Figure 3.7.e compared to other future climate models due to higher amounts of precipitation as presented in Table 3.3.



**Figure 3.7.** Historical and projected average annual streamflow ( $\text{m}^3/\text{s}$ ) for the USGS 06752280 gage station (see Figure 3.1) under all downscaled GCM climate models for each RCP.

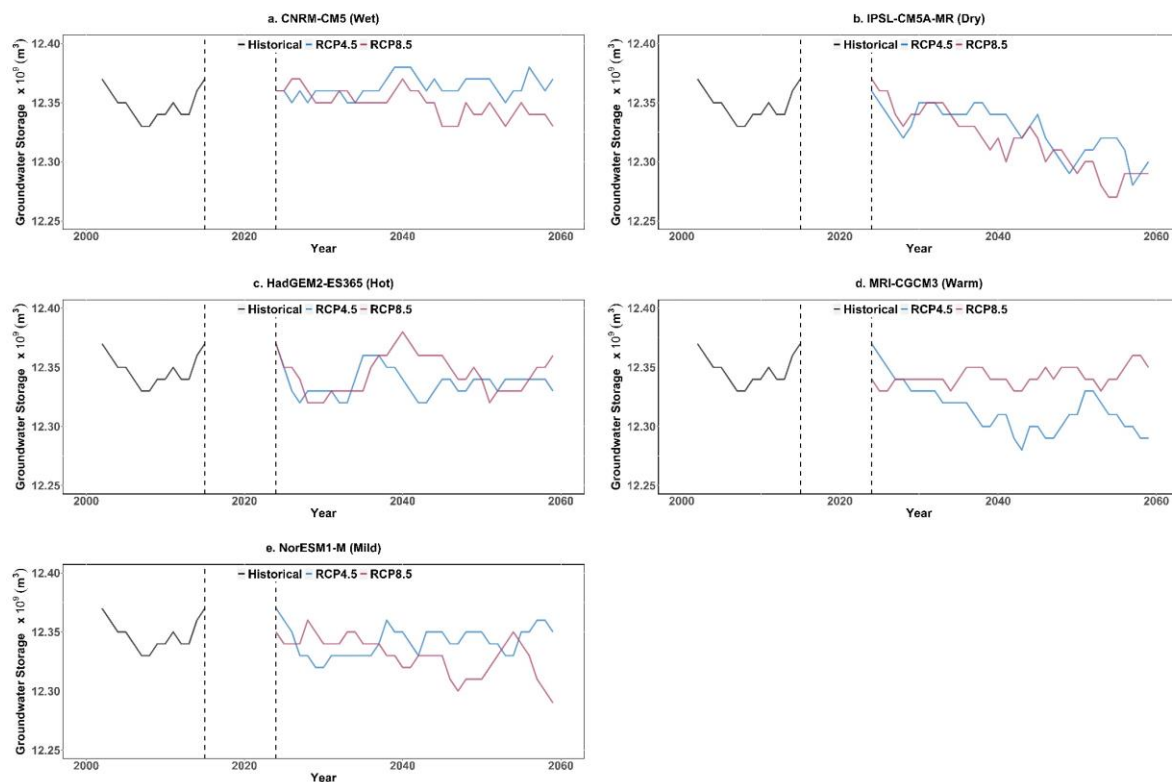
The average monthly stream discharge for the historical and projected climate by all climate models under both RCP scenarios (RCP 4.5 and RCP 8.5) for the USGS 06752280 gage station (see Figure 3.1) is presented in Fig 3.8. The highest reduction is observed under the IPSL-CM5A-MR (Dry) RCP 8.5 scenario for the month of June, 69% from historical average streamflow. Less water will be available for irrigation during irrigation months (April through September) due to decreased values of streamflow.



**Figure 3.8.** Historical (2000-2015) and projected (2024-2059) average monthly streamflow ( $\text{m}^3/\text{s}$ ) for the USGS 06752280 gage station (see Figure 3.1) under all downscaled GCM climate models for each RCP.

### 3.3.4 Impact of Future Climate Variation on groundwater storage for the Base Scenario

Figure 3.9 shows the total amount of groundwater stored in the CLP for both historical and future scenarios, as predicted by each climate model for each emission scenario. The most significant decrease in groundwater storage occurs under the IPSL-CM5A-MR (Dry) climate model in both RCPs, resulting in a 0.5% loss in storage. According to the worst-case climatic scenario (IPSL-CM5A-MR-8.5), if there is a 6% decline in annual precipitation and an 11% decrease in recharge, the groundwater storage will decrease by 0.5% by the year 2059. The groundwater storage will remain the same under the CNRM-CM5 (Wet) climate model for both emission scenarios due to increased amount of precipitation and groundwater recharge despite of increased surface ET.

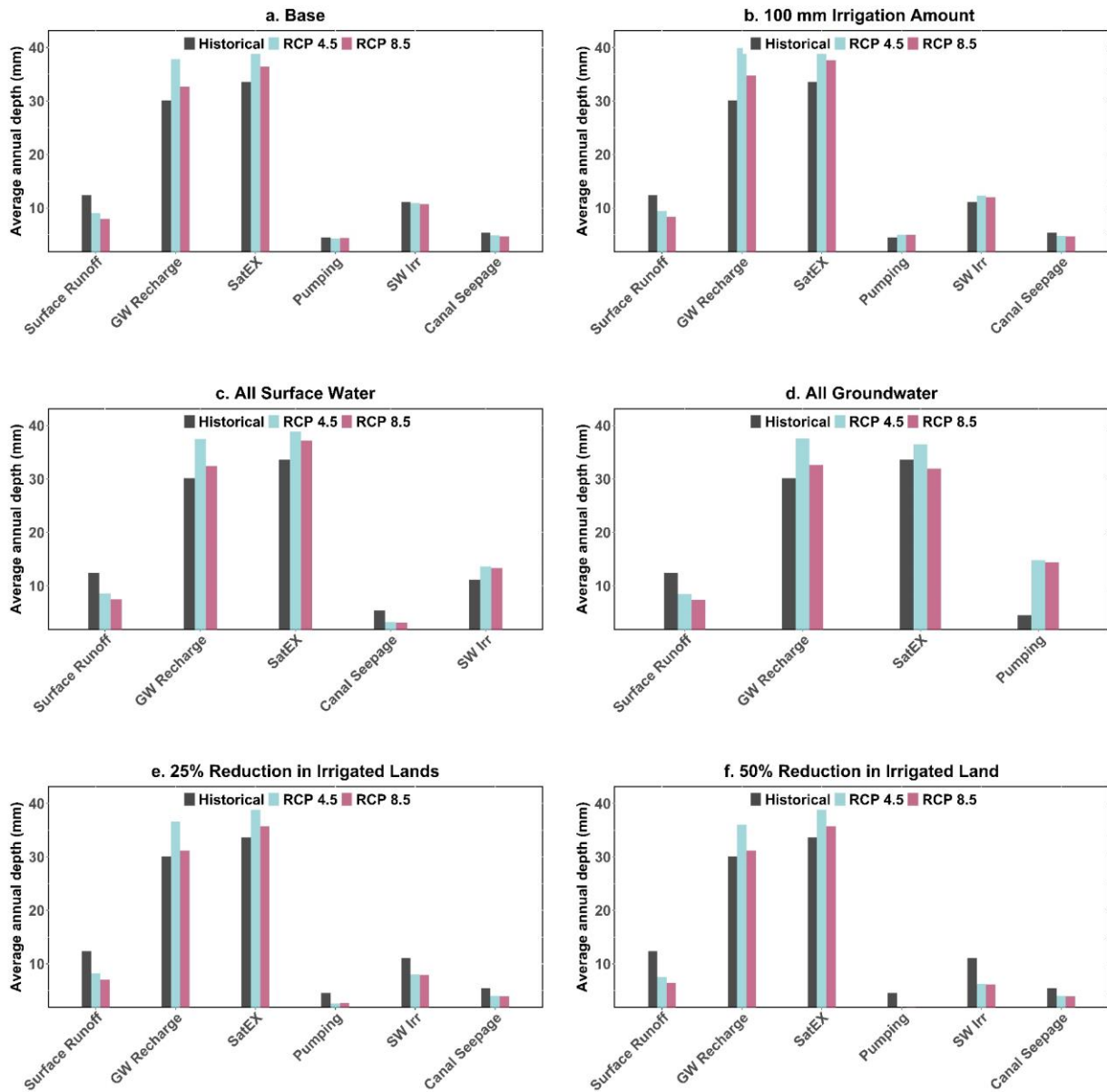


**Figure 3.9.** Historical and projected groundwater storage under all downscaled GCM climate models for each RCP.

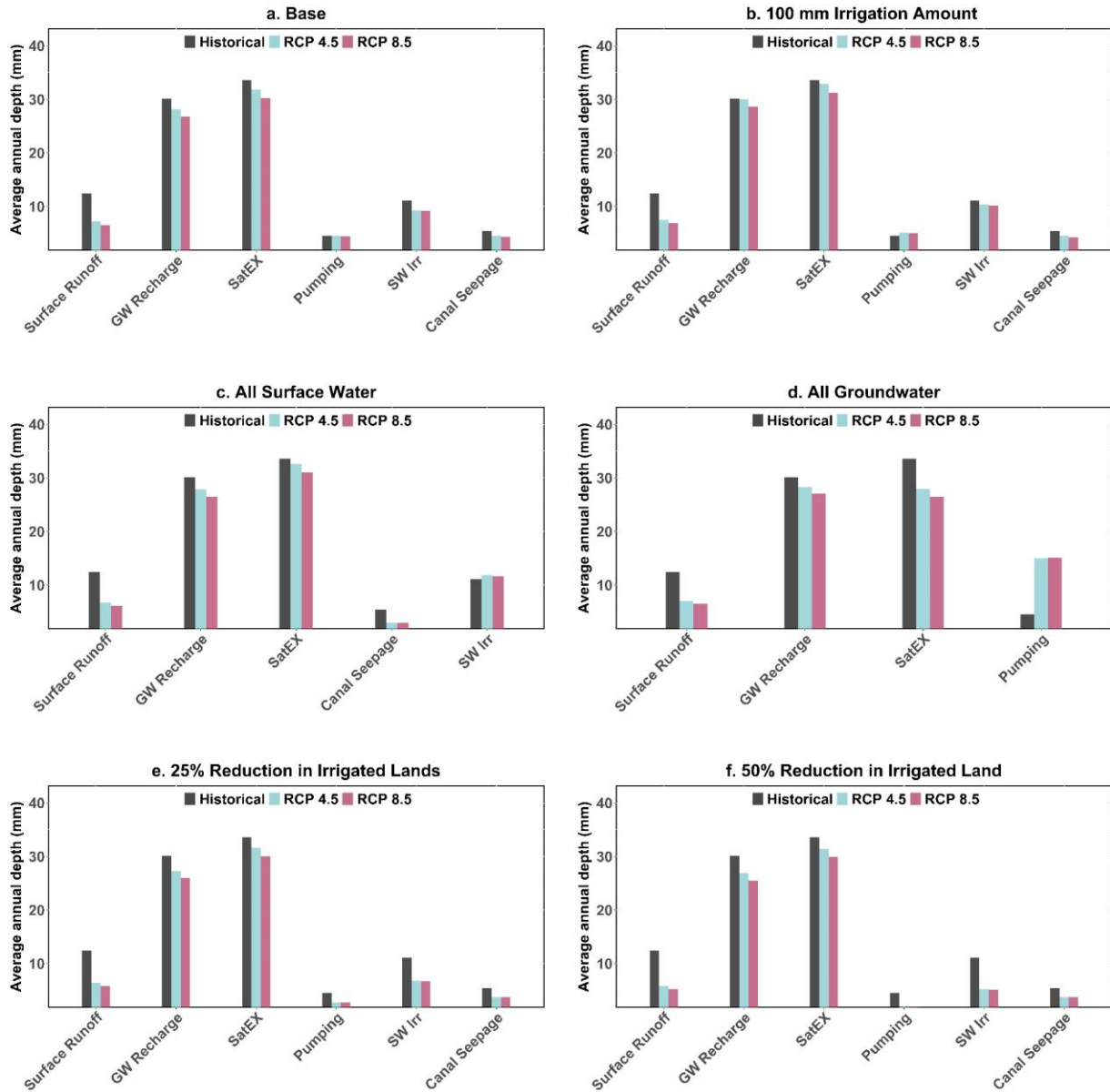
### 3.3.5 Impact of Future Irrigation Scenarios on Hydrologic Fluxes in a Changing Climate

The "base" scenario discussed in this section refers to the model simulation that has been calibrated and tested, as outlined in Chapter 2 and section 3.3.2 of this chapter. Figure 3.10 shows the basin annual average depth (mm) for different fluxes for the historical and the CNRM-CM5 (Wet) climate model under both emission scenarios for different irrigation scenarios. Figure 3.11 shows the basin annual average depth (mm) for different fluxes for the historical and the IPSL-CM5A-MR (Dry) climate model under both emission scenarios for different irrigation scenarios. Increased amount of precipitation and water applied for irrigation resulted in high values of recharge as shown in Figure 3.10.b (33% increase under the RCP4.5 scenario) while conversion from irrigated to dry land resulted in less amount of recharge as shown in Figures 3.10e and 3.10f but still higher than historical value because of increased precipitation. In contrast,

the amount of recharge remained relatively constant under IPSL-CM5A-MR (Dry) climate scenario and less than historical value as seen in Figure 3.11 because of decreased amount of precipitation. Using groundwater irrigation as the only method of irrigation resulted in decreased saturation excess flow for both wet and dry climate models compared to other irrigation scenarios. This is due to the lowering in groundwater table because of excessive pumping. The average value of annual flux under the CNRM-CM5 (Wet) climate model is higher than the CM5A-MR (Dry) one due to more water being introduced to the river basin through higher amounts of precipitation.



**Figure 3.10.** Basin annual average depth (mm) for different fluxes for the historical and the CNRM-CM5 (Wet) climate model under both emission scenarios for (a) base scenario; (b) irrigation water demand has doubled; (c) Surface water irrigation is the only method of irrigation; (d) Groundwater irrigation is the only method of irrigation; (e) 25% reduction in irrigated land; and (f) 50% reduction in irrigated land.



**Figure 3.11.** Basin annual average depth (mm) for different fluxes for the historical and the IPSL-CM5A-MR (Dry) climate model under both emission scenarios for (a) base scenario; (b) irrigation water demand has doubled; (c) Surface water irrigation is the only method of irrigation; (d) Groundwater irrigation is the only method of irrigation; (e) 25% reduction in irrigated land; and (f) 50% reduction in irrigated land.

### 3.4 Study Limitations

This study has several limitations, such as:

- Using statistically downscaled climate data that is biased. This bias has the potential to impact the precision of future climate projections and, as a result, can alter the accuracy of the model's forecasts regarding hydrologic fluxes and crop yields. The method of downscaling may not sufficiently reflect the local variations and extremes in climate, which could result in either an overestimation or underestimating of hydrologic fluxes.
- The model does not incorporate changes in land use. Alterations in land use, such as urbanization or deforestation can have a substantial impact on hydrological dynamics and the availability of water.
- The SWAT+*gwflow* model is unable to accurately incorporate variations in water source usage by farmers during times of water scarcity. In fact, in dry simulations, the model is unable to represent the expected rise in groundwater usage that would occur when there is not enough surface water available for irrigation.

### 3.5 Summary and Conclusion

Integrated basin-scale long-term water resource modeling serves as a valuable tool for supporting future water management strategies. The aim of our study is to analyze the potential impacts of climate change on water resources and hydrologic fluxes in a highly managed semi-arid river basin. The findings of this study enable water resources and agricultural managers to identify and address the most vulnerable regions under different climatic conditions. The methodology involves utilizing the SWAT+*gwflow* model to predict future streamflow, groundwater storage, and hydrologic fluxes. The model is run under five different CMIP5 climate models downscaled by MACA, each representing two different climate emission scenarios, RCP4.5 and RCP8.5.

Except for the CGCM3 (Warm) model, all climate models and emission scenarios predict an increase in the yearly average temperature. The projected variation in precipitation (that is, snow and rain) depends on the climate model used. However, the average annual precipitation across the entire basin is expected to increase by 6.1% under the RCP8.5 scenario for the NorESM1-M (Mild) model. On the other hand, the IPSL-CM5A-MR (Dry) model shows a maximum decrease rate of 6% from the average climate conditions under the RCP8.5 scenario. It is crucial for water and agricultural management to assess possible risks in the future by considering the worst-case scenario. The analysis reveals that the IPSL-CM5A-MR-8.5 climate model in the CLP is the most severe, as it combines two climatic stressors: less precipitation and increased temperature. Runoff is observed to be reduced by 47.6%, groundwater recharge to drop by 11%, and a 0.5% reduction in groundwater storage under this climate scenario.

Although the climate conditions in the past have been inconsistent, the transboundary water source that flows into the watershed has consistently maintained a stable discharge throughout the investigated historical period. This indicates the existence of regulated water management methods and agreements, irrespective of the impact of climate change. Different irrigation scenarios influence hydrologic fluxes, highlighting the need to understand and manage water resources effectively under a changing climate in the future. Source of irrigation has the highest impact on hydrologic fluxes among other irrigation scenarios.

In conclusion, the findings of this study offer an overview for future investigations on climate change at the basin level, utilizing integrated models that incorporate both surface water and groundwater:

- 1) Employ several climate scenarios generated by multiple global and regional climate models covering a range of projections including wet, dry, hot, warm, and mild.
- 2) Apply the model on a larger size, such as a basin or region, rather than on smaller scales like subbasins, watersheds, and sub-watersheds.

- 3) Account for different water management (irrigation source, irrigation amount, irrigation type).
- 4) Run the model for different possible future irrigation scenarios (such as conversion from irrigated land to dry land) under variation in climate patterns.

## References

- Abbas, S. A., Xuan, Y., & Bailey, R. T. (2022). Assessing climate change impact on water resources in water demand scenarios using SWAT-MODFLOW-WEAP. *Hydrology*, 9(10), 164. <https://doi.org/10.3390/hydrology9100164>
- Aliyari, F., Bailey, R. T., & Arabi, M. (2021). Appraising climate change impacts on future water resources and agricultural productivity in agro-urban river basins. *Sci. Total Environ.*, 788, 147717. <https://doi.org/10.1016/j.scitotenv.2021.147717>
- Aliyari, F., Bailey, R. T., Tasdighi, A., Dozier, A., Arabi, M., & Zeiler, K. (2019). Coupled SWAT-MODFLOW model for large-scale mixed agro-urban river basins. *Environmental Modelling & Software*, 115, 200-210. <https://doi.org/10.1016/j.envsoft.2019.02.014>
- Almahawis, M. K., Bailey, R. T., Abbas, S. A., Arnold, J. G., & White, M. J. (2024). Investigating the impact of irrigation practices on hydrologic fluxes in a highly managed river basin. *Agric. Water Manag.*, 301, 108954. <https://doi.org/10.1016/j.agwat.2024.108954>
- Bailey, R. T., Wible, T. C., Arabi, M., Records, R. M., and Ditty, J. (2016). Assessing regional-scale spatio-temporal patterns of groundwater–surface water interactions using a coupled SWAT-MODFLOW model. *Hydrol. Process.*, 30(23), 4420-4433. <https://doi.org/10.1002/hyp.10933>
- Bailey, R., Abbas, S., Arnold, J., White, M., Gao, J., and Čerkasova, N. (2023). Augmenting the national agroecosystem model with physically based spatially distributed groundwater modeling. *Environ. Model. Softw.*, 160, 105589. <https://doi.org/10.1016/j.envsoft.2022.105589>
- Bailey, R., Bieger, K., Arnold, J., and Bosch, D. (2020). A new physically-based spatially-distributed groundwater flow module for SWAT+. *Hydrology*, 7(4), 75. <https://doi.org/10.3390/hydrology7040075>
- Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., et al. (2013). The Norwegian Earth System Model, NorESM1-M–Part 1: description and basic evaluation of the physical climate. *Geosci. Model Dev.*, 6(3), 687-720. <https://doi.org/10.5194/gmd-6-687-2013>

- Bieger, K., Arnold, J. G., Rathjens, H., White, M. J., Bosch, D. D., Allen, P. M., Volk, M., and Srinivasan, R. (2017). Introduction to SWAT+, a completely restructured version of the soil and water assessment tool. *J. Am. Water Resour. Assoc.*, 53, 115–130, <https://doi.org/10.1111/1752-1688.12482>
- City of Fort Collins Utilities. (2010). *Horsetooth Reservoir water quality monitoring program report*. Retrieved from [https://www.fcgov.com/utilities/img/site\\_specific/uploads/HT\\_WQ\\_Monitoring\\_Program\\_2010\\_Report.pdf](https://www.fcgov.com/utilities/img/site_specific/uploads/HT_WQ_Monitoring_Program_2010_Report.pdf)
- Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Hinton, T., Jones, *et al.* (2008). *Evaluation of the HadGEM2 model* (Vol. 74). Exeter, UK: Met Office.
- Deen, T. A., Arain, M. A., Champagne, O., Chow-Fraser, P., & Martin-Hill, D. (2023). Impacts of climate change on streamflow in the McKenzie Creek watershed in the Great Lakes region. *Front. environ. sci.*, 11, 1171210. <https://doi.org/10.3389/fenvs.2023.1171210>
- Dufresne, J. L., Foujols, M. A., Denvil, S., Caubel, A., Marti, O., Aumont, O., ... & Vuichard, N. (2013). Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. *Clim. Dyn.*, 40, 2123-2165. <https://doi.org/10.1007/s00382-012-1636-1>
- Ferguson, I. M., & Maxwell, R. M. (2012). Human impacts on terrestrial hydrology: climate change versus pumping and irrigation. *Environ. Res. Lett.*, 7(4), 044022. <https://doi.org/10.1088/1748-9326/7/4/044022>
- Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., *et al.* (2013). Climate change impact on available water resources obtained using multiple global climate and hydrology models. *Earth Syst. Dyn.*, 4(1), 129-144. <https://doi.org/10.5194/esd-4-129-2013>
- Hayhoe, K., Edmonds, J., Kopp, R., LeGrande, A., Sanderson, B., Wehner, M., & Wuebbles, D. (2017). Climate models, scenarios, and projections. *Climate Science Special Report: Fourth National Climate Assessment, I* (2017), pp. 133-160.

- Larocque, M., Levison, J., Martin, A., & Chaumont, D. (2019). A review of simulated climate change impacts on groundwater resources in Eastern Canada. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, 44(1), 22-41. <https://doi.org/10.1080/07011784.2018.1503066>
- Li, C., & Fang, H. (2021). Assessment of climate change impacts on the streamflow for the Mun River in the Mekong Basin, Southeast Asia: Using SWAT model. *Catena*, 201, 105199. <https://doi.org/10.1016/j.catena.2021.105199>
- Liu, W., Bailey, R. T., Andersen, H. E., Jeppesen, E., Nielsen, A., Peng, K., *et al.* (2020). Quantifying the effects of climate change on hydrological regime and stream biota in a groundwater-dominated catchment: A modelling approach combining SWAT-MODFLOW with flow-biota empirical models. *Sci. Total Environ.*, 745, 140933. <https://doi.org/10.1016/j.scitotenv.2020.140933>
- Lukas, J., Barsugli, J., Doesken, N., Rangwala, I., & Wolter, K. (2014). Climate change in Colorado: a synthesis to support water resources management and adaptation. *University of Colorado, Boulder, Colorado*.
- Northern Water. (2022). *Colorado-Big Thompson Project*. Retrieved from <https://www.northernwater.org/what-we-do/deliver-water/colorado-big-thompson-project>
- Orkodjo, T. P., Kranjac-Berisavijevic, G., & Abagale, F. K. (2022). Impact of climate change on future availability of water for irrigation and hydropower generation in the Omo-Gibe Basin of Ethiopia. *Journal of Hydrology: Regional Studies*, 44, 101254. <https://doi.org/10.1016/j.ejrh.2022.101254>
- Ou, G., Munoz-Arriola, F., Uden, D.R. *et al.* (2018). Climate change implications for irrigation and groundwater in the Republican River Basin, USA. *Climatic Change* 151, 303–316. <https://doi.org/10.1007/s10584-018-2278-z>
- Paniconi, C., & Wood, E. F. (1993). A detailed model for simulation of catchment scale subsurface hydrologic processes. *Water Resources Research*, 29(6), 1601-1620. <https://doi.org/10.1029/92WR02333>

- Persaud, E., Levison, J., MacRitchie, S., Berg, S. J., Erler, A. R., Parker, B., & Sudicky, E. (2020). Integrated modelling to assess climate change impacts on groundwater and surface water in the Great Lakes Basin using diverse climate forcing. *J. Hydrol.*, 584, 124682. <https://doi.org/10.1016/j.jhydrol.2020.124682>
- Samimi, M., Mirchi, A., Townsend, N., Gutzler, D., Daggubati, S., Ahn, S., *et al.* (2022). Climate change impacts on agricultural water availability in the Middle Rio Grande basin. *JAWRA Journal of the American Water Resources Association*, 58(2), 164-184. <https://doi.org/10.1111/1752-1688.12988>
- Singh, A. (2024). Effective management of water resources problems in irrigated agriculture through simulation modeling. *Water Resour. Manag.*, 38(8), 2869-2887. <https://doi.org/10.1007/s11269-024-03796-x>
- Sulis, M., Paniconi, C., Rivard, C., Harvey, R., & Chaumont, D. (2011). Assessment of climate change impacts at the catchment scale with a detailed hydrological model of surface-subsurface interactions and comparison with a land surface model. *Water Resour. Res.*, 47(1). <https://doi.org/10.1029/2010WR009167>
- Vansteenkiste, T., Tavakoli, M., Ntegeka, V., Willems, P., De Smedt, F., & Batelaan, O. (2012). Climate change impact on river flows and catchment hydrology: a comparison of two spatially distributed models. *Hydrol. Process.*, 27(25), 3649-3662. <https://doi.org/10.1002/hyp.9480>
- Voldoire, A., Sanchez-Gomez, E., Salas y Mélia, D., Decharme, B., Cassou, C., Sénési, S., *et al.* (2013). The CNRM-CM5. 1 global climate model: description and basic evaluation. *Clim. Dyn.*, 40, 2091-2121. <https://doi.org/10.1007/s00382-011-1259-y>
- Yukimoto, S., Adachi, Y., Hosaka, M., Sakami, T., Yoshimura, H., Hirabara, M., *et al.* (2012). A new global climate model of the Meteorological Research Institute: MRI-CGCM3—Model description and basic performance. *J. Meteorol. Soc. Jpn.*, 90(0), 23-64. <https://doi.org/10.2151/jmsj.2012-A02>

## CHAPTER 4 - Assessing the Impact of Future Water Storage Practices on Water

### Availability in a Highly Managed River Basin

#### 4.1 Introduction

Understanding the factors that contribute to changes in streamflow is crucial for ensuring social and economic stability, as well as for protecting the environment. A sudden drop in streamflow can severely affect aquatic life and irrigation, while a significant increase in runoff can cause floods that endanger lives and property. The cumulative hydrological impacts of reservoir installation are most estimated using runoff (Chai et al., 2019). There is general consensus that constructing reservoirs will lead to fewer flood peaks (Ayalew et al., 2017, Nathan and Lowe, 2012, Thompson, 2012) up to 45%, especially since some reservoirs are built as stormwater retention ponds (Del Giudice et al., 2014). Most of the research has focused on annual streamflow, with average annual reductions reported to range from 0.2% (Hughes and Mantel, 2010) to 36% (Meigh, 1995). It is useful for most water management agencies to estimate the cumulative impact of reservoir installation on average annual runoff (Habets et al., 2018).

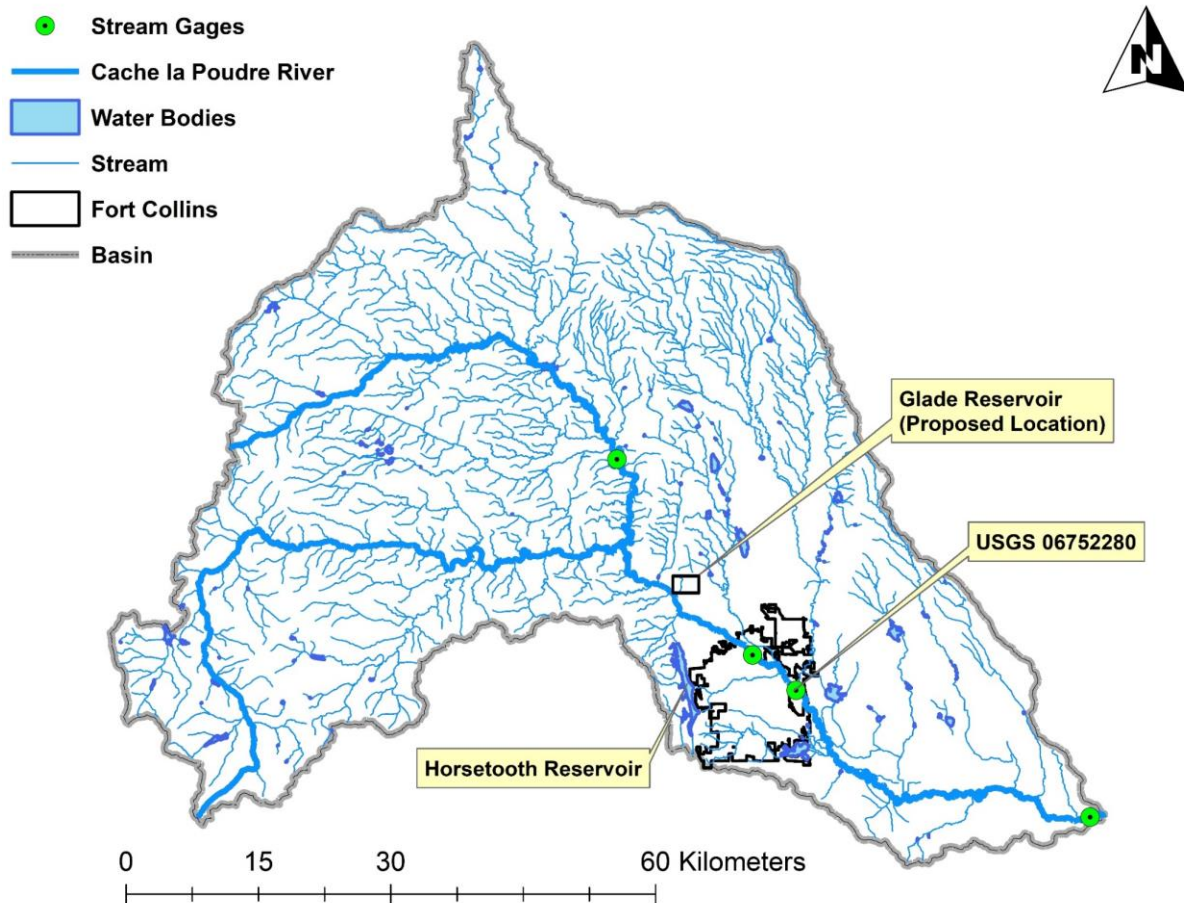
To our knowledge, no study has utilized a holistic coupled model of surface and groundwater to evaluate the impacts of reservoir construction on hydrologic fluxes within the context of a changing climate. Consequently, in this study, we employ a hydrologic modeling approach to measure the impacts of constructing a new reservoir in a semi-arid river basin. The Cache la Poudre Basin in Colorado, USA serves as a demonstrative case for our purposes. The chosen model is SWAT+ (Bieger et al., 2017), with the *gwflow* module to simulate groundwater storage, groundwater flow, and the interaction between groundwater and land surface and surface water components. The model has undergone calibration and testing using

streamflow and groundwater level data (Almahawis et al., 2024). It will now be employed to evaluate the effects of future water storage practices on streamflow and hydrologic fluxes.

## **4.2 Materials and Methods**

### **4.2.1 SWAT+*gflow* hydrologic simulation tool**

This chapter utilizes the modeling system of SWAT+*gflow*, as discussed in Chapter 2 and 3, to assess the effects of constructing a new reservoir under climate extremes on hydrologic fluxes in the Cache la Poudre River basin. An enhanced version of SWAT+*gflow*, calibrated and tested against historical groundwater levels and monthly streamflow at several stream gages along the Cache la Poudre River, was presented by Almahawis et al. (2024). The model includes detailed irrigation (e.g., irrigation source, irrigation type, etc.) as well as canal seepage, both essential parts of the hydrologic system of the river basin.



**Figure 4.1.** Model details for the Cache la Poudre River Basin, revealing the location of streams, water bodies, Glade Reservoir (proposed location), Horsetooth Reservoir, river gages and city of Fort Collins.

#### 4.2.2 Future Climate in CLP

The tested SWAT+*gwflow* model for the CLP is used in this study with projected climate data, as described in section 3.2.2 in the previous chapter, to quantify the impact of building a new reservoir on hydrologic fluxes under climate extremes from 2024 to 2059. The two climate scenarios considered in this chapter are CNRM-CM5 (Wet) and IPSL-CM5A-MR (Dry) under the RCP8.5 emission scenario.

### **4.2.3 Quantifying the impact of building a new reservoir on streamflow and hydrologic fluxes under climate extremes**

The population of Northern Colorado is projected to double by 2050, resulting in an increasing demand for water supply (Northern Water, 2024). Despite significant improvements in water usage efficiency through conservation efforts, it is important to acknowledge that conservation alone cannot guarantee a secure water future. To address the challenges posed by a growing population and limited water resources, Northern Water must allocate resources towards innovative and sustainable techniques that can effectively satisfy future demands. The Northern Integrated Supply Project will provide 15 water suppliers in the Northern Front Range with 40,000 acre-feet of additional and dependable water supplies per year, taking into consideration the projected growth in population. Northern Water is actively seeking permission, planning, and building the project on behalf of the participants, who will supply water to about 500,000 residents by 2050. A major part of the project components is building the Glade Reservoir (see Figure 4.1) with a 170,000 acre-feet capacity.

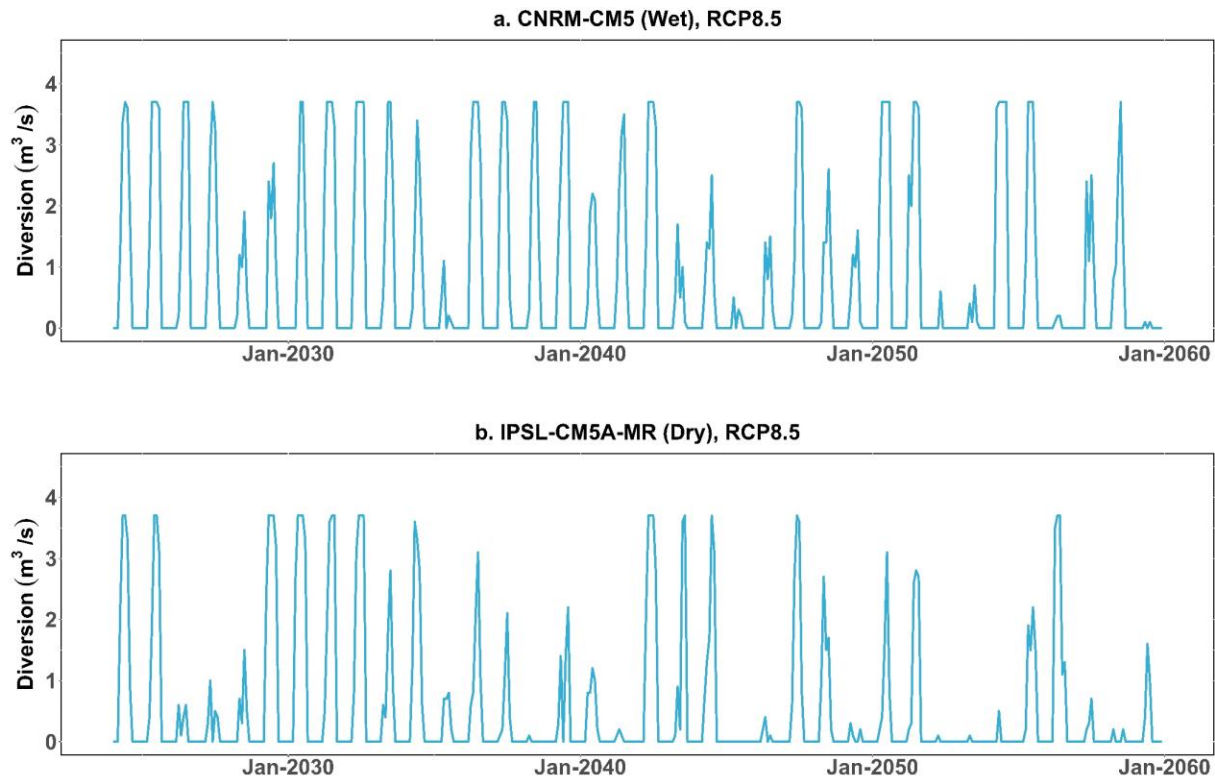
This water will be taken from the Cache la Poudre River during high flow seasons (spring and summer), ensuring that streamflow in the river does not go below 1.4 m<sup>3</sup>/s (50 ft<sup>3</sup>/sec) for environmental and social responsibility. Therefore, water will be diverted from the river to Glade Reservoir during the months of April to August if there is enough water available and the water rights are not exceeded (Northern Water, 2024).

The SWAT+*gwflow* model was used to investigate the impact of building a new reservoir on streamflow and hydrologic fluxes under climate extremes within the CLP Basin, under the CNRM-CM5 (Wet) and IPSL-CM5A-MR (Dry) of future climates for the RCP8.5 emission scenario. The reservoir is treated as a point source in the model and the USGS 06752280 gage station (downstream side of Fort Collins; see Figure 4.1) is used to assess the impact on the downstream flow.

## 4.3 Results and Discussion

### 4.3.1 Diversion to Glade Reservoir from Cache la Poudre River

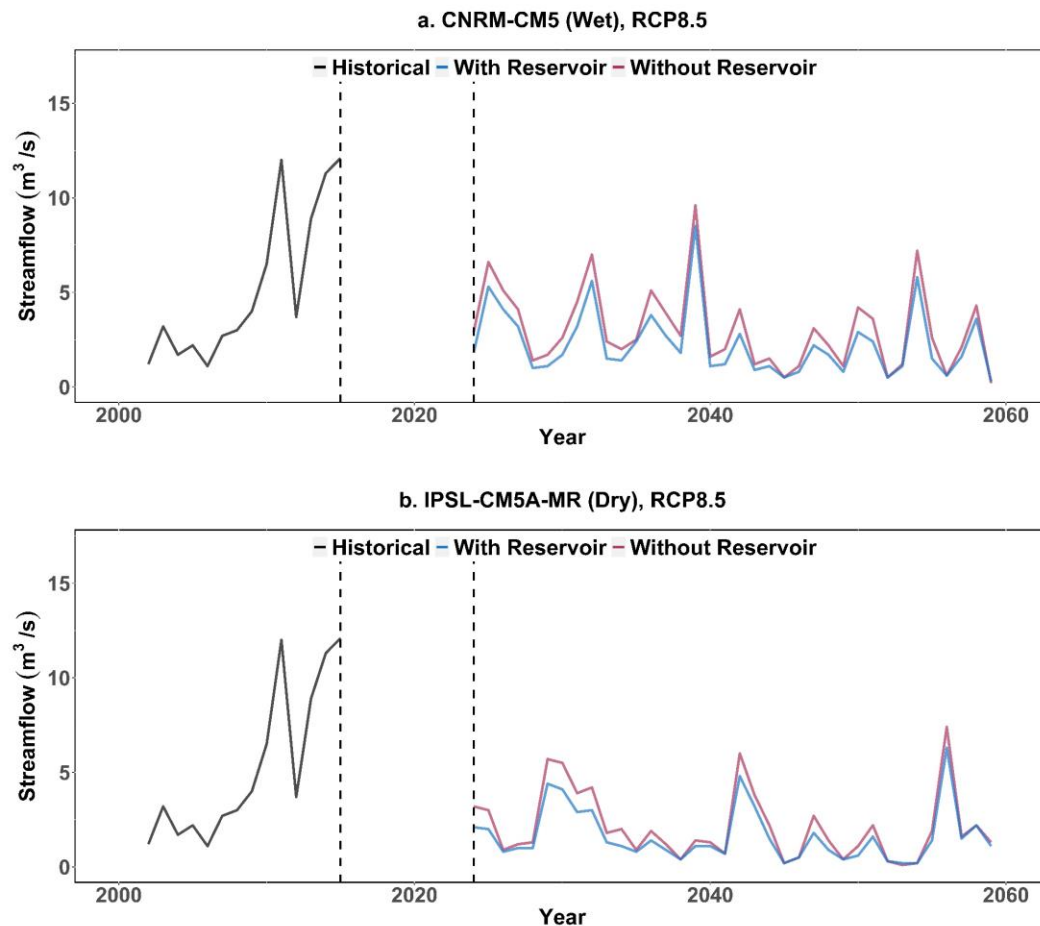
Figure 4.2 shows a possible scenario of future monthly diversion ( $\text{m}^3/\text{s}$ ) from the Cache la Poudre River to Glade Reservoir under two different climate scenarios, to satisfy annual demand of 40,000 ac-ft. The proposed diversion ensures a sufficient flow in the Cache la Poudre River ( $>1.4 \text{ m}^3/\text{s}$ ) and does not exceed the  $3.7 \text{ m}^3/\text{s}$  threshold for diversion. This ensures that the total annual diversion to the reservoir during the spring/summer period does not exceed the 40,000 acre-feet water right. Figure 3.2a shows a higher average monthly diversion rate during operation months ( $2.1 \text{ m}^3/\text{s}$ ) than Figure 3.2b ( $1.6 \text{ m}^3/\text{s}$ ) due to more water being available in the river under the wet climate scenario.



**Figure 4.2.** Suggested average annual diversion to Glade Reservoir under (a) CNRM-CM5 (Wet), RCP8.5 and (b) IPSL-CM5A-MR (Dry), RCP8.5 future climate scenarios.

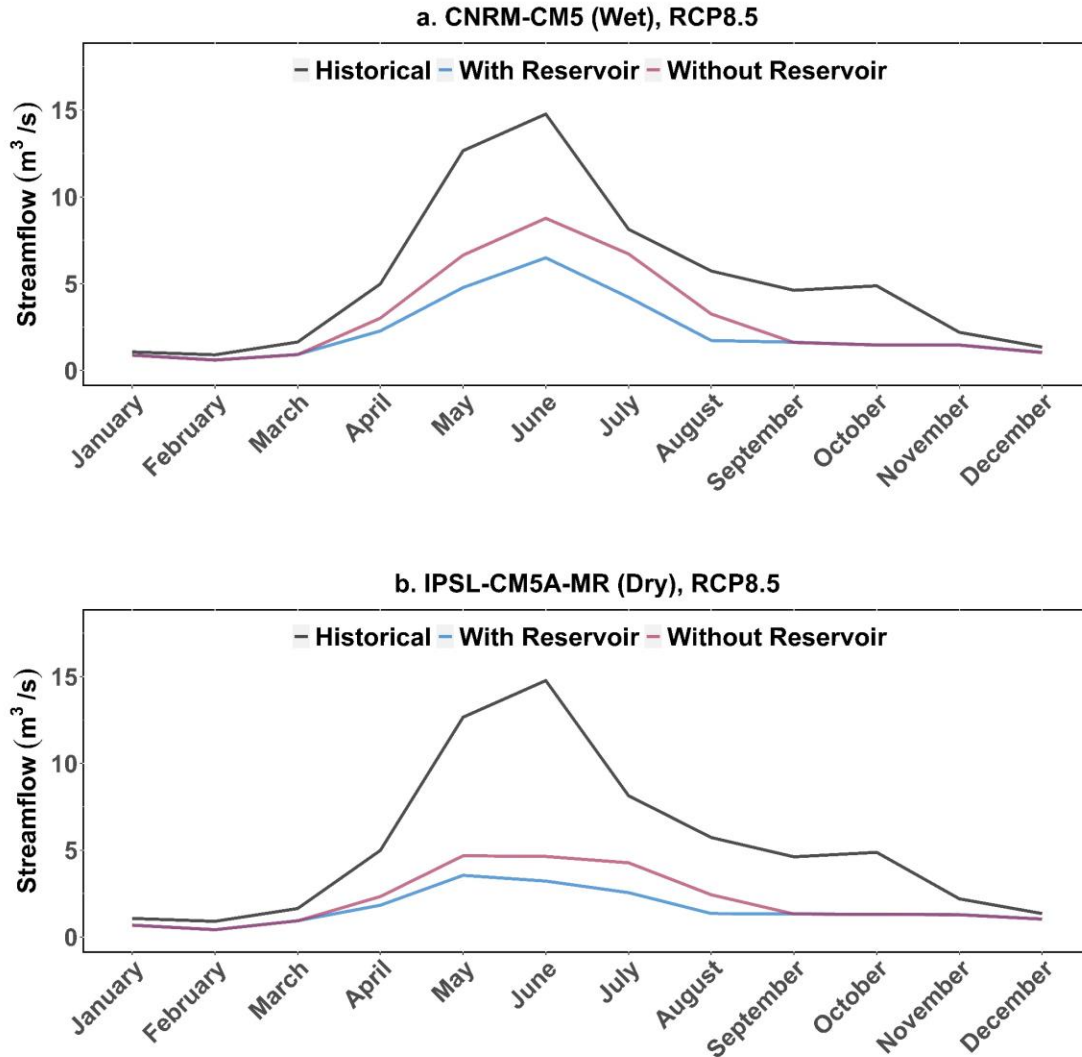
### 4.3.2 Impact of building a new reservoir on streamflow under climate extremes

The average annual stream discharge for the historical and projected climate, for both scenarios with and without Glade Reservoir, at the USGS 06752280 gage station (see Figure 4.1) is presented in Figure 4.3. A general decrease in streamflow is observed under both climate models when the reservoir is present. This decrease in stream discharge is a result of diverting water from the Cache la Poudre River to Glade Reservoir. The diversion mostly affects peak discharge for both scenarios, in compliance with protecting flow in the river and only diverting water when sufficient streamflow is available.



**Figure 4.3.** Historical and projected average annual streamflow (m<sup>3</sup>/s) for the USGS 06752280 gage station (see Figure 4.1) under (a) the CNRM-CM5 (Wet) and (b) the IPSL-CM5A-MR (Dry) future climate models for RCP8.5 emission scenario.

The average monthly stream discharge for the historical and projected climate models under both CNRM-CM5 (Wet) RCP8.5 and IPSL-CM5A-MR (Dry) RCP8.5 scenarios for the USGS 06752280 gage station (see Figure 4.1) for both with and without reservoir scenarios is presented in Figure 4.4.



**Figure 4.4.** Historical (2000-2015) and projected (2024-2059) average monthly streamflow ( $\text{m}^3/\text{s}$ ) for the USGS 06752280 gage station (see Figure 4.1) under (a) the CNRM-CM5 (Wet) and (b) the IPSL-CM5A-MR (Dry) climate models for RCP8.5 emission scenario.

The highest reduction is observed under the IPSL-CM5A-MR (Dry) RCP8.5 with reservoir scenario for the month of June, showing a 78% decrease from the historical average streamflow. Figure 4.4 shows that less

water will be available in the Cache la Poudre River during the diversion operation months (April through August) under the reservoir scenario compared to the scenario without the reservoir.

#### 4.3.3 Impact of building a new reservoir on hydrologic fluxes under climate extremes

Table 4.1 shows the basin annual average depth (mm) for different fluxes for the historical period, the CNRM-CM5 (Wet) RCP8.5, and the IPSL-CM5A-MR (Dry) RCP8.5 climate models under both with and without reservoir scenarios. A decreased amount of runoff is observed under the reservoir scenario for both climate models, resulting in a decreased amount of water available for irrigation. A 39% and 49% reduction in runoff from historical value (12.4 mm) under the reservoir scenario led to a 13% and 24% reduction in surface water irrigation for the wet and dry climate scenarios, respectively, compared to historical value (11 mm).

**Table 4.1.** Average annual hydrologic fluxes (mm) for historical and future climates for both with and without reservoir scenarios.

Hydrologic Flux (mm/yr)									
Scenario	Precipitation	Surface Runoff	Soil Lateral Flow	GW Recharge	Saturation Excess Flow	Pumping	Surface ET	Canal Seepage	Surface Water Irrigation
Historical	467.5	12.4	15.0	30.1	33.6	4.5	411.7	5.4	11.1
CNRM-CM5, 8.5 (Wet)									
Without Reservoir	475.1 (+1.5%)	7.9 (-36%)	10.5 (-30%)	32.7 (+9%)	36.4 (+8%)	4.4 (-2%)	434.3 (+5%)	4.7 (-13%)	10.7 (-3.6%)
With Reservoir	475.1 (+1.5%)	7.6 (-39%)	10.5 (-30%)	32.5 (+8%)	36.2 (+8%)	4.3 (-4%)	433.5 (+5%)	4.6 (-15%)	9.7 (-13%)
IPSL-CM5A-MR, 8.5 (Dry)									
Without Reservoir	433.8 (-7.2%)	6.5 (-48%)	8.0 (-47%)	26.8 (-11%)	30.2 (-10%)	4.4 (-2%)	402.1 (-2%)	4.3 (-20%)	9.2 (-17%)
With Reservoir	433.8 (-7.2%)	6.3 (-49%)	8.0 (-47%)	26.6 (-12%)	30.0 (-11%)	4.4 (-2%)	401.4 (-3%)	4.2 (-22%)	8.4 (-24%)

#### 4.5 Summary and Conclusion

Utilizing integrated basin-scale long-term water resource modeling is a useful tool for assisting future water management strategies. Our study aims to assess the potential effects of constructing a new reservoir in a highly managed semi-arid river basin, specifically focusing on the influence on streamflow and hydrologic fluxes under changing climatic conditions. This study's findings allow water resources and agricultural managers to recognize and mitigate the effects of reservoir construction under different climatic scenarios. The methodology involves using the SWAT+*gwflow* model for predicting future streamflow and hydrologic fluxes. The model was run using two different CMIP5 climate models downscaled by MACA, CNRM-CM5 (Wet) and IPSL-CM5A-MR (Dry) under RCP8.5 emission scenario. The analysis revealed that the CNRM-CM5 (Wet) climate scenario had a higher average monthly diversion rate from the CLP river to the Glade Reservoir during operation months (2.1 m<sup>3</sup>/s) compared to the IPSL-CM5A-MR (Dry) scenario (1.6 m<sup>3</sup>/s). Both climate models show a consistent reduction in the average annual streamflow of the CLP river when the reservoir is present. The largest reduction in the average monthly streamflow in CLP river was observed under the IPSL-CM5A-MR (Dry) RCP8.5 with reservoir scenario for the month of June, showing a 78% decrease from the historical average streamflow. The reduction in streamflow, under the reservoir scenario, for both future climate models led to a 13% and 24% reduction in surface water irrigation for the wet and dry climate scenarios, respectively, compared to historical values.

The results lead to the following conclusions:

1. Assessing the magnitude of the impacts of constructing a new reservoir on water availability and hydrologic fluxes is crucial for water management. The quantity of water diverted from the river to the reservoir, as well as the period of this operation, are key factors for reducing negative impacts and maximizing the advantages of the reservoir.
2. The reservoir's construction reduced the streamflow in the river, which in turn reduced the amount of water available for irrigation. This may lead to more groundwater pumping for irrigation, which

can lead to groundwater depletion and a decrease in groundwater discharge to streams (baseflow), particularly in summer and fall months when flows are already typically very low. These consequences should be considered when implementing basin management strategies that will result in an overall decrease in streamflow during the irrigation season.

## References

- Almahawis, M. K., Bailey, R. T., Abbas, S. A., Arnold, J. G., & White, M. J. (2024). Investigating the impact of irrigation practices on hydrologic fluxes in a highly managed river basin. *Agric. Water Manag.*, 301, 108954. <https://doi.org/10.1016/j.agwat.2024.108954>
- Ayalew, T. B., Krajewski, W. F., Mantilla, R., Wright, D. B., & Small, S. J. (2017). Effect of spatially distributed small dams on flood frequency: Insights from the Soap Creek Watershed. *J. Hydrol. Eng.*, 22(7), 04017011. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001513](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001513)
- Bieger, K., Arnold, J. G., Rathjens, H., White, M. J., Bosch, D. D., Allen, P. M., Volk, M., and Srinivasan, R. (2017). Introduction to SWAT+, a completely restructured version of the soil and water assessment tool, *J. Am. Water Resour. Assoc.*, 53, 115–130, <https://doi.org/10.1111/1752-1688.12482>
- Chai, Y., Li, Y., Yang, Y. *et al.* (2019). Influence of Climate Variability and Reservoir Operation on Streamflow in the Yangtze River. *Sci. Rep.*, 9, 5060. <https://doi.org/10.1038/s41598-019-41583-6>
- Del Giudice, G., Rasulo, G., Siciliano, D., & Padulano, R. (2014). Combined effects of parallel and series detention basins for flood peak reduction. *Water Resour. Manag.*, 28(10), 3193-3205. <https://doi.org/10.1007/s11269-014-0668-1>
- Devia, G. K., Ganasri, B. P., & Dwarakish, G. S. (2015). A review on hydrological models. *Aquatic procedia*, 4, 1001-1007. <https://doi.org/10.1016/j.aqpro.2015.02.126>
- Habets, F., Molénat, J., Carluet, N., Douez, O., & Leenhardt, D. (2018). The cumulative impacts of small reservoirs on hydrology: A review. *Sci. Total Environ.*, 643, 850-867. <https://doi.org/10.1016/j.scitotenv.2018.06.188>
- Hughes, D. A., & Mantel, S. K. (2010). Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. *Hydrological Sciences Journal*, 55(4), 578–592. <https://doi.org/10.1080/02626667.2010.484903>

- Meigh, J. (1995, February). The impact of small farm reservoirs on urban water supplies in Botswana. In *Natural Resources Forum* (Vol. 19, No. 1, pp. 71-83). Oxford, UK: Blackwell Publishing Ltd. <https://doi.org/10.1111/j.1477-8947.1995.tb00594.x>
- Nathan, R., & Lowe, L. (2012). The hydrologic impacts of farm dams. *Australas. J. Water Resour.*, 16(1), 75-83. <https://doi.org/10.7158/13241583.2012.11465405>
- Northern Water. (2024). Environmental impacts of the Northern Integrated Supply Project (NISP). Retrieved August 3, 2024, from <https://www.northernwater.org/NISP/environmental>
- Thompson, J. C. (2012). *Impact and management of small farm dams in Hawke's Bay, New Zealand* (Doctoral dissertation, Open Access Te Herenga Waka-Victoria University of Wellington).
- Valayamkunnath, P., Barlage, M., Chen, F., Gochis, D.J. and Franz, K.J., 2020. Mapping of 30-meter resolution tile-drained croplands using a geospatial modeling approach. *Sci. data*, 7(1), pp.1-10. <https://doi.org/10.1038/s41597-020-00596-x>

## CHAPTER 5 – SUMMARY AND CONCLUSIONS

### 5.1 Summary and major findings

The aim of this dissertation is to investigate the impact of irrigation and water storage practices on hydrologic fluxes under climate change in a highly managed river basin. A thorough methodology was employed to model hydrologic processes at the watershed scale in the Cache la Poudre River Basin, which is classified as a HUC8 watershed. The study employed a new groundwater modeling routine called the *gwflow* module, which is integrated within the SWAT+ watershed modeling system. This routine is characterized by its spatial distribution and physical basis. The daily water balance in the unconfined aquifer is calculated by employing a collection of connected grid cells, with each cell representing a volume of the unconfined aquifer. To explore the effect of irrigation practices, the SWAT+ modeling code was modified to include detailed, field-based surface water and groundwater irrigation practices as well as canal-groundwater exchange due to the extensive network of earthen canals. The process of model calibration was conducted utilizing the PEST software, taking into consideration the observed data of stream flow and groundwater head. Cell-by-cell raster maps were utilized to validate the accuracy of hydrologic fluxes in a watershed by representing various groundwater fluxes such as canal seepage, recharge, saturation excess flow, tile drainage, pumping, and groundwater-surface water exchange.

The model was subsequently employed to assess the quantitative effects of several irrigation scenarios including surface water and groundwater on water availability and hydrologic fluxes within the river basin. A total set of 22 scenarios was carried out, encompassing five distinct categories: irrigation source, irrigation amount, irrigation type, canal bed thickness, and partial or full sealing of irrigation canals. The model was also run under five different CMIP5 climate models to analyze the potential impacts of climate change on water resources and hydrologic fluxes. The climate models are downscaled

by MACA, each representing two different climate emission scenarios, RCP4.5 and RCP8.5. Moreover, the constructed and test SWAT+*gflow* model was used to assess the potential effects of constructing a new reservoir using two different CMIP5 climate models under RCP8.5 emission scenario.

The following major findings are drawn from the results:

1. Quantifying the impact of surface water and groundwater irrigation scenarios on water availability and hydrologic fluxes is important for water management. Irrigation source, irrigation amount, and irrigation type are essential for minimizing negative impacts and maximizing the benefits of irrigation practices.
2. The source of irrigation plays the biggest role among all factors impacting hydrologic fluxes.
3. The canal seepage fluxes had an impact on the overall comprehensive hydrologic fluxes, a loss from the surface water system and an increased groundwater discharge. The inclusion of canal seepage in hydrologic models is crucial for enhancing the precision of hydrological simulations and plays a vital role in facilitating efficient water resource management and planning.
4. The findings from the Morris analysis demonstrate the significance of certain model parameters in governing the hydrological mechanisms at individual gage sites. Gaining insight into these sensitivities has significant value in enhancing the precision of the distributed hydrologic model and in facilitating well-informed decision-making pertaining to water resource management within the watershed.
5. The analysis reveals that the IPSL-CM5A-MR-8.5 climate model in the CLP is the most severe, as it combines two climatic stressors: less precipitation and increased temperature.
6. Employing several climate scenarios generated by multiple global and regional climate models covering a range of projections including wet, dry, hot, warm, and mild when running future

simulations. Taking into consideration the inherent uncertainties in climate modeling, this diversity is necessary for thorough risk assessment and planning.

7. Account for different water management (irrigation source, irrigation amount, irrigation type) is crucial to establish water management techniques that are effective and sustainable to ensure the adaptability and efficiency of agricultural systems in response to changing environmental conditions.
8. The transboundary water source that flows into the watershed has consistently maintained a stable discharge throughout the investigated historical period. This indicates the existence of regulated water management methods and agreements, irrespective of the impact of climate change.
9. Assessing the magnitude of the impacts of constructing a new reservoir on water availability and hydrologic fluxes is crucial for water management. The quantity of water diverted from the river to the reservoir, as well as the period of this operation, are key factors for reducing negative impacts and maximizing the advantages of the reservoir.
10. The reservoir's construction reduced the streamflow in the river, which in turn reduced the amount of water available for irrigation. In reality, this may lead to an increase in groundwater pumping for irrigation, which can lead to groundwater depletion in the watershed and an overall decrease in groundwater discharge to streams (baseflow), particularly during the summer and fall months.

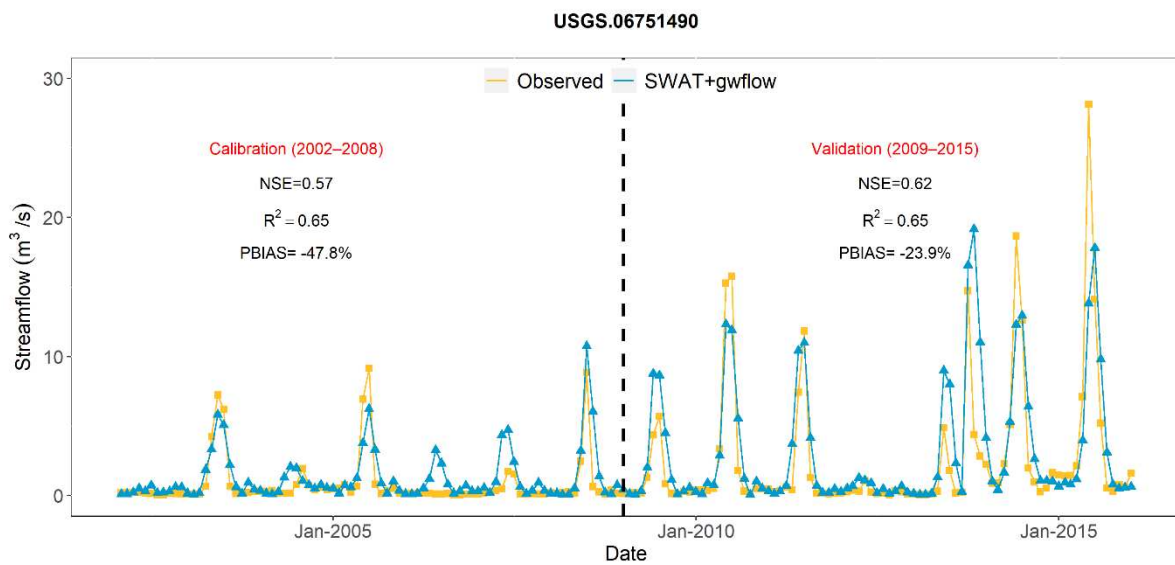
## 5.2 Future research directions

Over the study period, multiple possibilities for further research were found:

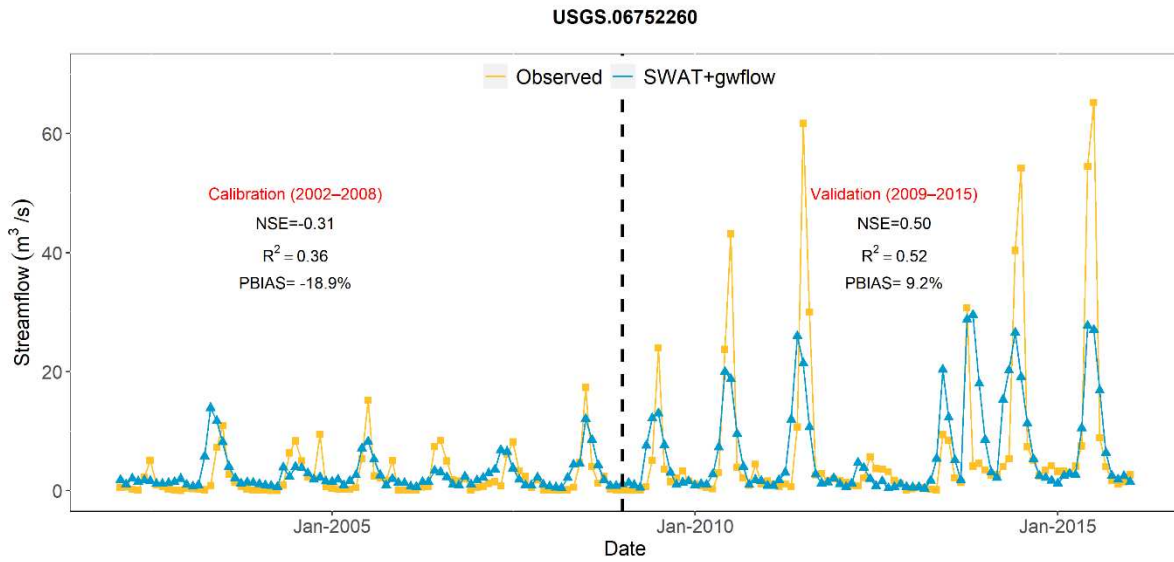
1. Given that the *gflow* module only accounts for a single-layer unconfined aquifer with heterogeneity, it is worth exploring the implementation of a multiple layer groundwater module that can incorporate the network of fields, channels, and reservoirs.
2. The simulation explicitly models the recharge from cultivated fields to the unconfined aquifer. However, the recharge from non-field HRUs is not explicitly represented due to the lack of delineation of these HRUs in the NAM. Hence, the calculation of recharge for non-field HRUs is based on the average recharge rate for the 12-digit catchment. Therefore, a more detailed modeling of the recharge for both the irrigated and non-irrigated HRUs could be employed to improve the recharge simulation.
3. The SWAT+*gflow* model doesn't account for certain variations in agricultural practices, such as crop rotation and varying planting dates. Accordingly, a better representation of agricultural practices will enhance the model outcome.
4. An unstructured grid within the *gflow* module could be employed to have a better representation of the groundwater system at local (field) scales and near streams and canals, to more completely account for the complexity and heterogeneity of the system.
5. This study did not consider land use change when running the future simulations. Therefore, including dynamic land use changes can enhance the accuracy of the model, resulting in more reliable predictions.

## Appendix

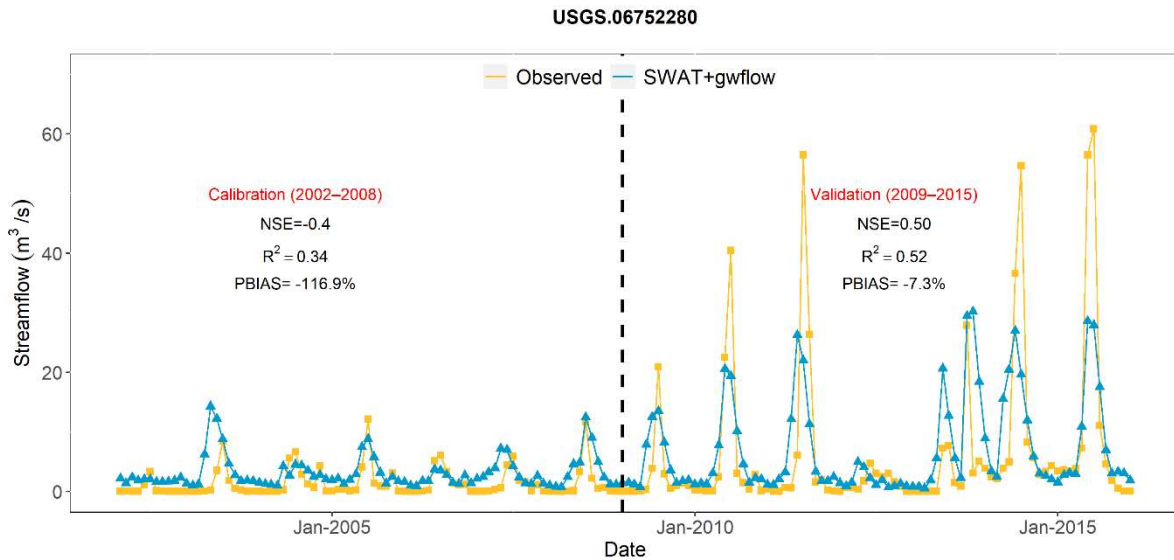
The results of using the dry period (2002–2008) as the calibration period, and the wet period (2009–2015) as the testing period are presented in this section. While the streamflow response during the dry period is captured adequately, the peak flows during the wet period are greatly underestimated, particularly in the downstream portion of the river basin.



**Figure A1.** Measured and simulated monthly streamflow for SWAT+*gflow* models for the USGS 06751490 stream gaging sites within the CLP watershed. Performance statistics (NSE, PBIAS,  $R^2$ ) are shown.



**Figure A2.** Measured and simulated monthly streamflow for SWAT+*gwfow* models for the USGS 06752260 stream gaging sites within the CLP watershed. Performance statistics (NSE, PBIAS,  $R^2$ ) are shown.



**Figure A3.** Measured and simulated monthly streamflow for SWAT+*gwfow* models for the USGS 06752280 stream gaging sites within the CLP watershed. Performance statistics (NSE, PBIAS,  $R^2$ ) are shown.