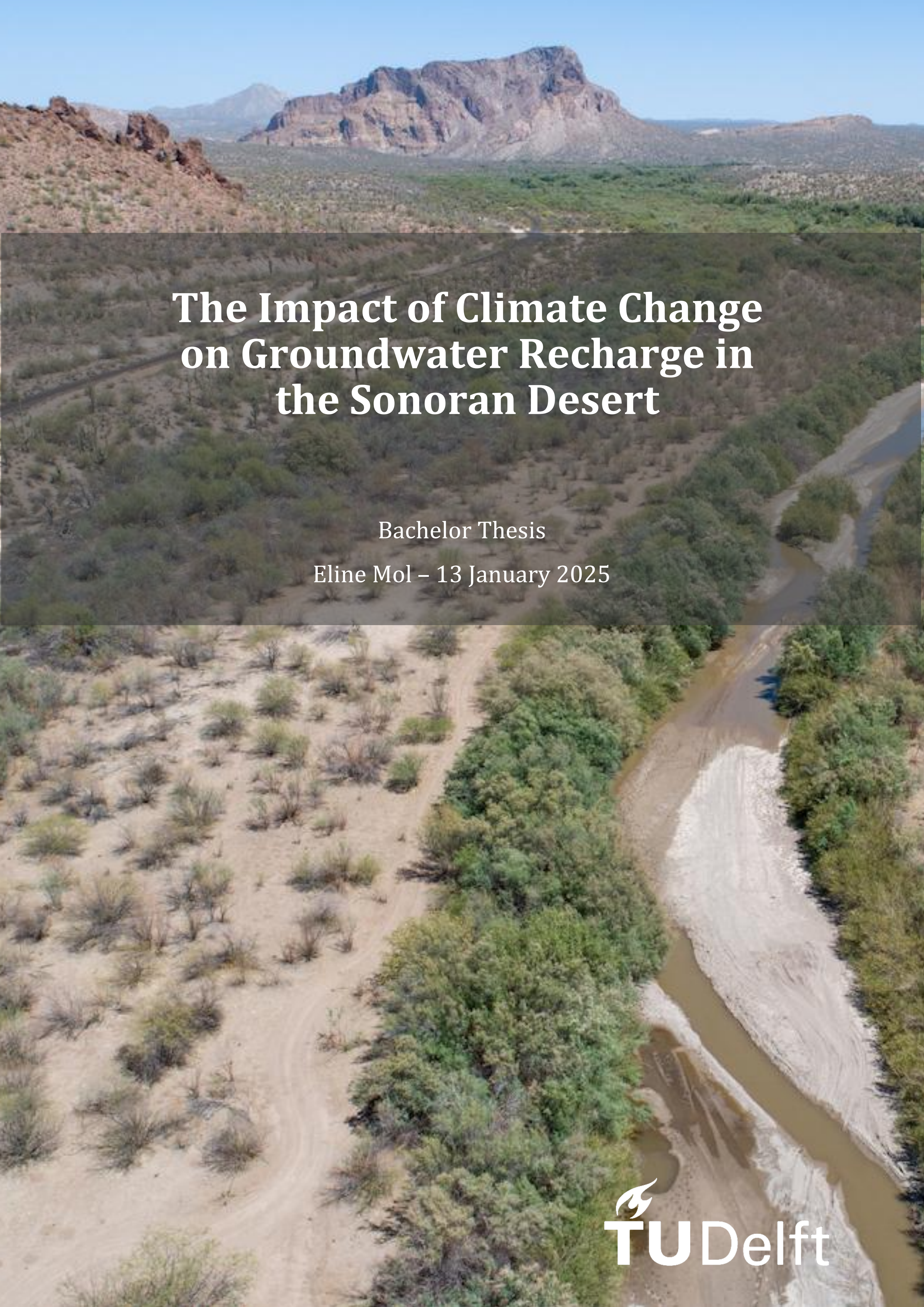

The Impact of Climate Change on Groundwater Recharge in the Sonoran Desert

Bachelor Thesis

Eline Mol – 13 January 2025

TU Delft

The Impact of Climate Change on Groundwater Recharge in the Sonoran Desert

Bachelor Thesis

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January 13th, 2025

Cover image: Robbins & Wood (2021)

Preface

Before you lies the bachelor thesis on "*The Impact of Climate Change on Groundwater Recharge in the Sonoran Desert*", which is written for the course 'Bachelor Eindwerk' (CTB3000-16). This thesis fulfils one of the graduation requirements for the Bachelor of Science in Civil Engineering at Delft University of Technology.

The topic of climate change has been a subject of interest throughout my studies. Therefore, it was clear that this is a topic I want to research. In exploring areas I want to focus on, I was drawn to the Sonoran Desert. This region is characterized by its arid climate and impending water shortage.

I would like to express my sincere gratitude to my supervisors dr. ir. R. Hut and ir. V. Hoogelander for guiding me and providing support throughout this research. Their knowledge on hydrological systems and the hydrological models in eWaterCycle helped me navigate through this project. Additionally, I would like to thank Bart from the eScience Center for providing technical assistance during this project.

Eline Mol
Delft, January 13th, 2025

Abstract

This report researched the impact of climate change on groundwater recharge in the Sonoran Desert. The Sonoran Desert is an arid region, located in the southwestern United States and northwestern Mexico. Known for its susceptibility to water scarcity, the region has implemented policies addressing (ground)water availability to ensure future water security. Groundwater currently serves as the primary source, supporting urban, industrial and agricultural sectors.

Climate change is expected to affect the region, following the trend where wet regions become wetter and dry regions become drier. Given these concerns, this research aims to address the following research question: *"How will climate change influence groundwater recharge in the Gila River basin in the Sonoran Desert over the 21st century?*".

This research has utilized the eWaterCycle platform, which currently contains six different hydrological models. For this study, the hydrological model PCR-GlobWB has been used. This model can simulate groundwater recharge. Through the application a water balance, an approximation of groundwater recharge can be simulated.

Historical groundwater recharge data were simulated using an ERA5 forcing , providing a benchmark for evaluating future climate scenarios. These future climate scenarios were simulated using a CMIP6 forcing, focusing on three scenarios: SSP1-2.6, SSP2-4.5 and SSP5-8.5. These scenarios correspond to an optimistic climate scenario, a middle road scenario and the worst-case scenario, respectively.

The findings of the research indicate that the simulated groundwater recharge values, directly derived from PCR-GlobWB, are not realistic values. In contrast, the approximated groundwater recharge values provide a more realistic magnitude. The main findings from the approximated groundwater recharge simulations suggest a decline in groundwater recharge in all scenarios. The scenario SSP1-2.6 has a decrease in groundwater of 2.9%, SSP2-4.5 has a decrease of 6.2% and SSP5-8.5 has a decrease of 5.6%.

Efforts to address the anticipated reduction in groundwater recharge have already been initiated by institutions in Arizona, California and Mexico through implementation of strict water regulations. However, additional measures are needed to further reduce the negative effects. For instance, sustainable water management and restoration of natural water flow are critical. Current policies aim at replenishment of aquifers are a promising start, and should be sustained and expanded to enhance long-term water security and environmental sustainability.

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1. Introduction

Over the last century, the Earth's climate has warmed more than 1 ˚C. In some regions more drought will occur, while other regions will be wetter (IPCC, 2021). In times limited of rainfall, groundwater storages will act as a natural buffer. These storages will provide against water scarcity, limiting evaporation in areas with shallow water tables and sustaining river and wetland baseflows which supports ecosystems and biodiversity (de Graaf et al., 2017). The process of water infiltrating into soil layers and replenishing groundwater is called groundwater recharge. Generally, groundwater is recharged through processes that are controlled by: geology, temperature, precipitation, potential evapotranspiration, humidity and land use (Castillo et al., 2021).

Arid regions such as the Sonoran Desert (Figure 1) rely on groundwater as the primary water source, supporting the urban, environmental and agricultural sector. For instance, the agricultural sector uses the biggest amount of the available water, about 75% of the available groundwater and surface water (Arizona Department of Water Resources, 2023; Public Policy Institute of California, n.d.). However, long-term groundwater over-pumping poses a significant threat to this resource (PPIC, n.d.). In the Sonoran Desert region, groundwater management has been a pressing priority for decades. For instance, Arizona started regulating groundwater in its largest cities under a new law in 1980, the Groundwater Management Code. This law stated a goal of achieving a long-term balance between the amount of groundwater pumping and the amount of replenishing these buffers (James, 2021). In 2014, California adopted a similar law (Sustainable Groundwater Management Act) to manage and regulate its groundwater sources, as attempt to prevent and recover groundwater depleted basins (Mason, 2014). In Mexico, the Law of the Nation's Water (LAN) is adopted in 1992, stating the management and regulation of water entitlement. It states the appropriation, allocation and concession of groundwater rights (Cruz-Ayala & Megdal, 2020).

Figure 1: Desert areas of North America (Shelton, 1972)

Due to growing concerns of the groundwater availability in the future, this report researches what the impact of climate change will be on the groundwater recharge in the Sonoran Desert. Therefore, the following research question will be answered:

"How will climate change influence groundwater recharge in the Gila River basin in the Sonoran Desert over the 21st century?"

The analysis to answer this research question involves simulation of historical data and future climate projections of groundwater recharge in this region. Using the hydrological model, PCR-GlobWB, on the eWaterCycle platform, these simulations will be modelled. The main research question will be answered by simulating the groundwater recharge using the PCR-GlobWB model. Sub-questions to answer the main research question are as follows:

- What forcings are of importance in the Sonoran Desert?
- Which parameters will have an influence on the groundwater recharge?
- For which climate scenarios will groundwater recharge be simulated, and which scenario will have the biggest impact?

This report consists of five chapters. Chapter 1 serves as the introduction, outlining the research motivation, the problem analysis and the objectives of this study. Chapter 2 details the methodology of this study, which illustrates the study area and focuses on the eWaterCycle platform and the application of the hydrological model PCR-GlobWB. Chapter 3 contains the results generated by this model. Chapter 4 includes a discussion, evaluating the results and reflecting on implications. Finally, Chapter 5 concludes the report, gives recommendations for the future and provides the answer to the research question.

2. Methodology

The chapter outlines the methods used to analyse the impact of climate change on groundwater recharge. First, Section 2.1 discusses the study area. Section 2.2 focuses on the hydrological model PCR-GlobWB. Section 2.3 discusses the climate projections and the application of CMIP6. Lastly, in Section 2.4 the water balance in the study area is discussed.

2.1 Study Area

The Sonoran Desert is an arid region with a subtropical climate in the Southwestern of the United States and Northwestern of Mexico. According to the National Park Service (NPS, 2024) the desert covers approximately 260 000 km^2 of this region, as shown in Figure 1. In this region, the hydrological system includes many streams and two primary rivers, the Colorado River and the Gila River, Figure 2. A majority of the smaller streams remain dry for most of the year (Kampf et al., 2018).

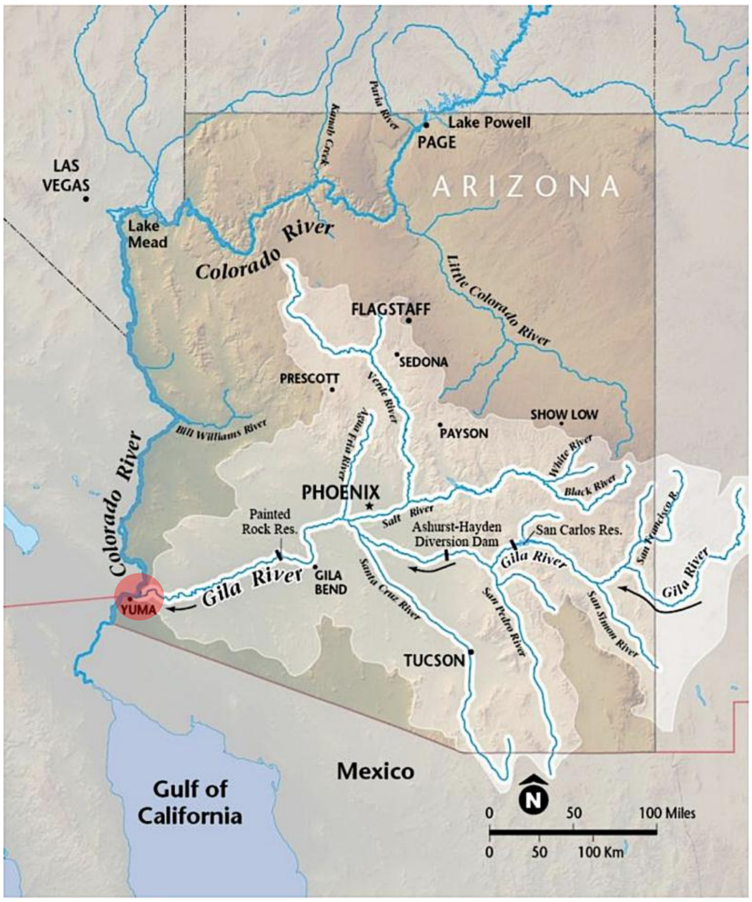


Figure 2: Rivers in Arizona (Robbins & Wood, 2021)

The Sonoran Desert receives an average annual precipitation of 76-500 mm. Majority of the rainfall occurs during the summer monsoon thunderstorms. However, it also receives frequent low-intensity winter rains and a significant amount is occurring as snowfall at higher elevations. Precipitation is an important factor to recharge groundwater. Another critical factor is temperature, which influences the rate of evapotranspiration. High temperatures increase the rate of evapotranspiration, reducing the amount of water available for groundwater recharge (Dimitriadou & Nikolakopoulos, 2021). During the summer, air temperatures exceed 40°C. The temperatures in the winter are mild and mostly free of frost (NPS, 2024).

The Gila River spans a greater stretch within the Sonoran Desert compared to the Colorado River (Figure 2). The Colorado River extends to the Rocky Mountains and flows through multiple regions, which can be categorized into the Upper basin and the Lower basin. The discharge in the basins is influenced by several factors, including the milder temperatures and the amount of precipitation (Salehabadi et al., 2020). Appendix B provides figures with the mean temperature, mean precipitation and mean runoff of the two basins. Since many factors influencing the discharge of the Colorado river originate outside the Sonoran Desert, this research focuses on the Gila River. The rivers converge near the city Yuma, which is highlighted in Figure 2.

This study simplified the groundwater flow by assuming it occurs in a single direction, along the streamflow of the Gila River. This will simplify the results. However, in reality the groundwater flow is often a multiple directions and is influenced by several factors (USGS, n.d.).

2.2 PCR-GlobWB

This study will focus on the impact of climate change on the groundwater recharge in the Sonoran Desert. To assess the impact, the eWaterCycle platform will be used. In eWaterCycle, hydrological models are made FAIR (findable, accessible, interoperable and reproducible) by adding a Basic Model Interface (BMI). These models can be run through the open interface of eWaterCycle and run using Jupyter notebooks provided by the platform. The eWaterCycle platform currently supports the following hydrological models: PCR-GlobWB, wflow, Hype, LISFLOOD, MARRMoT and WALRUS. To predict the effects on the groundwater recharge, the PCR-GlobWB model will be used (Hut et al., 2022).

The PCR-GlobWB model is a grid based, global hydrology and water resources model. Because the computational grid covers all the continents, except Greenland and Antarctica, it can be used to simulate the area of the Sonoran Desert (Sutanudjaja et al., 2018).

The PCR-GlobWB model incorporates various aspects of water use, including sector specific water demand, groundwater and surface water withdrawals, water consumption and return flows. It is capable of simulating soil moisture storage and the exchange of water between the soil, atmosphere and the underlying groundwater reservoir. The components enable the model to estimate groundwater recharge. All of these processes are computed at each time step and are integrated into the simulated hydrology. However, certain factors in the model, such as irrigation, stay constant over time (Sutanudjaja et al., 2018). This limitation should be considered when interpreting the simulated outputs.

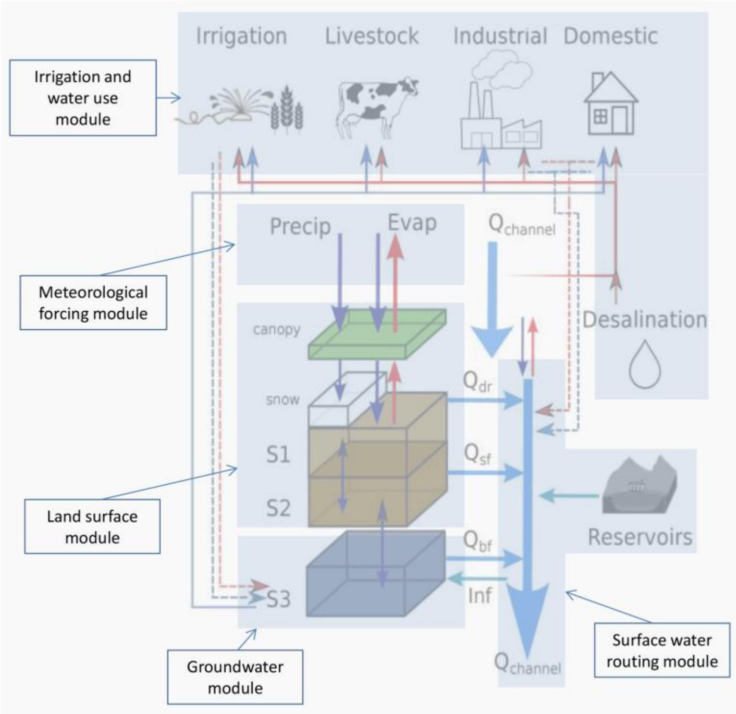


Figure 3: PCR-GlobWB 2.0 cell (Sutanudjaja et al., 2018)

In Figure 3 a simplified overview of a PCR-GlobWB cell can be found to give an impression of all the fluxes in a system. In this figure, the thin red and blue line indicate surface water withdrawal and groundwater extraction, respectively. The dashed lines indicate return flows. PCR-GlobWB simulates at a spatial resolution of 5 arc-minute, which is ~10x10 km at the equator (Sutanudjaja et al., 2018).

2.3 Historical Data

The hydrological models on the eWaterCycle platform generally need two inputs: a forcing and a parameter. Forcings are defined as a time-varying input. In contrast, a parameter is a constant input (Hut et al., 2022). The parameter input is the time that needs to be simulated and the catchment area, in this case the Sonoran Desert. This input remains the same for the historical data and for the climate projections.

The forcing input for hydrological models such as PCR-GlobWB in eWaterCycle is derived from ERA5 datasets (Hut et al., 2022). ERA5 offers comprehensive recorded data on the global atmosphere, the land surface and ocean waves from 1950 to the present (Hersbach et al., 2020). To prepare the ERA5 dataset for direct application in the PCR-GlowbWB model, the ESMValTool in eWaterCycle is enabled. In this research, precipitation and temperature serve as the input for forcing. Additionally, a parameter set including is required as model input, which includes the catchment area and the time period (Hut et al., 2022). Figure 4 presents a flow chart of the PCR-GlobWB model, with ERA5 and a parameter set as input.

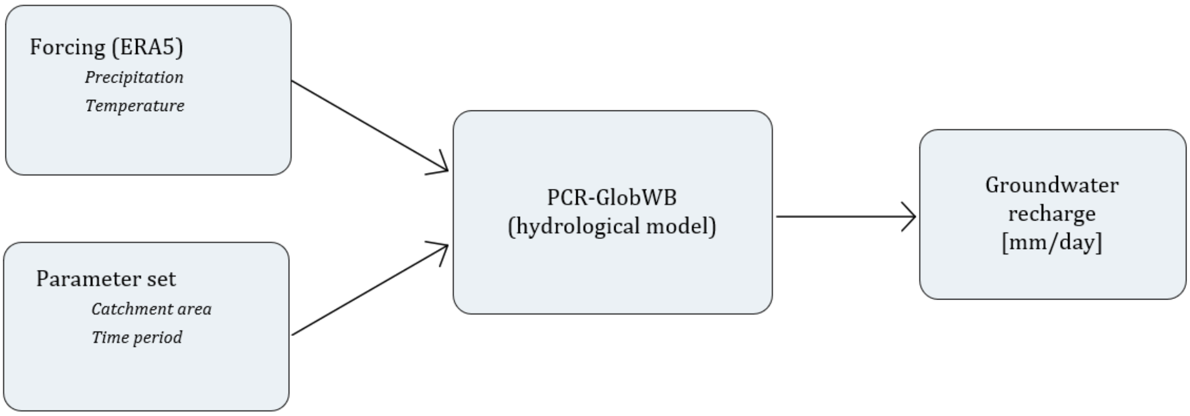


Figure 4: PCR-GlobWB flowchart (ERA5)

2.4 Climate Projections

To evaluate the potential impact of climate change, the Coupled Model Intercomparison Project Phase 6 (CMIP6) will be used for climate simulations. Three Shared Socioeconomic Pathways (SSPs) are selected for analysis: SSP1-2.6, SSP2-4.5 and SSP5-8.5. These pathways correspond to an optimistic scenario limiting the future warming to 1.3-2.4°C, a middle road limiting the warming to 2.1-3.5°C and the worst-case scenario which limits the future warming to 3.3-5.7°C in 2100, respectively (Masson-Delmotte et al., 2021). Appendix A explains the narratives of each of the selected SSPs and contains a graph of the increase of CO2 emissions and global mean temperature. The mentioned SSPs is used as forcing input to simulate the future groundwater recharge. Figure 5 provides a flowchart of the PCR-GlobWB model with CMIP6 as forcing input.

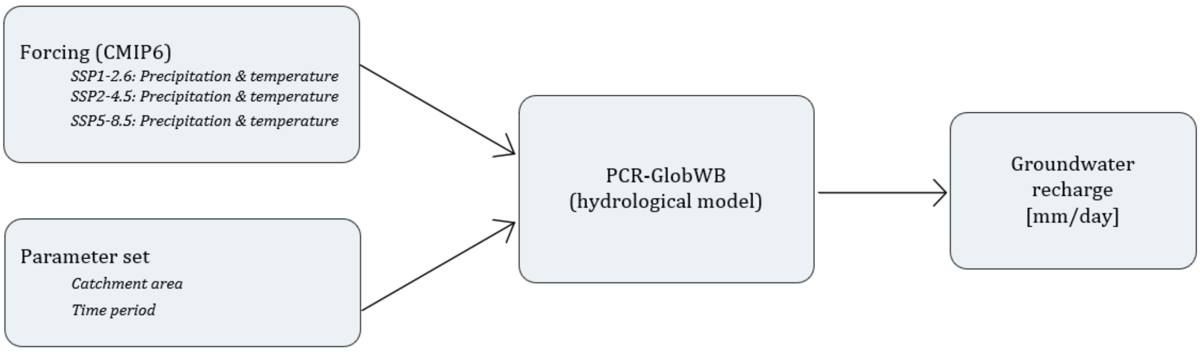


Figure 5: PCR-GlobWB flowchart (CMIP6)

2.5 Water Balance

As outlined in Sections 2.2 and 2.3, the requested output of the PCR-GlobWB model is groundwater recharge. To validate the groundwater recharge values obtained, a water balance is assessment is required. A water balance represents the water input and water output within a system (Srivastava et al., 2020). For the Gila River basin, the water balance components include the change in groundwater storage (ΔS), the minimum river discharge (Q), the average precipitation (P), the average surface runoff (R), the average evaporation transpiration (ET) and agricultural water extraction (Agr). The water balance is given by Equation 1.

$$Groundwater\ recharge = \Delta S + Q + P + R - ET - Agr \qquad (Eq.\ 1)$$

The mean annual change in groundwater storage is -0.2 m/year (Arizona Groundwater Dashboard, 2024). In arid regions on regional scale, the baseflow of rivers is often indicative of the minimum groundwater recharge that is required to sustain streamflow (Schilling et al., 2021). The baseflow of the Gila River near Yuma is 0 ft^3/s (USGS, n.d.). According to the maps provided in Appendix B, the mean annual precipitation is 15 in/year and the mean annual runoff is 0 in/year. The groundwater extraction for agricultural use is 1.15 MAF/year (ADWR, 2022). The mean annual evapotranspiration in the Santa Cruz aquifer is estimated at $8.83*10^6$ m^3/year (Tapia-Villaseñor, 2022). As this region lies within the Sonoran Desert, it is assumed that similar climatic conditions lead result in comparable evapotranspiration rates. Therefore, the evapotranspiration of Santa Cruz aquifer has been scaled proportionally to estimate the evapotranspiration for the Gila River basin. The evapotranspiration and the other values are summarized in Table 1. The derivations of the values of the metric system are explained in Appendix C.

	Imperial units	Metrical units [m^3/year]
ΔS	-0.6 [in/year]	$-3*10^9$
Q	0 [ft^3/s]	0
P	15 [in/year]	$5.9*10^{10}$
R	0 [in/year]	0
ET	-	$4.05*10^8$
Agr	1.15 [MAF/year]	$1.42*10^9$

Table 1: Input water balance in imperial units and metrical units.

Based on the values in Table 1 and using Equation 1, the groundwater recharge is calculated to be -0.29 m/year (-0.78 mm/day). A positive value would indicate an increase in groundwater recharge. However, this negative value indicates a decrease in groundwater recharge. Since this value is derived from observations and measurements, this value is used to validate the simulated output generated by PCR-GlobWB.

The water balance is also be applied while performing the simulation, to further validate the simulated groundwater recharge. Using the available corresponding variables from PCR-GlobWB, the following are in the water balance: precipitation (P), total evaporation (E), total groundwater abstraction (Abs), land surface runoff (R) and discharge (Q). These values are used to approximate the simulated groundwater recharge, as represented in Equation 2.

$$Approximated\ groundwater\ recharge = Q + P + R - E - Abs \qquad (Eq.\ 2)$$

A flowchart to obtain the approximated groundwater recharge is given in figure 6. This is simulated for both ERA5 and CMIP6.

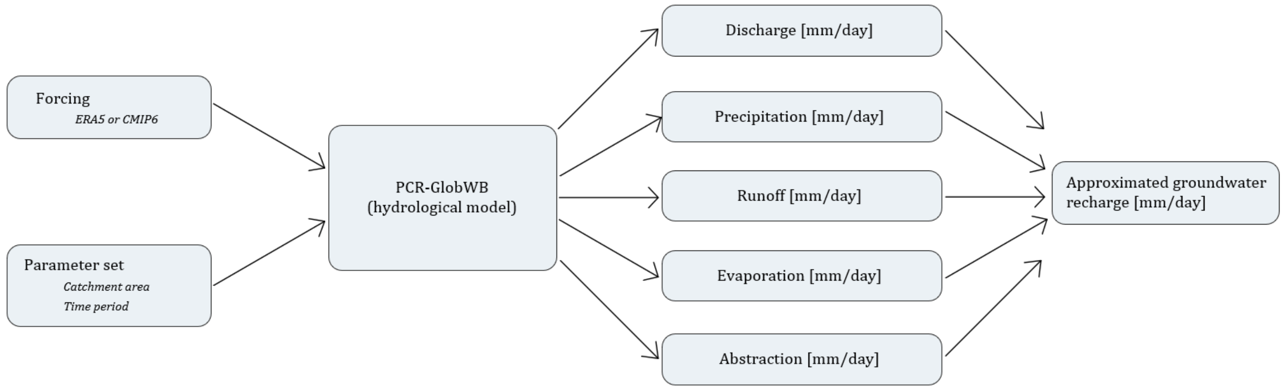


Figure 6: PCR-GlobWB flowchart (approximated groundwater recharge)

3. Results

This chapter presents the results derived from the methodology outlined in Chapter 2. Using the hydrological model PCR-GlobWB, simulations are conducted to provide insights into the impact of climate change on groundwater recharge. Section 3.1 the historical groundwater recharge and its approximation are simulated to establish a baseline. Section 3.2 focuses on the simulated groundwater recharge, while Section 3.3 focuses on the approximated groundwater recharge. These latter two sections focus on the future climate scenarios.

3.1 Historical Groundwater Recharge

To generate a forcing dataset with historical data, an ERA5-dataset spanning the period 1990 to 2020 is used in a generate forcing notebook. The parameter set defines a specific catchment area by defining several coordinates on the ERA5-grid. The outcomes obtained from this forcing dataset and the parameter set in notebooks, the results are simulated (https://github.com/eWaterCycle/projects/tree/draft_eline/book/thesis_projects/BSc/2024_Q2_ElineMol_CEG/Report/results). This serves as a baseline for evaluating results simulated with CMIP6. Both the groundwater recharge and the approximated groundwater recharge have been analysed and plotted for the 1990-2020 period, as illustrated in Figure 7.

The groundwater recharge depicted in Figure 7 demonstrates relatively low values, with outliers ranging from 0.024 to 0.002 mm/day. Comparing the groundwater recharge values to the calculated groundwater recharge from Section 2.5, these values are significantly lower, and do not align with the realistic magnitude of the benchmark established earlier. In contrast, the values of the approximated groundwater recharge are more closely aligned with the magnitude of the benchmark provided in Section 2.5.

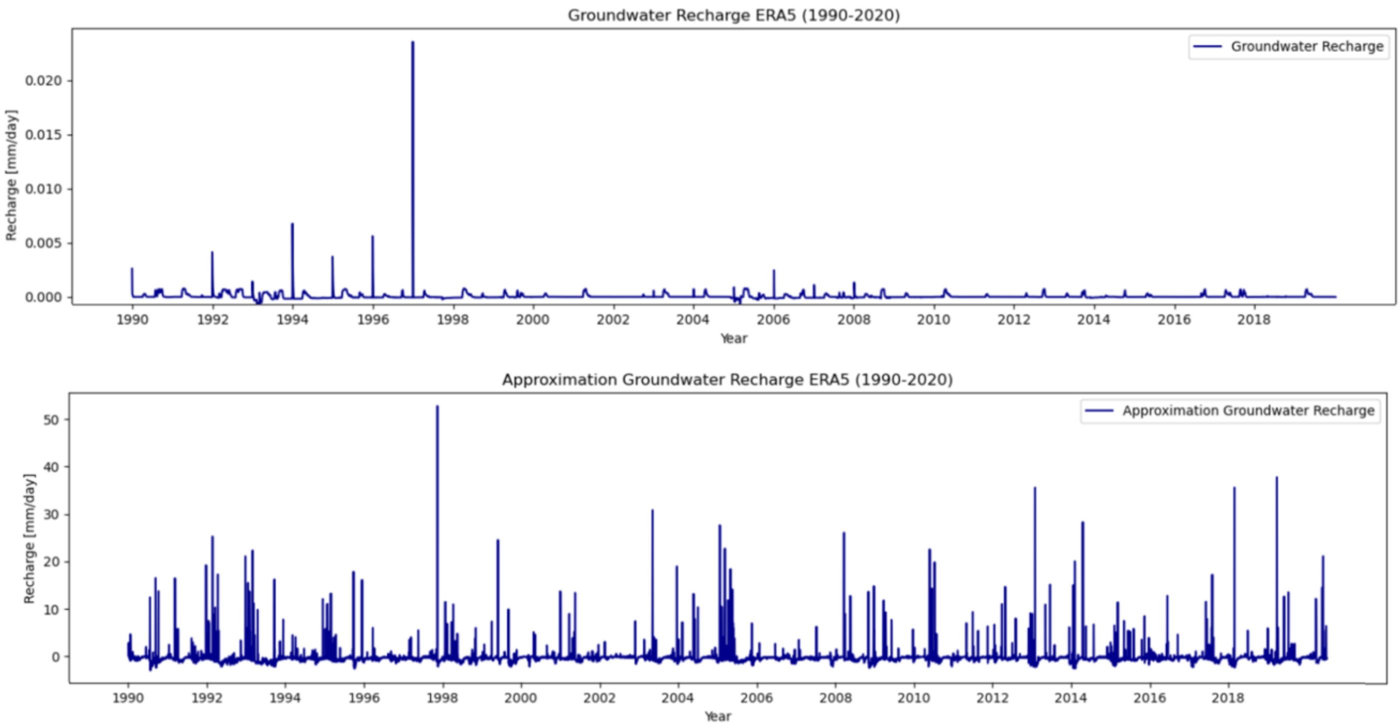


Figure 7: Groundwater recharge ERA5 and approximated groundwater recharge ERA5 for period 1990 to 2020

Figure 8 presents the boxplots for the groundwater recharge and approximated groundwater recharge, highlighting the discrepancy between these values. These boxplots demonstrate that the groundwater recharge values are notably lower than those of the approximated groundwater recharge. Appendix D contains a concise analysis of the outliers in the boxplots. The analysis uses the Z-value to detect and evaluate outliers, based on their standard deviation and mean. The appendix also includes revised boxplots that exclude the outlier, offering a clearer representation of the data.

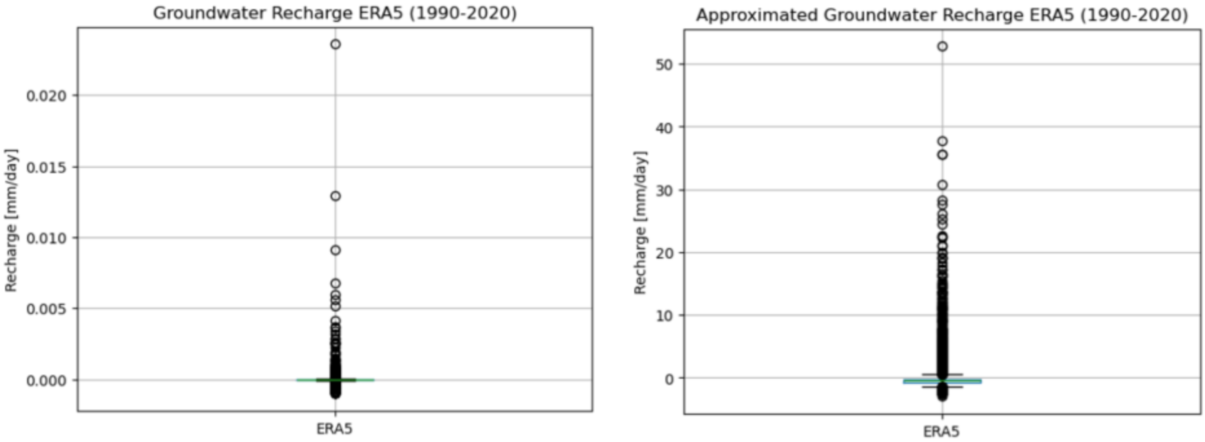


Figure 8: Boxplots of groundwater recharge ERA5 (left) and approximated groundwater recharge ERA5 (right) over period 1990 to 2020

Table 2 provides a quantitative summary of the boxplots and the mean summation of groundwater recharge per year. Specifically, the summation of the approximated groundwater recharge, calculated as -123.05 mm, serves as a benchmark for evaluating future climate simulation results in Sections 3.2 and 3.3.

	Groundwater Recharge [mm/day]	Approximated Groundwater Recharge [mm/day]
Min.	-0.001	-3.009
Mean	4.961	-0.337
Max.	0.024	52.786
Sum	0.544	-123.046

Table 2: Quantitative summary of the boxplots

3.2 Simulated Groundwater Recharge

The three future climate scenarios are simulated by re-using the established parameter set, and adjusting the CMIP6 grid size to the ERA5 grid size in the generate forcing notebook. This modification accounts for the differing spatial resolution between the ERA5 and CMIP6 dataset. Three forcing datasets were created for the three SSPs (SSP1-2.6, SSP2-4.5 and SSP5-8.5), covering the period from 2025 to 2100. By applying the generated forcing and the parameter set in a notebook, results based on CMIP6 data were obtained (https://github.com/eWaterCycle/projects/tree/draft_eline/book/thesis_projects/BSc/2024_Q2_ElineMol_CEG/Report/results).

Figure 9 illustrates the groundwater recharge over the near-term and mid-term period of 2025 to 2065. Outliers in the graph have a small range. These value are consistent with the outcome of Section 3.1 and, once again, do not align with the magnitude of the benchmark set in Section 2.5. To offer further clarity, Figure 10 provides a detailed visual representation of groundwater recharge for the years 2025 and 2050. This figure shows the low groundwater recharge value for a year.

Given that the simulated groundwater recharge values remain significantly smaller than the realistic benchmark magnitude set in Section 2.5, this variable is unrealistic and is unsuitable for further analysis within this study.

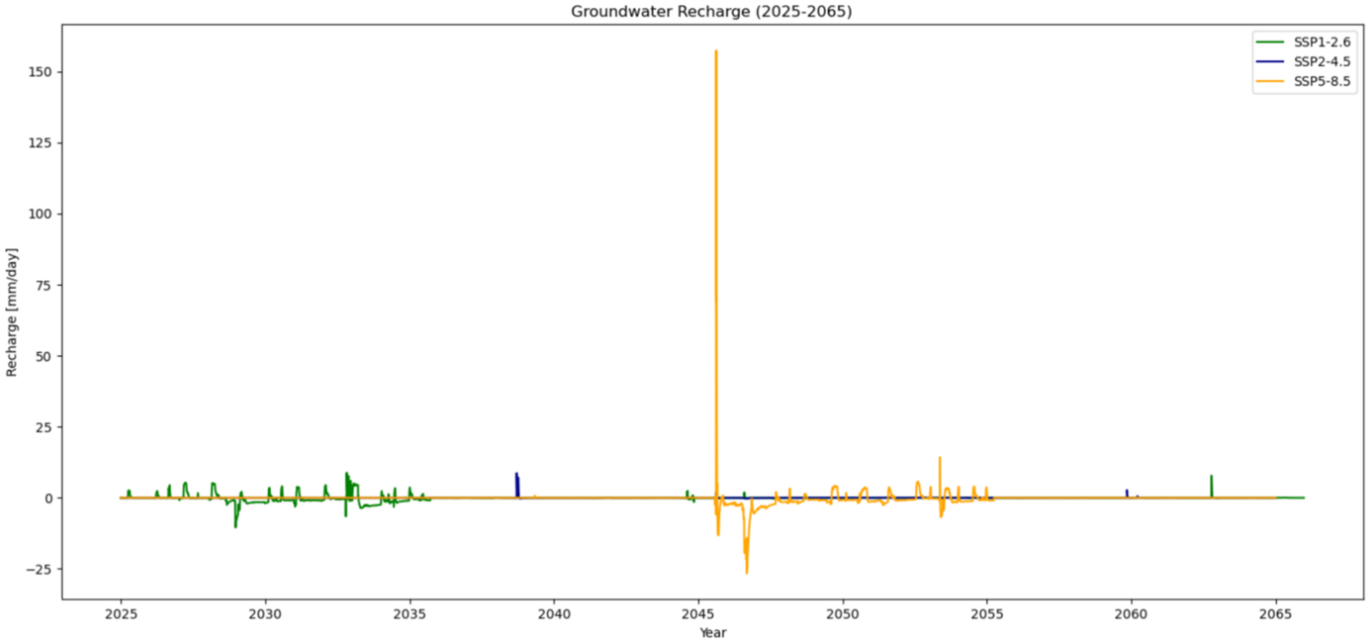
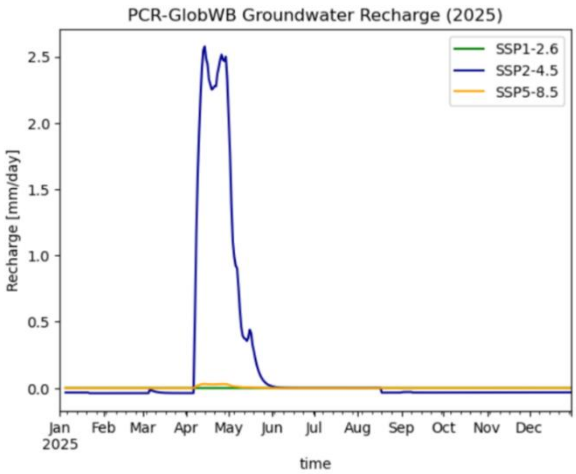


Figure 9: Groundwater recharge (2025-2065)



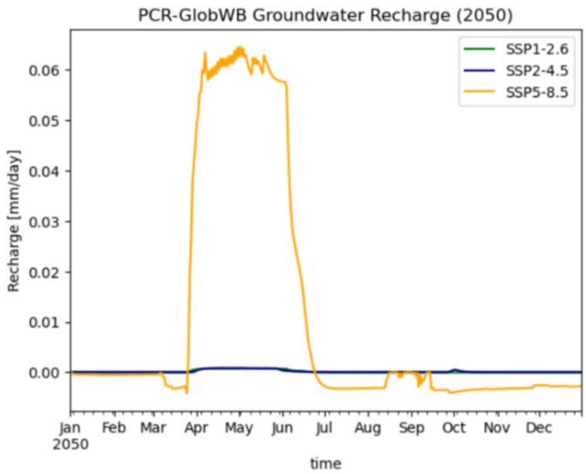


Figure 10: PCR-GlobWB simulated groundwater recharge for future climate scenarios for 2025 (left) and 2050 (right)

3.3 Simulated Approximation Groundwater Recharge

The simulation of approximated groundwater recharge uses the same forcing dataset and parameter set as described in Section 3.2. Initially, the precipitation, the total evaporation, the total groundwater abstraction, the land surface runoff and the discharge were generated for the period 2025-2100. These components were integrated in the water balance to estimate the approximated groundwater recharge.

Figure 11 illustrates the 21st century divided in two halves, specifically for 2025-2065 and 2065-2100. The century is divided into two halves to improve the clarity of the graph. Appendix E provides a more detailed analysis by dividing graphs into ten-year intervals, offering a more clear visualization of trends within each decade.

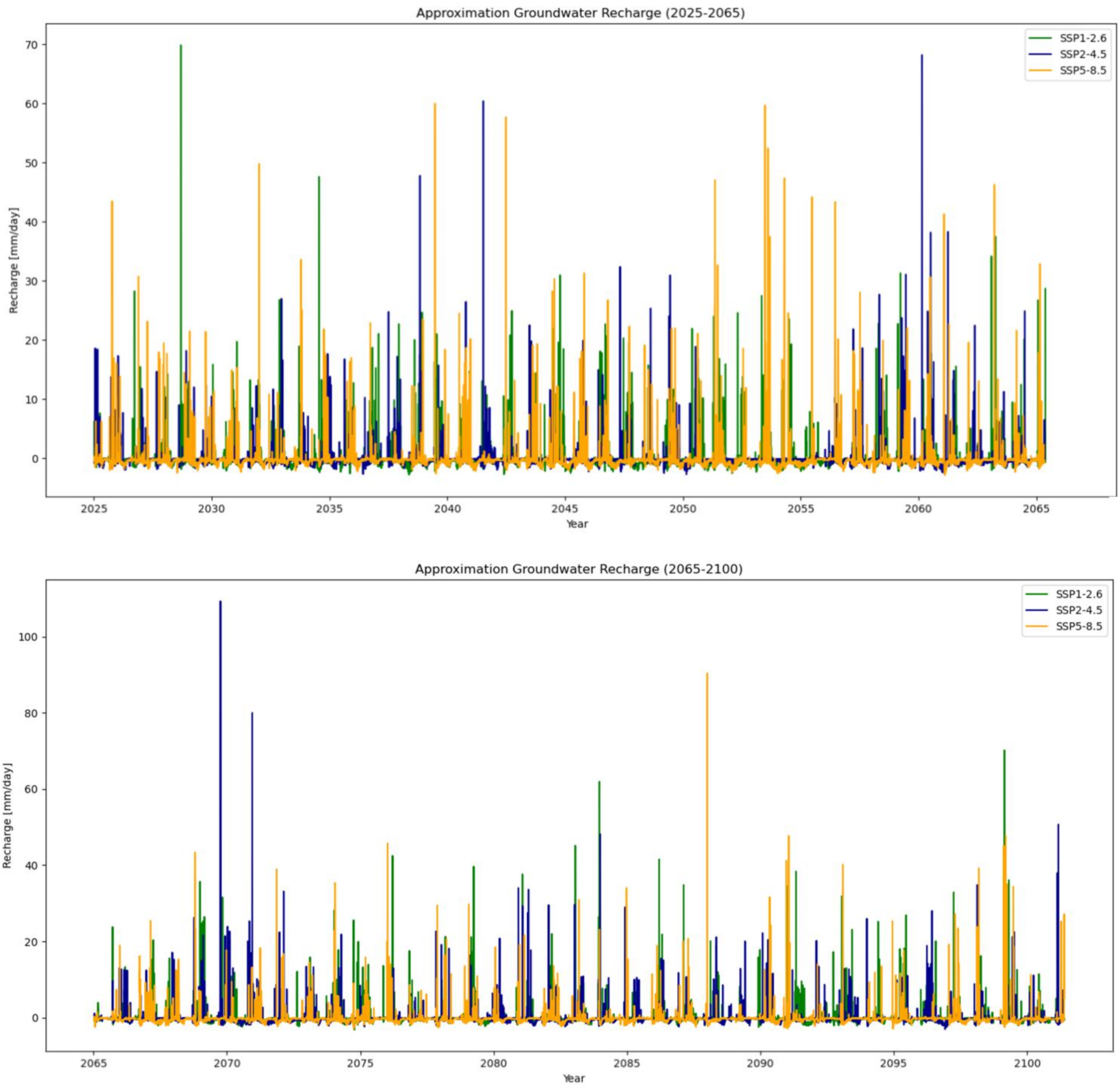


Figure 11: Approximated groundwater recharge for 2025-2065 and 2065-2100

To provide a clearer visual representation of the data depicted in Figure 11, Figure 12 focuses on the years 2025, 2050, 2075 and 2100. These graphs illustrate the approximated groundwater recharge and its seasonal variations. For instance, in 2075, the influence of winter rainfall is evident, with an observed increase during the winter months. Across all highlighted years, it is apparent that the summer season experiences drought conditions.

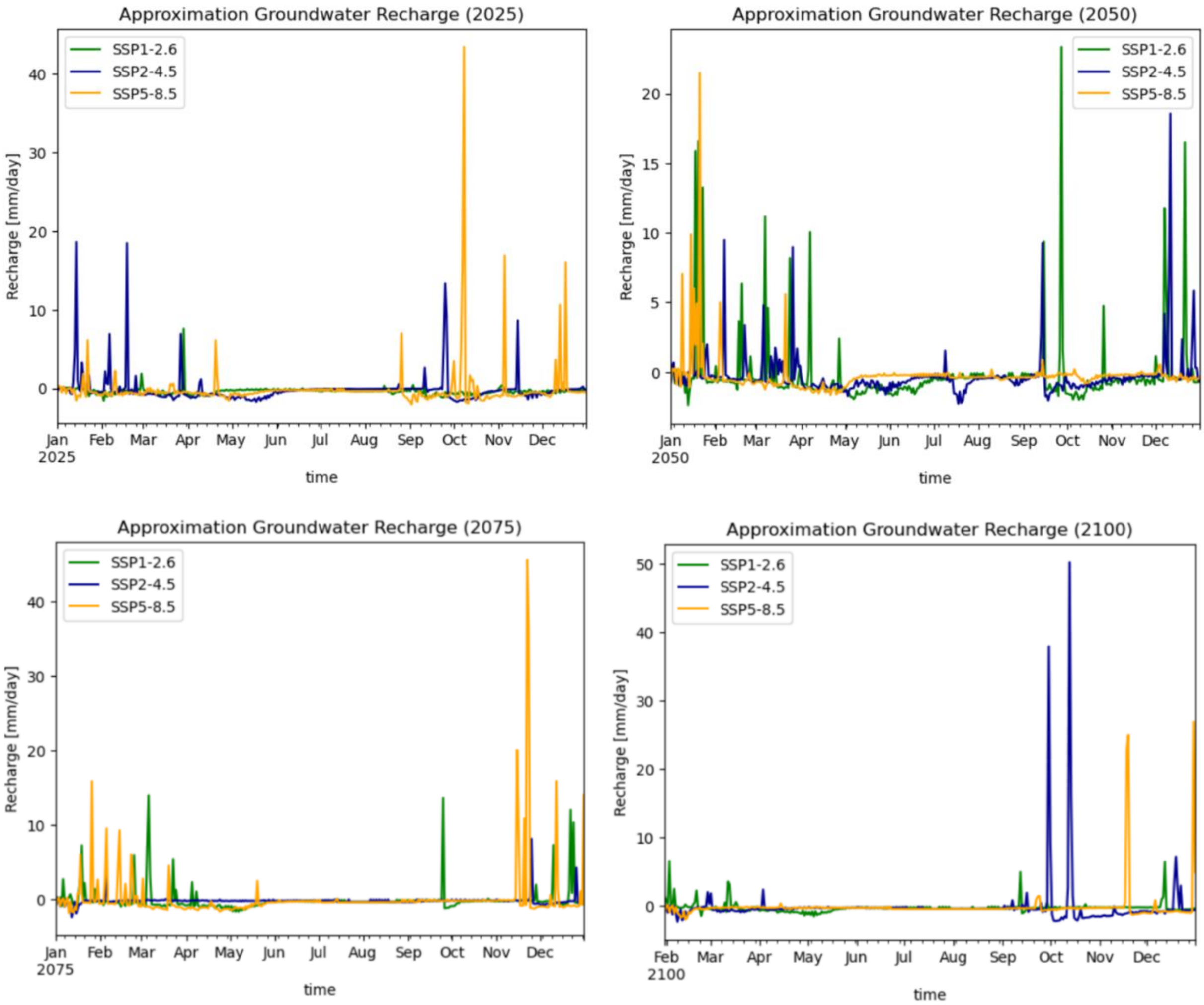


Figure 12: Approximated groundwater recharge for the year 2025 (top left), 2050 (top right), 2075 (bottom left) and 2100 (bottom right)

To evaluate the simulated data, Figure 13 presents boxplots summarizing the approximated groundwater recharge for the period 2025-2100. These plots reveal differences in outliers between the climate scenarios. Notably, SSP5-8.5 displays a greater number of outliers ranging between 20 and 50 mm/day. Appendix D includes a Z-value outlier analysis and provides a boxplot without outliers. From this analysis, it is evident that the upper quartile, median and lower quartile display minor differences across the SSPs.

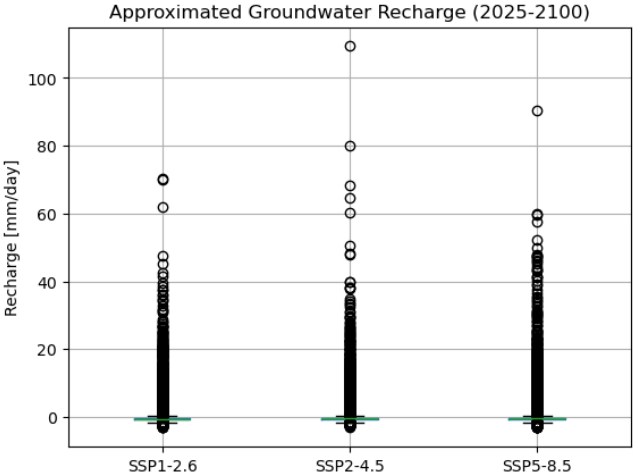


Figure 13: Boxplot approximated groundwater recharge for three SSPs (2025-2100)

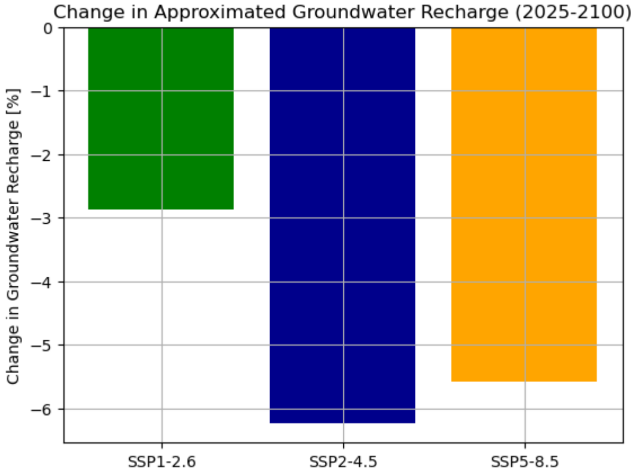


Figure 13: Relative change in approximated groundwater recharge for three SSPs (2025-2100)

The total approximated groundwater recharge for each SSP was determined, and changes were evaluated against the benchmark derived from historical data in Section 3.1. Figure 14 illustrates these changes for the period 2025-2100. Indicating that SSP1-2.6 shows a change of -2.9%, SSP2-4.5 a change of -6.2% and SSP5-8.5 a change of -5.6%. Figure 15 illustrates four diagrams, displaying the changes of near-term, mid-term and long-term periods. The plots are divided into a twenty-year interval (2025-2045, 2045-2065, 2065-2085 and 2085-2100). An overview of the change per SSP is presented in Table 3. This table indicates that the increase in long-term is significantly.

Period	SSP1-2.6	SSP2-4.5	SSP5-8.5
2025-2045	9.4%	-5.1%	-13.2%
2045-2065	-1.9%	-12.7%	0.7%
2065-2085	-13.7%	-7.3%	-1.3%
2085-2100	-6.2%	2.4%	-9.5%

Table 3: change in approximated groundwater recharge per period

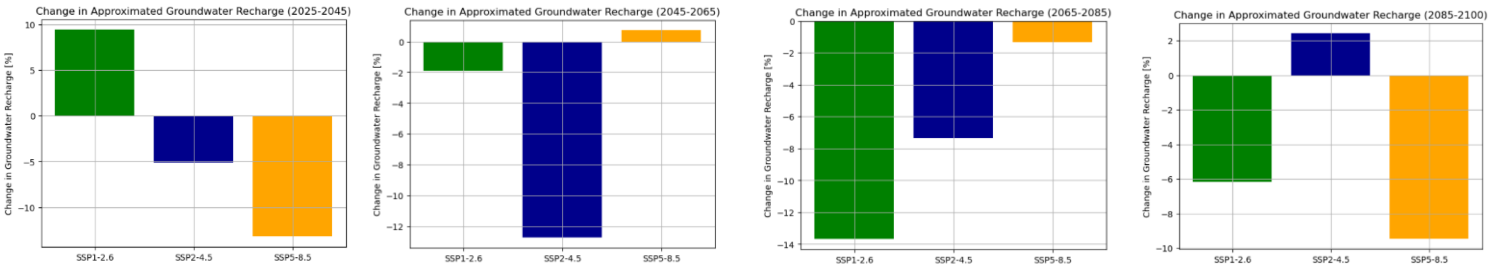


Figure 14: Relative change in approximated groundwater recharge for 2025-2045, 2045-2065, 2065-2085 and 2085-2100, relatively shown

4. Discussion

This chapter provides an analysis of the results obtained in the previous chapter. Section 4.1 discusses the uncertainties of the hydrological model PCR-GlobWB. Section 4.2 compares the results obtained in Chapter 3 to other researches. Lastly, Section 4.3 discusses future research directions.

4.1 Uncertainties of PCR-GlobWB

This research relies on a hydrological model rather than direct measurements, introducing potential for uncertainties in the results. These uncertainties arise from various factors, including input data, spatial scales and model structure.

The input data consists out of a parameter set and a forcing dataset. For example, the ERA5 datasets may contain errors in observed data or missing data, which could account for some extreme outliers. Similar concerns apply to the CMIP6 dataset, as inaccuracies and unavailable data can be the origin of uncertainties in the simulations. Additionally, the spatial scales of the datasets differ. ERA5 and CMIP6 operate on grids of varying resolution. The coarser the resolution of CMIP6, especially after rescaling to align with ERA5, can temper the precision of the results and potentially affecting their accuracy.

The structure of the model can also be a source of uncertainties. The model incorporates many hydrological components, and not all of which vary over time. For instance, as mentioned in Section 2.2, the irrigation factor in PCR-GlobWB is constant over time. In reality, this factor fluctuates. Therefore, it is a static representation and it likely influences the simulation outcomes.

The results of groundwater recharge simulation, presented Sections 3.1 and 3.2, possibly contain an uncertainty. The low groundwater recharge values suggest potential issues with either the model, the input data, or the interpretation of the simulated outputs. These values are near zero, and indicate an absence of groundwater recharge, which is inconsistent with reality. This suggests that the model's outcome or the quality of the data may be flawed. It is important to acknowledge the model that is simulating future climate scenarios is not an exact reflection of reality.

4.2 Comparing the Results with Other Researches

To evaluate the results of this research it is compared to a report of the USGS, researching the same region with comparable future climate scenarios. The United States Geological Survey published a report in 2020, containing a research on the trends in recent historical and projected climate data from 2020 to 2100 for the Colorado River basin. The projected climate data evaluated 97 Coupled Model Intercomparison Project phase 5 (CMIP5) projections and all Representative Concentration Pathways (RCP) from year 1951 to 2099. In this research, it is expected that the lower Colorado River basin will experience a slight decrease in precipitation, and an increase in temperature. The projected groundwater infiltration decreases rapidly, compared to the historical data.

These findings align with the results generated by the PCR-GlobWB model, which similarly predict a decline in groundwater recharge under more extreme future climate scenarios. The alignment of these results reinforces the reliability of the PCR-GlobWB model.

4.3 Future Research

To achieve more reliable and accurate outcomes in hydrological modelling, several factors are in need of further investigation. One approach is to apply and compare multiple hydrological models. By incorporating a range of models, researchers can identify similarities and differences in the outcomes, improving the accuracy of the results.

Additionally, more focus on important hydrological factors could enhance the reliability. For example, analysing how temperature changes with each climate scenario, analysing shifts in precipitation patterns and evaluating changes in discharge. Understanding the hydrological cycle in more detail can give more insight into the effect on groundwater recharge.

As mentioned in Section 2.5, this study simplified the groundwater flow by assuming it occurs in a single direction. While this simplifies the results, it does not accurately reflect reality. The groundwater flow is often a multiple directions and is influenced by several factors. Incorporating the realistic groundwater flow would yield more accurate groundwater recharge results.

Lastly, to obtain the future climate simulations, three SSPs (SSP1-2.6, SSP2-4.5 and SSP5-8.5) were used. However, CMIP6 contains many more scenarios. Therefore, in future research, evaluating more scenarios can lead to a higher reliability.

5. Conclusion

This bachelor thesis researched the impact of climate change on groundwater recharge in the Sonoran Desert. The PCR-GlobWB model was used to simulate both historical and future (approximated) groundwater recharge. The simulated data were analysed using boxplots and diagrams stating the change of approximated groundwater recharge.

The findings indicate the optimistic climate scenario, SSP1-2.5, projects the smallest change in approximated groundwater recharge, -2.9 %. This represents a slight reduction in the amount recharge compared to the ERA5 baseline. The intermediate scenario, SSP2-4.5, demonstrates the largest change in approximated recharge, -6.2%. This indicates a significant reduction in groundwater recharge. The worst case scenario, SSP5-8.5, simulates a comparable decrease at -5.6%, reflecting a substantial reduction in groundwater recharge.

Efforts to mitigate the decline in groundwater recharge have already been initiated by institutions in Arizona, California and Mexico through implementation of strict water regulations. However, additional measures need to be taken, to further reduce the negative impacts. For instance, sustainable water management and restoration of natural water flow are critical.

Sustainable water management involves promoting efficient water use across all sectors, particularly in agriculture, which the largest consumer of groundwater resources. Implementing sustainable irrigation techniques and leveraging innovative technologies could significantly reduce water consumption.

Existing policies, such as the Groundwater Management Code in Arizona and the Law of the Nation's Water in Mexico, focus on replenishing the current confined and unconfined aquifers (Tenney, 2021; Cruz-Ayala & Megdal, 2020). These initiatives contribute to groundwater resource replenishment and help maintain riparian zones, which plays a crucial role in stabilizing groundwater levels (Hester & Fox, 2020). These policies should be sustained and expanded, to enhance water security and environmental sustainability further.

In conclusion, to answer the research question: *"How will climate change influence groundwater recharge in the Gila River basin in the Sonoran Desert over the 21st century?"*. The results simulated with the PCR-GlobWB model suggest that climate change will lead to a decrease in groundwater recharge. While the optimistic scenario indicates a relatively minor decline over the 21st century, the moderate and worst-case scenario foresees a significant decrease, possibly underscoring the need for effective water management strategies to mitigate the impacts of climate change in the future.

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Appendix A: SSPs narratives

Figure A1 below provides narratives of the Shared Socioeconomic Pathways (SSPs) used in this report. Figure A2 illustrates the expected CO2 emissions and increase of global mean for each SSP.

SSP1 **Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)**
The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2 **Middle of the Road (Medium challenges to mitigation and adaptation)**
The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP5 **Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)**
This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Figure A1: Definition of analysed SSP narratives (Hausfather, 2018)

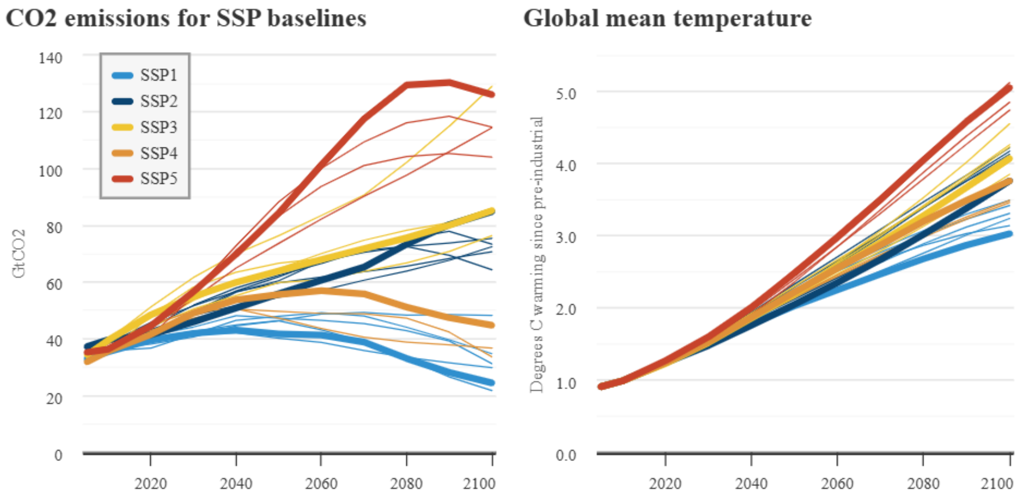


Figure A2: CO2 emissions in gigatonnes and global mean surface temperature change (Hausfather, 2018)

Appendix B: Conditions Colorado River

Figure B1 contains the average temperature, precipitation and runoff of the Upper basin and Lower basin of the Colorado River. These conditions have been observed between 1981 to 2010 (Salehabadi et al., 2020).

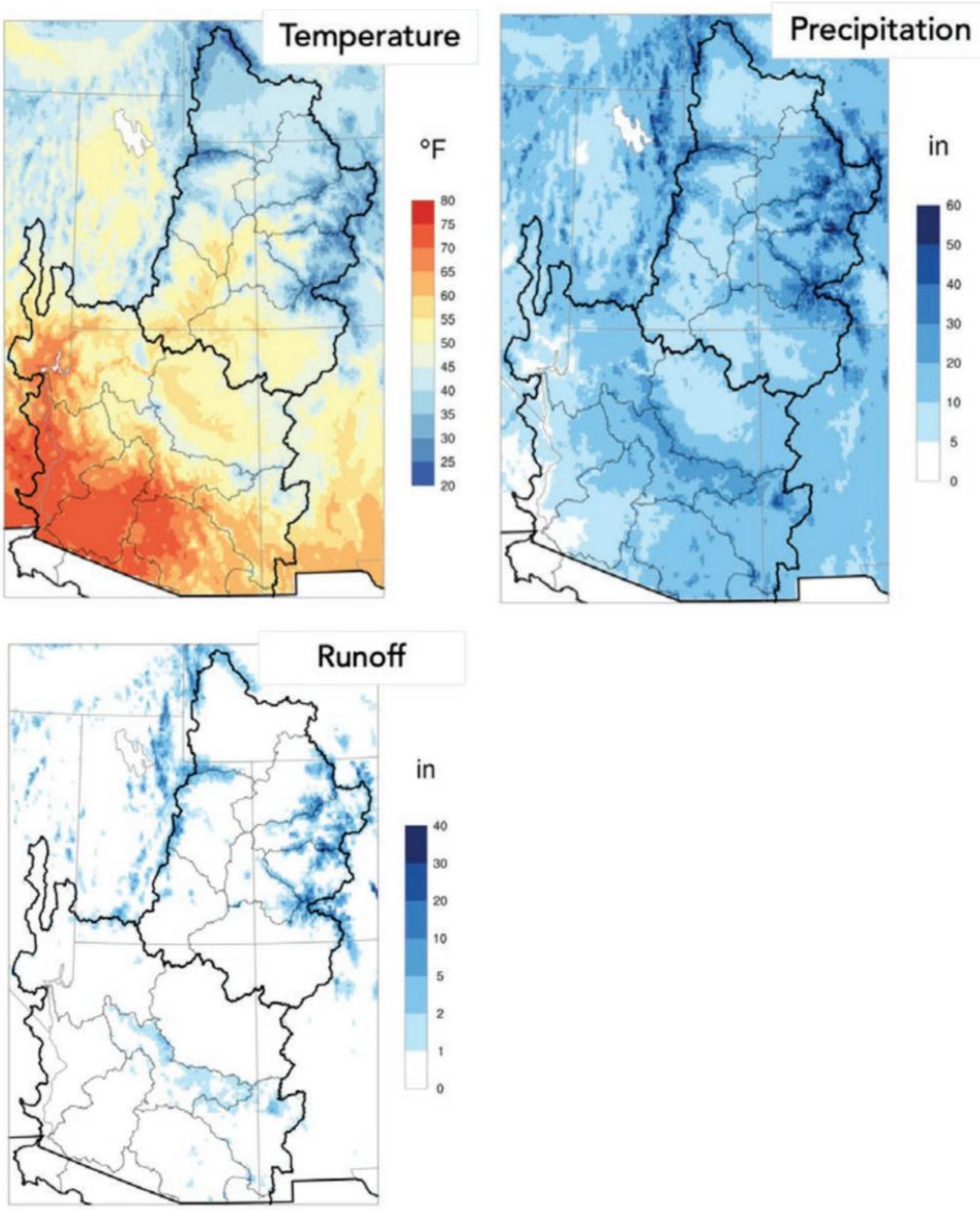


Figure B1: Average temperature, precipitation and runoff of the Upper basin and Lower basin of the Colorado River (Salehabadi et al., 2020)

Appendix C: Water Balance

The groundwater recharge in the Gila River basin is estimated with the water balance equation, which is given below (Equation C1). Each of these values and how they are derived is explained in this appendix.

$$Groundwater\ recharge = \Delta S + Q + P + R - ET - Agr \qquad (Eq.\ C1)$$

ΔS	Change in groundwater storage	[m^3/year]
Q	Discharge Gila River	[m^3/year]
P	Precipitation	[m^3/year]
R	Runoff	[m^3/year]
ET	Evapotranspiration	[m^3/year]
Agr	Extraction by agricultural sector	[m^3/year]

Change in Groundwater Storage

Using the Arizona Groundwater Dashboard (n.d.) the annual mean rate of groundwater level change of basins within the Gila River basin were analysed. The average change in groundwater across the basin is estimated to be is -0.02 m/year. When scaled to the entire Gila River basin, equates to a total groundwater storage change of approximately $-3*10^9$ m^3/year. Table C1 presents the changes in groundwater storage per basin.

Basin	ΔS [in/year]	ΔS [m/year]
Yuma	-0.7	-0.02
Wellton-Mohawk	-0.2	-0.005
Dendora Valley	-2.0	-0.05
Hassayampa	-0.1	-0.003
West Salt River Valley	-0.2	-0.005
Mean	-0.6	-0.02

Table C1: Mean annual groundwater storage in Imperial units and metrical units (Arizona Groundwater Dashboard, n.d.).

Discharge

In arid regions on regional scale, the baseflow discharge of rivers is often indicative of the minimum groundwater recharge that is required to sustain streamflow (Schilling et al., 2021). Before the Gila River converges with the Colorado River, near Yuma, the USGS (n.d.) measured the discharge of the Gila River annually. Figure C1 shows the discharge of 2024. The baseflow is measured at 0 m^3/s.

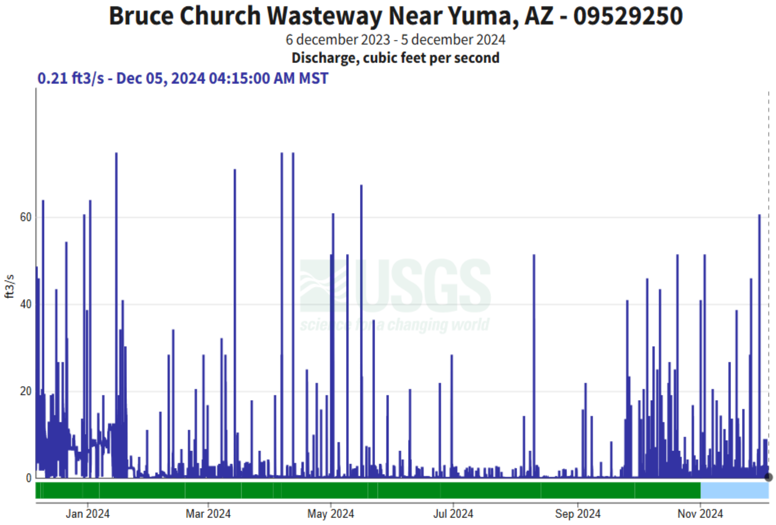


Figure C1: Discharge Gila River near Yuma (USGS, n.d.)

<u>Precipitation and Runoff</u>
As mentioned in Section 2.5, the precipitation and runoff are based on the map in appendix B. The average annual precipitation is 15 inch and the runoff is 0 inch.

<u>Evapotranspiration</u>
As mentioned in Section 2.4, it is assumed that the Santa Cruz aquifer has similar climatic conditions as the Sonoran Desert. This would lead to comparable evapotranspiration rates. Therefore, the evapotranspiration of Santa Cruz aquifer has been scaled proportionally to estimate the evapotranspiration for the Gila River basin. The Santa Cruz aquifer has an ET of $8.83*10^6$ m^3/year, over an area of 3 391.48 km^2 (Tapia-Villaseñor et al, 2022). The Gila River basin has an area of 60 000 square miles (155 399 km^2) (American Rivers, n.d.). Therefore, the evapotranspiration in the Gila River basin is estimated at $4.05*10^8$ m^3/year.

<u>Extraction by Agricultural Sector</u>
According to the Arizona Department of Water Resources (2022) the agricultural sector is irrigation a total of 541 451 Acres ($2.19117*10^9$ m^2). The total groundwater use to irrigate these Acres is 1.15 AF/year ($1.42*10^9$ m^3/year) (ADWR, 2022). Scaling these values proportionally to the Gila River basin, the extraction by the agricultural sector is estimated at $1.01*10^{11}$ m^3/year.

Appendix D: Z-Value

This appendix presents an evaluation of the boxplots from Sections 3.1 and 3.3 using the Z-value. The Z-value is calculated using the equation below (Equation D1) (Datatab, n.d.). Using the simulated data from ERA5 and CMIP6 the mean and the standard deviation are determined. Value x is the value of the simulated data. Applying this method yields a Z-value of 4. Given the large volume of the simulated data and the amount of outliers, a Z-value of 4 is appropriate.

$$Z = \frac{x-\mu}{\sigma} \qquad \textit{(Eq. D1)}$$

Z = Z-value
x = observed value
μ = mean value
σ = standard deviation

Figure D2 illustrates the boxplot of ERA5 for the period 1990-2020, without outliers. Similarly, Figure D1 illustrates the boxplot of CMIP6, representing the three future climate scenarios, also with outliers removed. These boxplots give a clearer visualization, offering more insights into the approximated groundwater recharge simulations. It is clear that the mean of these data set do not vary significantly.

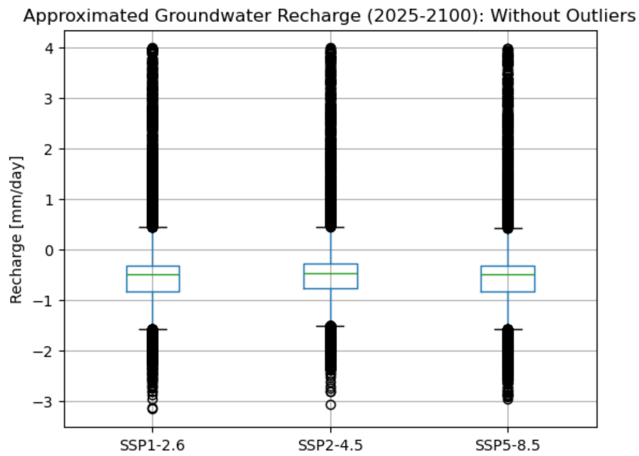


Figure D1: Approximated groundwater recharge CMIP6 without outliers

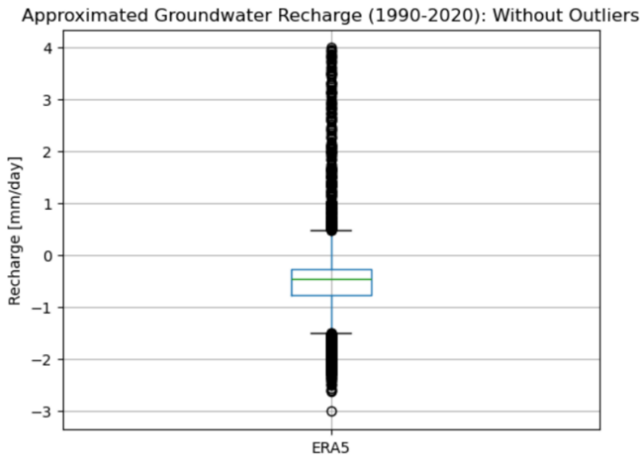
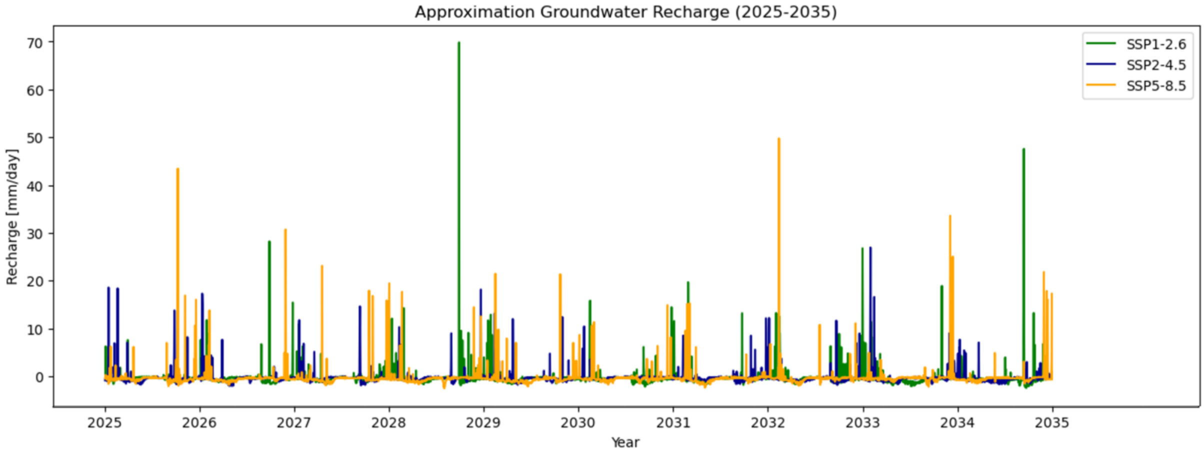
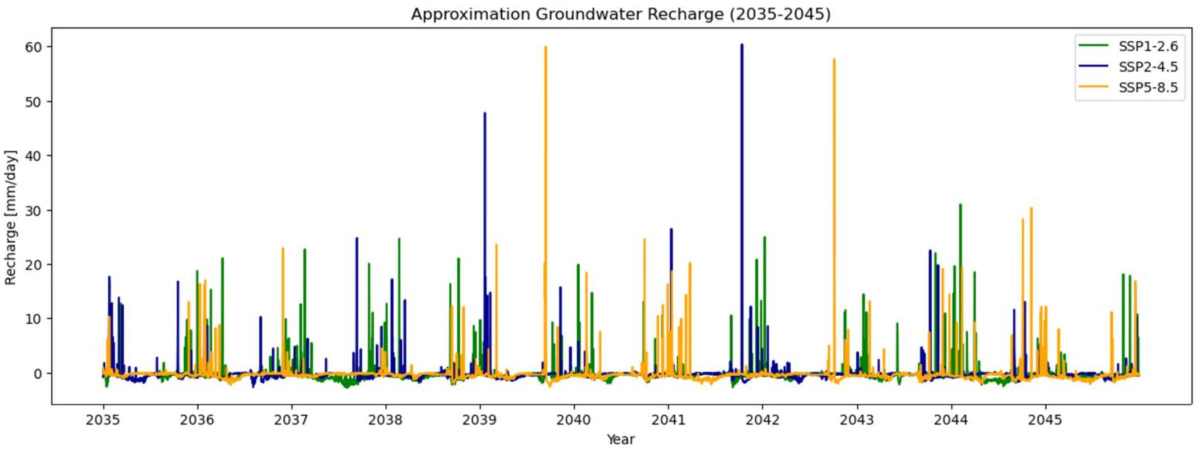


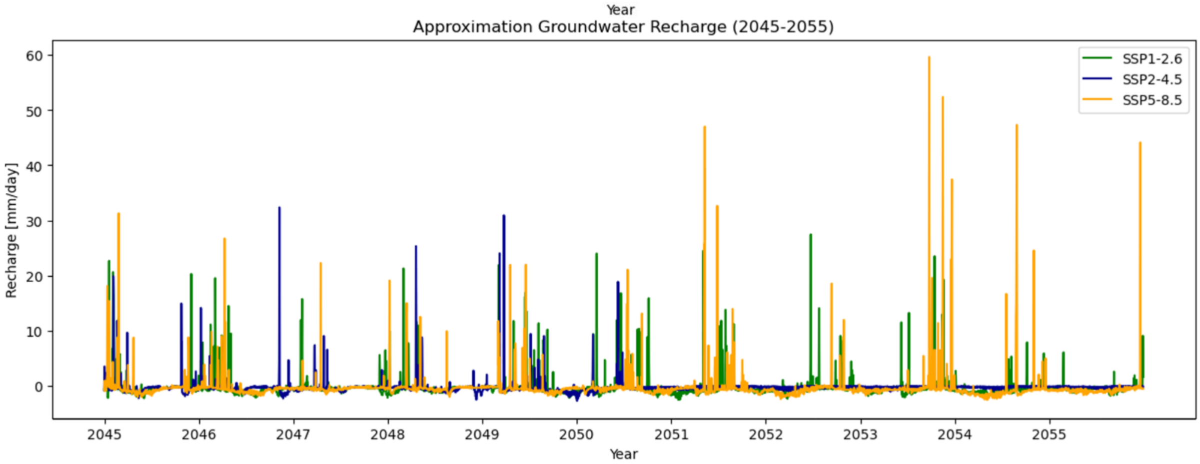
Figure D2: Approximated groundwater recharge ERA5 without outliers

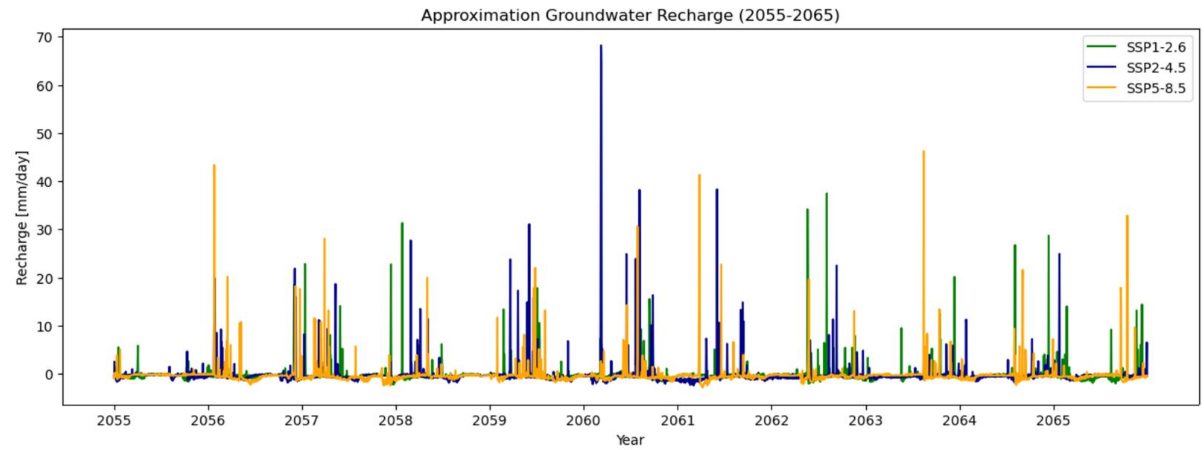
Appendix E: Approximation Groundwater Recharge CMIP6

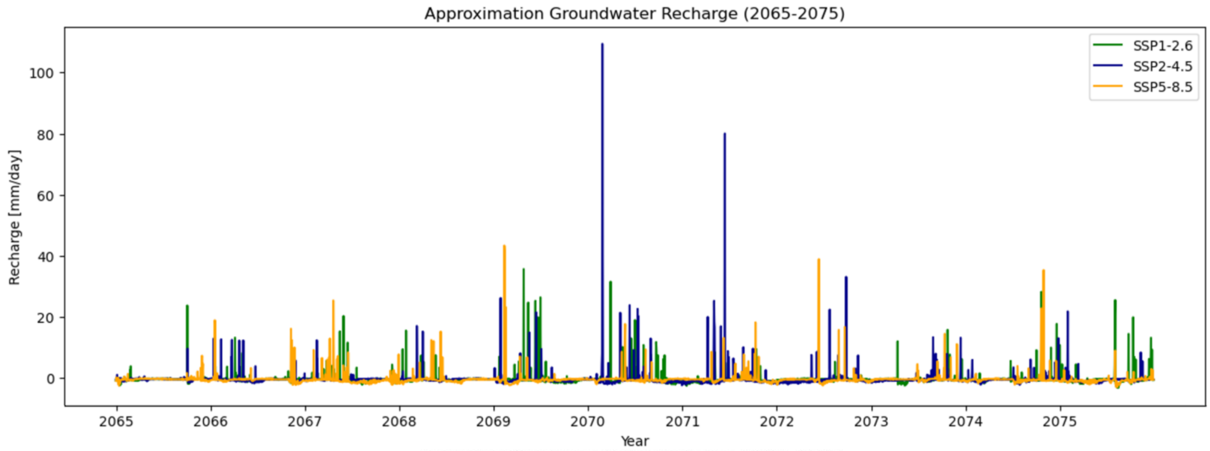
This appendix includes eight graphs illustrating the approximated groundwater recharge over the period from 2025 to 2100. To enhance a clearer visualization, the data has been divided into ten-year intervals and one five-year interval. These results are obtained from https://github.com/eWaterCycle/projects/tree/draft_eline/book/thesis_projects/BSc/2024_Q2_ElineMol_CEG/Report/results.

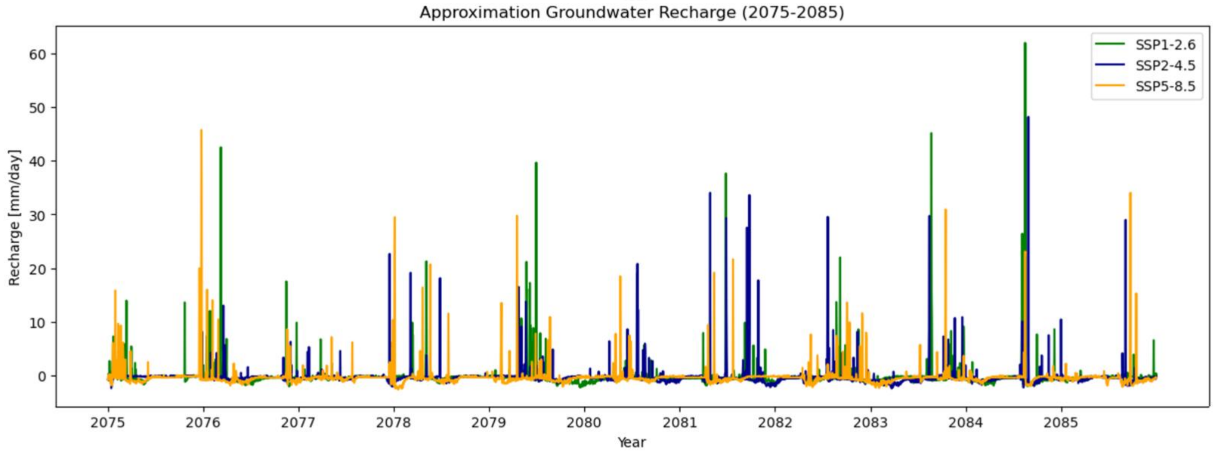


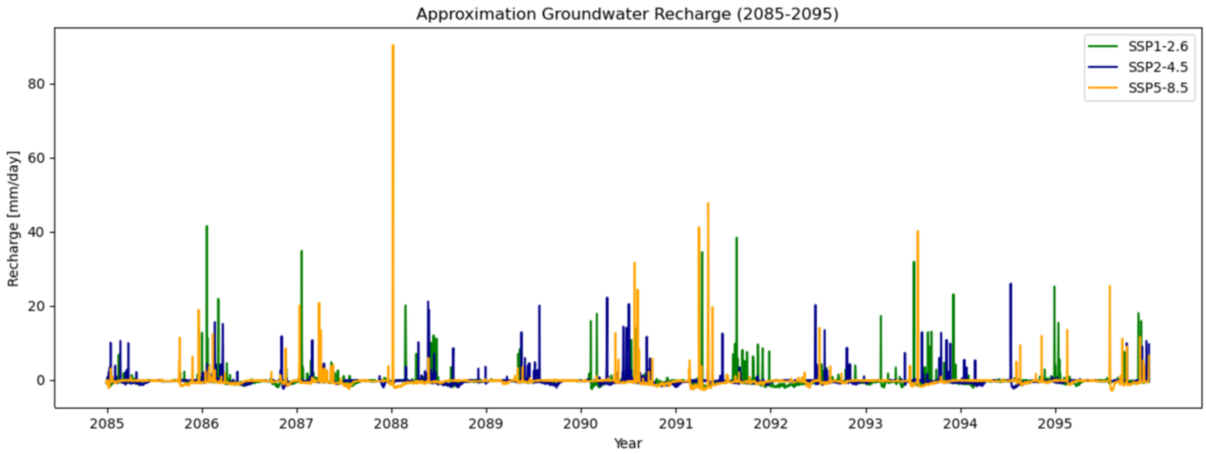


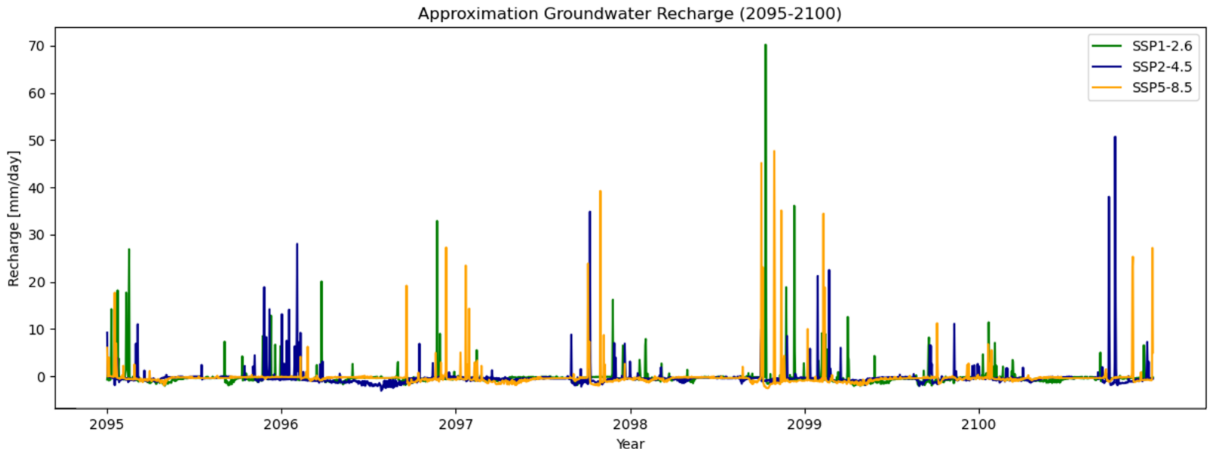



Approximation Groundwater Recharge (2055-2065)
Recharge [mm/day]
Year
SSP1-2.6
SSP2-4.5
SSP5-8.5


Approximation Groundwater Recharge (2065-2075)
Recharge [mm/day]
Year
SSP1-2.6
SSP2-4.5
SSP5-8.5


Approximation Groundwater Recharge (2075-2085)
Recharge [mm/day]
Year
SSP1-2.6
SSP2-4.5
SSP5-8.5


Approximation Groundwater Recharge (2085-2095)
SSP1-2.6
SSP2-4.5
SSP5-8.5
Recharge [mm/day]
Year
0
20
40
60
80
2085
2086
2087
2088
2089
2090
2091
2092
2093
2094
2095


Approximation Groundwater Recharge (2095-2100)
SSP1-2.6
SSP2-4.5
SSP5-8.5
Recharge [mm/day]
Year
0
10
20
30
40
50
60
70
2095
2096
2097
2098
2099
2100