Box model for Kabul River basin

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Chitral-Kabul River Basin

Project: Satellite Enhanced Snowmelt Flood and Drought Predictions for the Kabul River Basin (KRB) with surface and groundwater modeling

AUTHOR:
Abdikaiym Zhiyenbek

PROJECT ADMINISTRATOR:
Prof. Dr. Jay Sagintayev

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1 Abstract

Water resources in arid and semi-arid are tend to be scarce. Furthermore, the scarcity makes it more sensitive to a natural and anthropogenic external forcing such as climate change. In this study, Kabul River basin were analyzed in term of groundwater drawdown due to agricultural, industrial and domestic consumption.

A box model was implemented to study the groundwater level changes in relation of different water managements. The model was also tested for parameter sensitivity and model uncertainty was taken into account using Monte Carlo simulation and ensemble run.

2 Introduction

Afghanistan is a developing country in Central Asia. It is a semi-arid region and therefore prone to water scarcity issues. Majority of the water is consumed for agriculture sector (more than 90 %). Around 20 % of groundwater resources are consumed to irrigation. Furthermore, due to climate change or other natural and anthropogenic factors, the river water might become scarce. As a results, the demand for groundwater will rise and unsustainable water abstraction might results in significant consequences. [1] [2] [3]

Therefore, a proper analysis of groundwater resources are required in oder to have better water resources management and planning. Groundwater modeling can answer many questions regarding the sustainable management of aquifers. The Box models are the first steps to do in groundwater modeling. These models can answers the bigger scale questions such as the recharge potential within a whole region. Box models are parsimonious, meaning it requires significantly less parameters than 3D modeling. 3D models like Modflow require more parameters and some parameters has to be derived by pumping tests at experimental sites. These procedures are time consuming and costly. Thus, the first step of groundwater modeling should be box models that calculates mass balances of aquifer to get an overview of the situation. [4] [5] [6]

The goal of the study was to develop a box model and toolbox which can help in assessing the current situation in Kabul River basin in relation to its groundwater recharge potentials. In addition, the roles of sectors like agriculture, industry and domestic use which can cause a drawdown of the groundwater table will be studied in detail.

Furthermore, the comparison of current management with the alternative aquifer managements such as artificial recharge methods that can temporarily store the water in aquifer for later use, especially in dry periods. For these reasons, a box model for Kabul River basin was developed in python environment as toolbox for assessing groundwater. The model is parsimonious (requires a minimum amount of parameters) and comprehensive (considers all the important processes within the system).

3 Materials and Methods

3.1 Input data

Climate data was retrieved from WorldClim , which is a 1km resolution open source database. The climate data is monthly averaged and derived from a long term time series (1970-2000) [7]. Soil data was retrieved from the SoilGrids [8] source database. The retrieved climate data and soil data is pre-processed and saved in HDF5 file format with its GIS parameters. Additional information about the water and agricultural management and practices in Kabul River basin was taken from the FAO AquaStat database.

3.2 The Box model development

The box model is based on mass balances of groundwater flows. The complete system of groundwater inflows, outflows and change in the storage is too complex to compute. Hence, some simplifications and approximations are required to make the solutions feasible. Thus, mass balances for three separate system types were developed:

- Potential recharge system
- Agricultural recharge system
- Mixed recharge system including domestic and industrial sectors

The differentiating recharge systems are useful especially in spatially distributed simulations. For example, depending on the land use type, the recharge systems can be selected automatically so that proper mass balance equations are applied to the right location and at the right time. In the following paragraphs, detailed explanations of formulations of the recharge systems are described. [9]

3.2.1 Potential recharge system

In terms of the potential recharge system, the simplified equation is:

$$Q_r = Q_{inf} - Q_{phr} \tag{1}$$

$$Q_{inf} = P - (1 - C), \;\; where\; C = f(soiltype,\; slope,\; landuse) \tag{2}$$

$$Q_{phr} = f(d_{ext},\; h_{gw},\; ET_0) \tag{3}$$

Where:

- Q_r: is groundwater recharge
- Q_{inf}: is infiltration
- Q_{phr}: is phreatic evaporation
- P: is precipitation

- C: is infiltration coefficient
- d_{ext}: is the extinction depth of evaporation
- h_{gw}: is groundwater head
- h_{gw}: is evapotranspiration

3.2.2 Agricultural recharge system

The Agricultural system is slightly different from the potential recharge system (1), because it has the irrigation demand and irrigation backflow components:

$$Q_r = Q_{inf} + Q_{perc} - Q_{phr} - Q_{irr} \tag{4}$$

Where:

- Q_{perc}: is irrigation backflow due to percolation
- Q_{irr}: is irrigation demand

During the irrigation, some water goes back to groundwater depending on the irrigation type. This percolation process mainly happens in flood and surface irrigation types. The irrigation backflow due to deep percolation is:

$$Q_{perc} = f(irrigation\,type,\ irrigation\,demand) \tag{5}$$

The irrigation demand was calculated using daily crop coefficients for potential evapotranspiration and crop parameters were taken from Allen at el. [10]:

$$Q_{irr} = P_{eff} - ET_0 * K_c - L_{irr} \tag{6}$$

Where:

- P_{eff}: is effective precipitation
- ET_0: is potential evapotranspiration
- K_c: is daily crop coefficient
- L_{irr}: is irrigation losses

3.2.3 Mixed recharge system

In the mixed recharge system, some additional water consuming sector are added. Particularly, domestic water consumption and industrial water consumption taken from groundwater sources. The recharge equation for mixed system is:

$$Q_r = Q_{inf} + Q_{perc} - Q_{phr} - Q_{irr} - Q_{dm} - Q_{ind} \tag{7}$$

Where:

- Q_{dm}: is groundwater consumed for domestic uses
- Q_{ind}: is groundwater consumed by industry

4 Results

4.1 Point scale simulations

The box model was run for a point scale to produce results of each module and processes in detail. Long term climate data and soil parameters were derived for Kabul area. Different land use, slope, irrigation and crop types were selected as scenarios to see the variations of the simulation results. By means of the point scale simulation in this chapter, each main components of the model were separately analyzed and visualized.

4.1.1 Potential recharge system results

Figure 1 shows the monthly groundwater level changes in terms of potential recharge system. The time horizon was only two years. The longer the time horizon, the more uniform and stable gets the monthly water levels. The plot illustrates the seasonal variations of the groundwater head. The head does not vary significantly, because this system does not include the agricultural water abstraction which is the main consumptive use and cause of drawdowns.

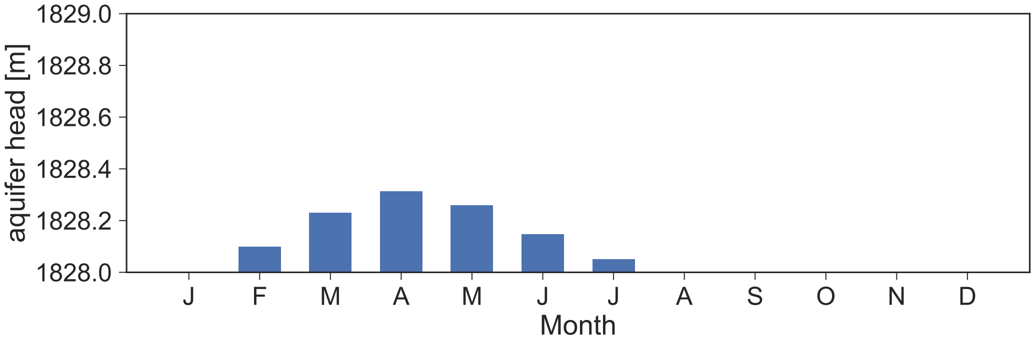

Figure 1: Monthly average groundwater level for the potential recharge system

In contract, the figure 2 illustrates the yearly changes in water level. As this system simplified to the infiltration and phreatic evaporation balance only, for 20 years time horizon a groundwater drawdown does not happen.

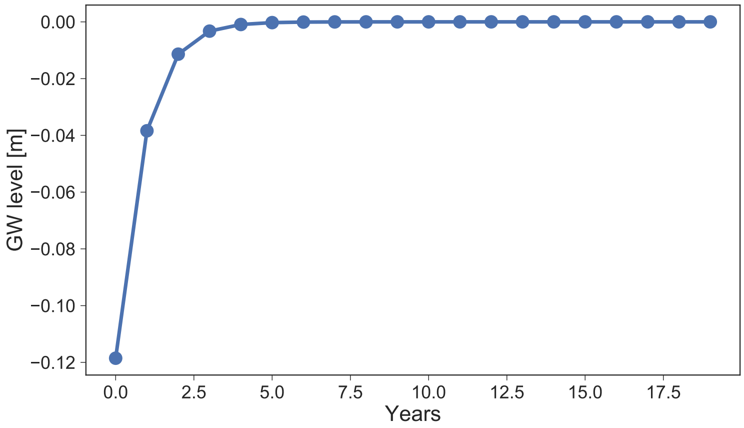

Figure 2: Yearly groundwater drawdown for the potential recharge system

4.1.2 Agricultural system results

Agricultural recharge system is the most important system, because more than 90 percent of total water consumption used for growing crops and maintaining livestock. Figure 3 shows the 10 % abstraction of groundwater for irrigation purposes.

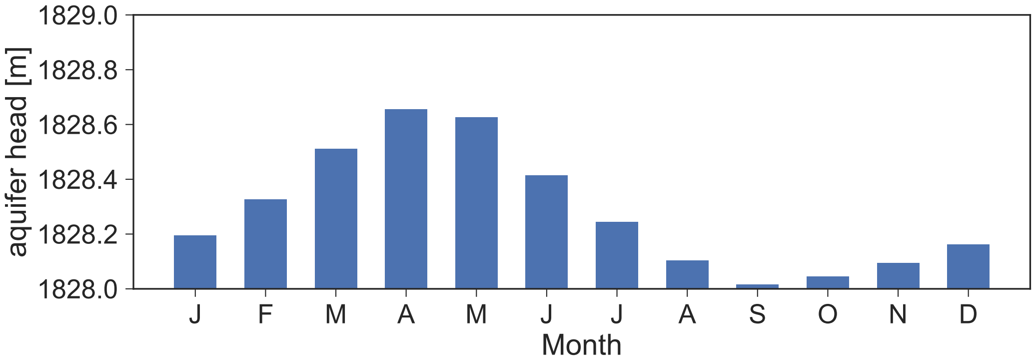

Figure 3: Monthly average groundwater level for the agriculture system with 10 % irrigation demand

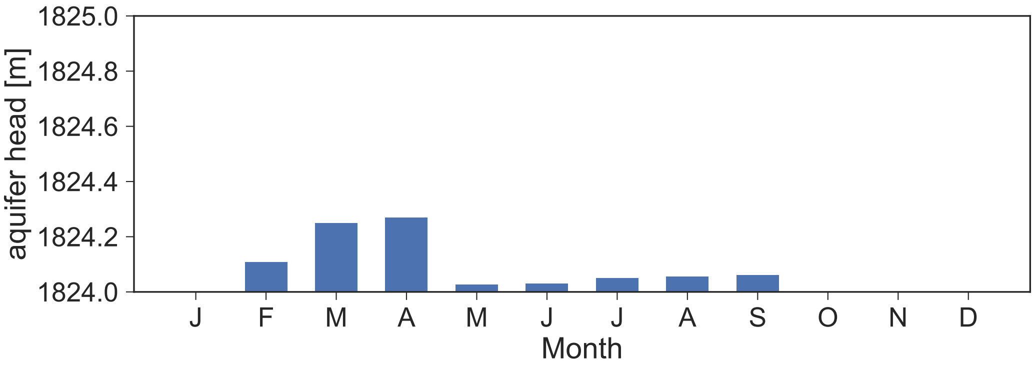

Figure 4: Monthly average groundwater level for the agriculture system with 50 % irrigation demand

In the following plots, the drawdowns of different irrigation regimes are shown. For example, figure 5 demonstrates the abstraction of 40 % groundwater for irrigation purposes and its consequent drawdown in 30 years. If 50 % of groundwater is used for irrigation and the rest from surface waters, the groundwater water level goes down around by 4 meters (figure 6).

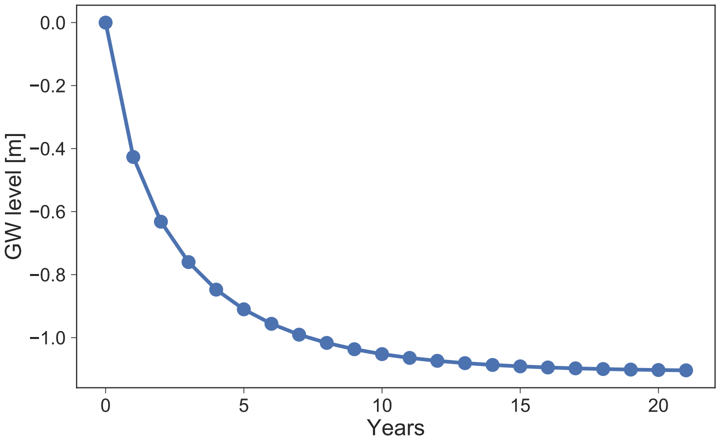

Figure 5: Yearly groundwater drawdown for 40 % irrigation demand

In figure 6), the shape of the drawdown is smoother than the 40 % abstraction and it last for a longer period until it reaches equilibrium.

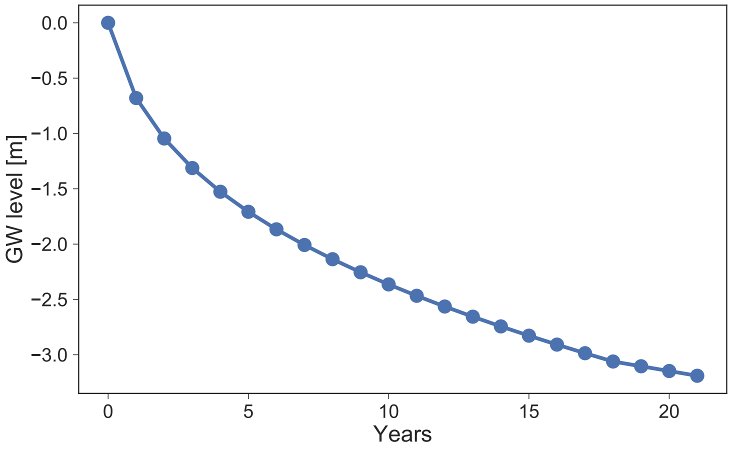

Figure 6: Yearly groundwater drawdown for 50 % irrigation demand

The model was run for more extreme scenarios in the following plots. For instance, the figure 7 visualizes the 80 % irrigation demand from groundwater sources that results in the water level decreases of 30 meters.

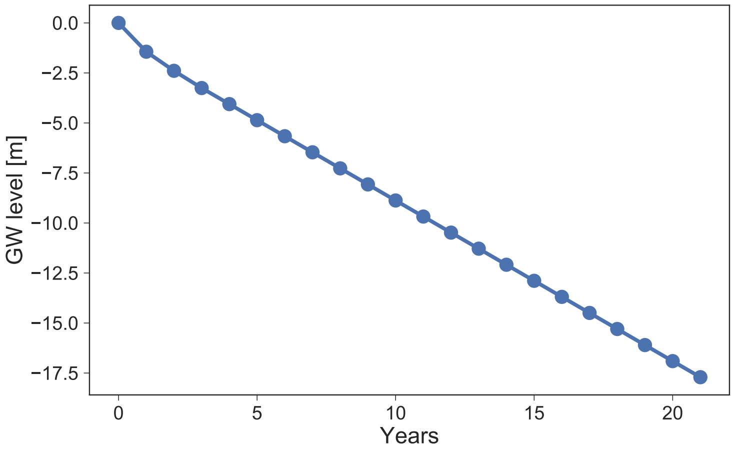

Figure 7: Yearly groundwater drawdown for 80 % irrigation demand

The worst case scenario was run for 80 % irrigation demand for 100 year time horizon. The result is the significant water level drawdown of around 80 meters. The worst case scenarios shows that, groundwater is very sensitive and can get depleted easily.

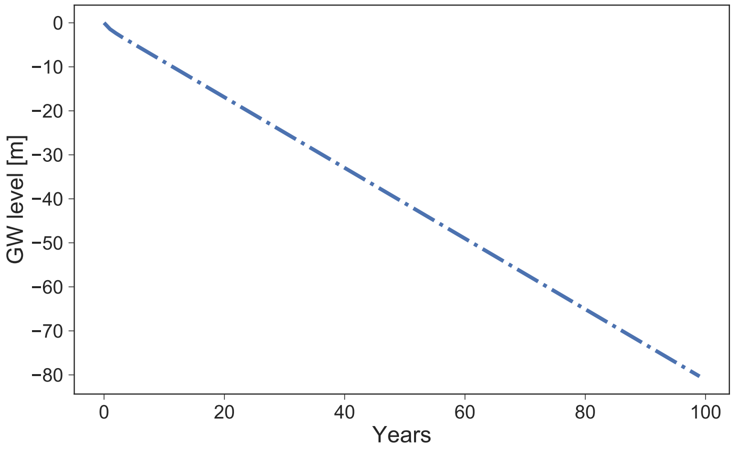

Figure 8: Yearly groundwater drawdown for 80 % irrigation demand, but 100 year time horizon simulation

4.1.3 Mixed system results

In this section, the results of the mixed system is illustrated.

In figure 9 the historical time series of the population of Afghanistan is plotted. The data starts from 1950 to 2015 with give years time step. This data was used to forecast next 15 year population.

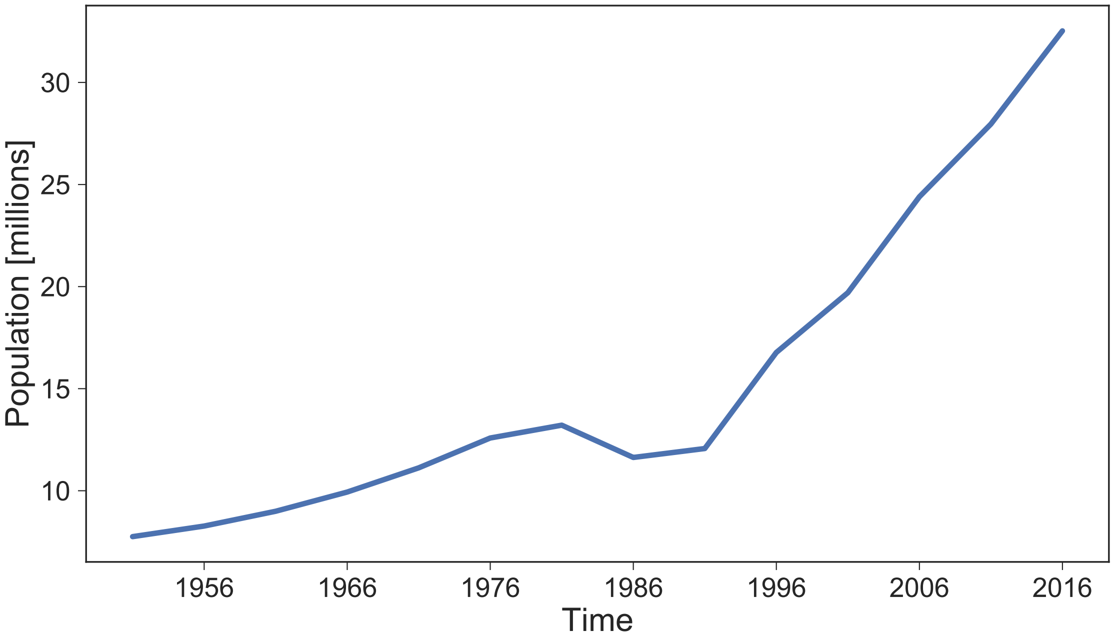

Figure 9: Population in Afghanistan between 1950 and 2015

It can seen that the population will grow drastically from 35 million up to 50 million (figure 10). This forecasted population data will be used for estimating the domestic water demand.

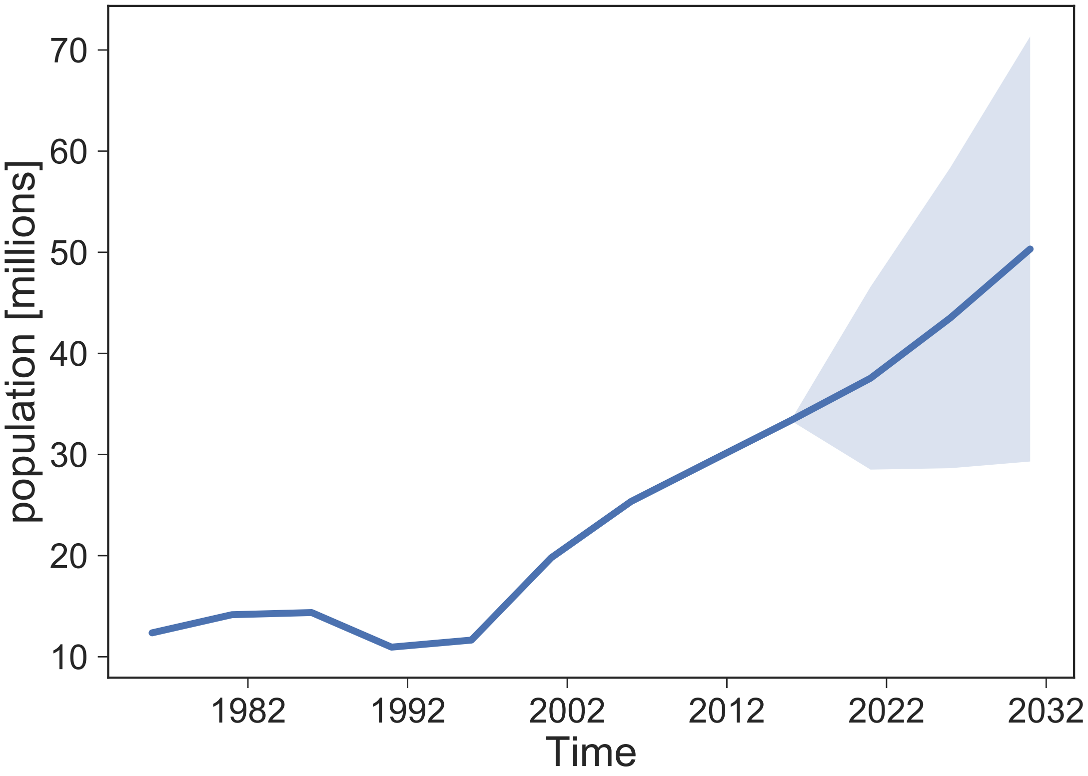

Figure 10: Forecasted population in Afghanistan for the next 15 years

4.1.4 Parameter sensitivity

After implementing the all model components, it was run for various scenarios in terms of its parameters sensitivity. The figure 11 shows the different porosity values and its corresponding results to groundwater head change.

It was determined from literature that porosity in Kabul River basin ranges from 7 % to 20 %. However, to analyze the parameter sensitivity, the range of porosity values were selected between 5 % to 40 %.

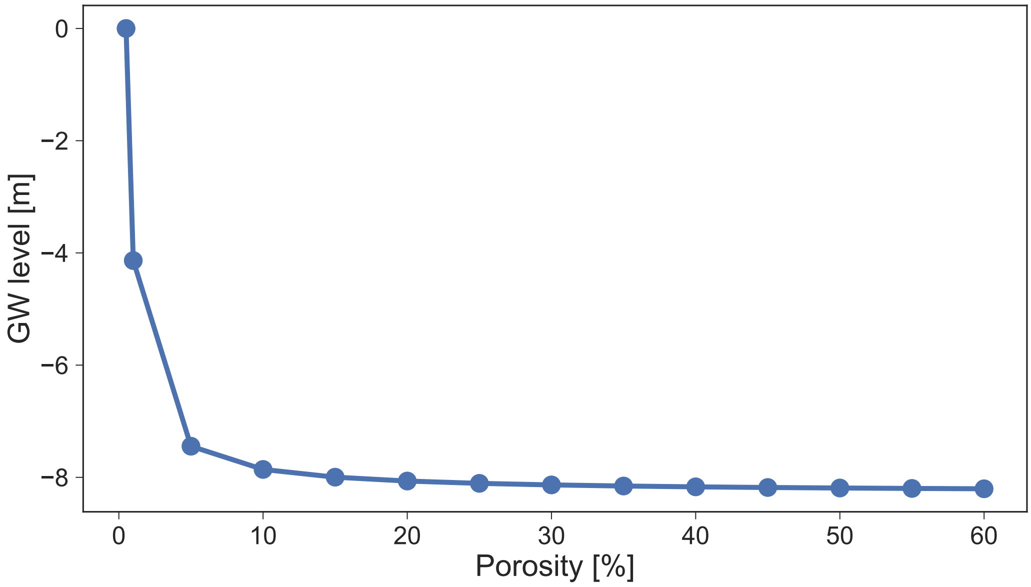

Figure 11: Porosity sensitivity analysis

Despite the fact that porosity is the main parameter for the box model, the phreatic evaporation components also play a crucial role. Therefore, the phreatic evaporation parameter, evapotranspiration extinction depth, was also analyzed (figure 12).

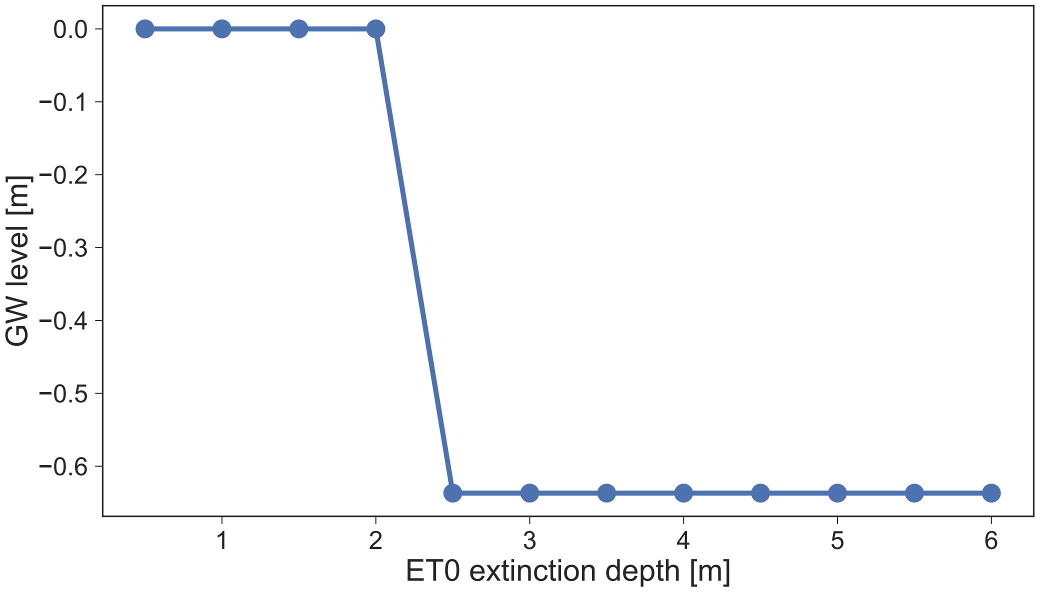

Figure 12: Evapotranspiration (ET0) extinction depth sensitivity

4.2 Uncertainty analysis

After conducting the parameter sensitivity, the uncertainty analysis were done to take into account the limitations of the modeling and input data. Monte Carlo simulation and ensemble modeling were applied for this purpose. The results of the uncertainty analysis is described in the following paragraphs.

4.2.1 Monte Carlo simulation

For the uncertain parameters, continuous probability distributions were generated. As the data for parameters is scarce and the statistics of parameter distributions are not known, the triangular distribution was selected. Using triangular distribution, it is possible to generate probability distribution by only minimum and maximum possible values of those parameters.

The figure 13 shows the assumed continuous probability distribution samples ranging from 10 % to 40 % with the peak value of 20 % for the porosity parameter.

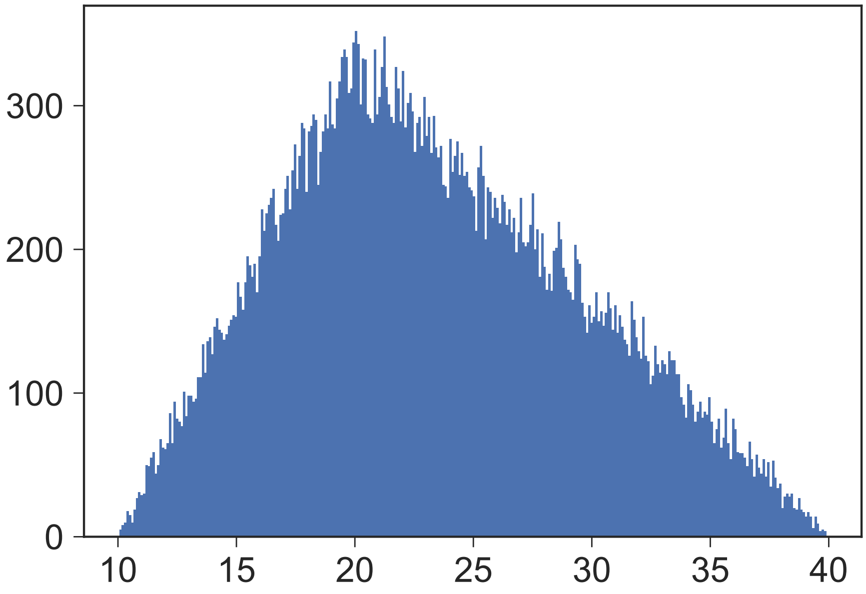

Figure 13: Porosity distribution

The ratio of irrigation water demand from groundwater it also very uncertain as it changes in space and time. Thus, it was assumed that consumption for irrigation ranges between 30 % to 50 % peaking at 40 % for uncertainty analysis purposes (figure 14).

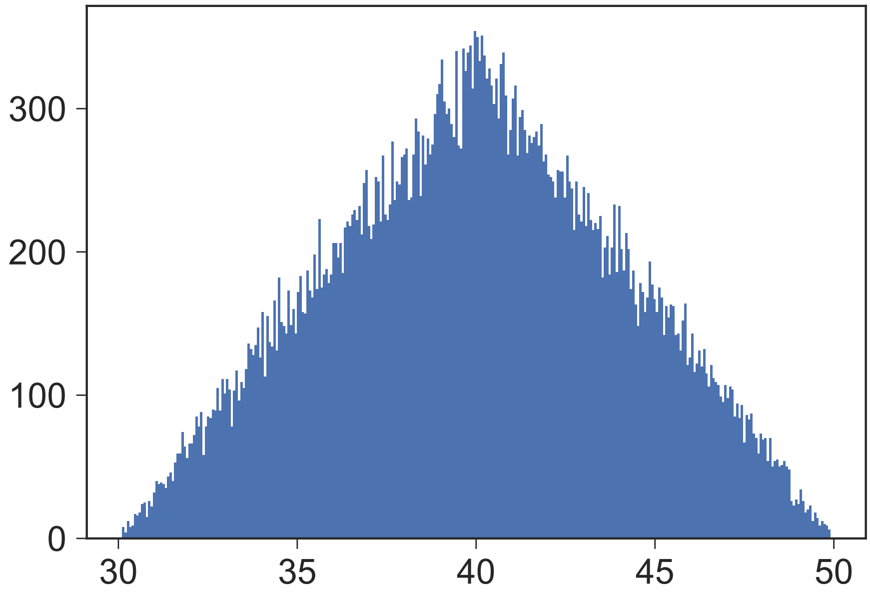

Figure 14: Irrigation abstraction percentage distribution

These probability density functions were used in simulations of ensemble of models. The results of the ensemble simulation are demonstrated in the following paragraphs.

4.2.2 Ensemble of models

By sampling the distributions of parameters, the model was run for several time horizons and for thousands of scenarios of changing parameters. The triangular distribution has three parameters: left, mode and right. For the porosity case, left = 10 %, mode = 20 % and right = 40 %. These values are used throughout the ensemble simulations. However, the values for irrigation abstraction ratio was different for each case and they are explained under each plot.

Firstly, the ensemble of models were run for sampled porosity and irrigation ratio values simultaneously. This case in a way covers the simulation of reality and current situation where the porosity ranges from 10-40 % and irrigation demand from 30-50 % in Kabul river basin (figure 15). In all ensemble simulation visualizations, the black line is the mean of all realizations (scenario trajectories).

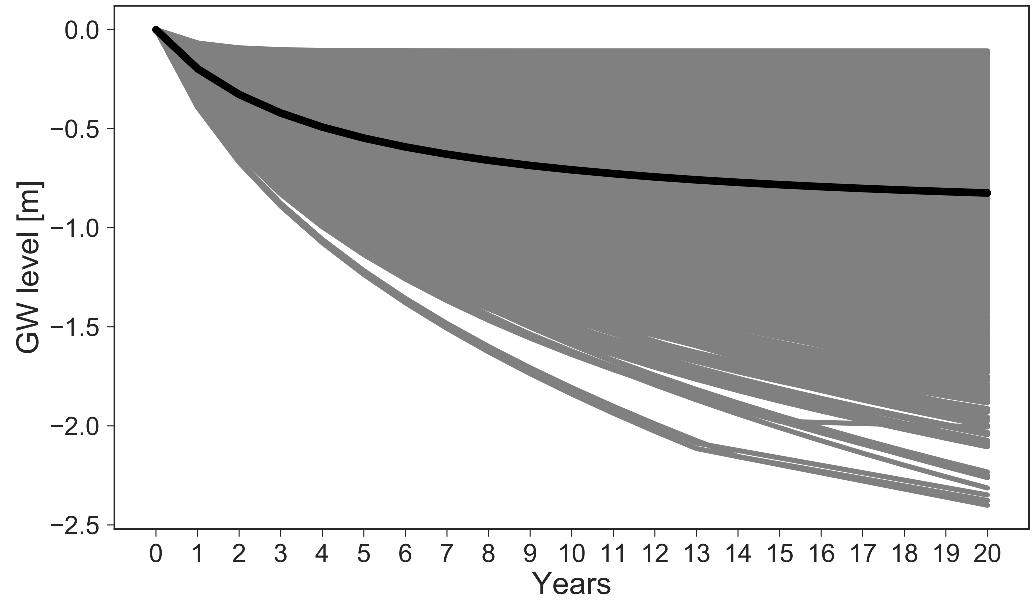

Figure 15: Ensemble modeling of drawdown where irrigation percentage distribution parameters: left = 30 %, mode = 40 % and right = 50 %

In other the scenarios, the irrigation demand percent was set to a static value so that to only account for the uncertainty of the porosity which is the key parameter. The figure 16 illustrates the case for 30 % irrigation water abstracted from groundwater.

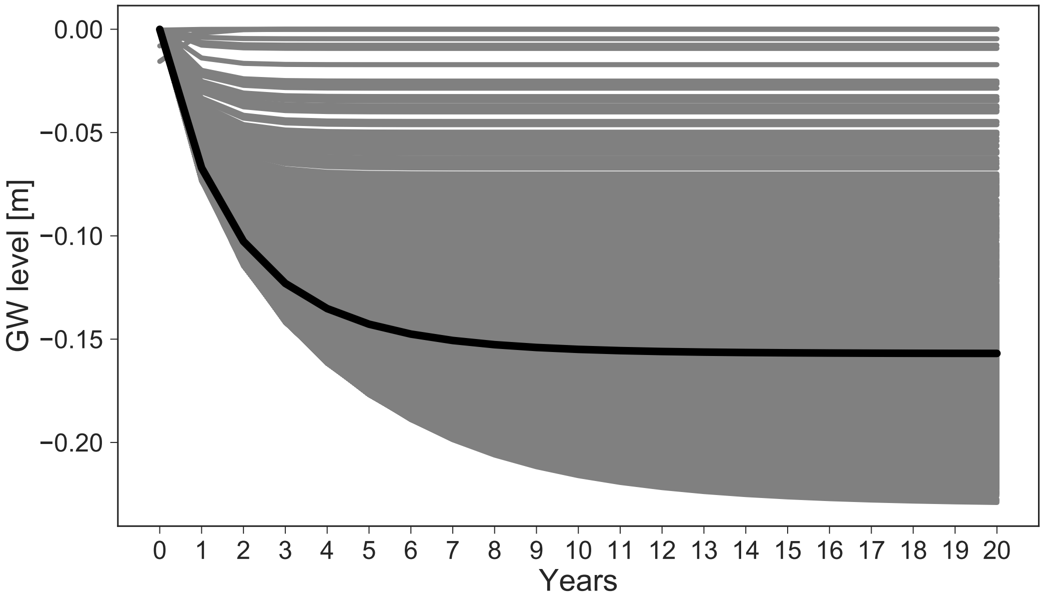

Figure 16: Ensemble modeling of drawdown where irrigation percentage = 30 %

When the irrigation demand is equal to 50 %, the realizations get narrowed (figure 17). However, if irrigation increases, ensemble realizations get more broader towards the end of the time horizon (figure 18)

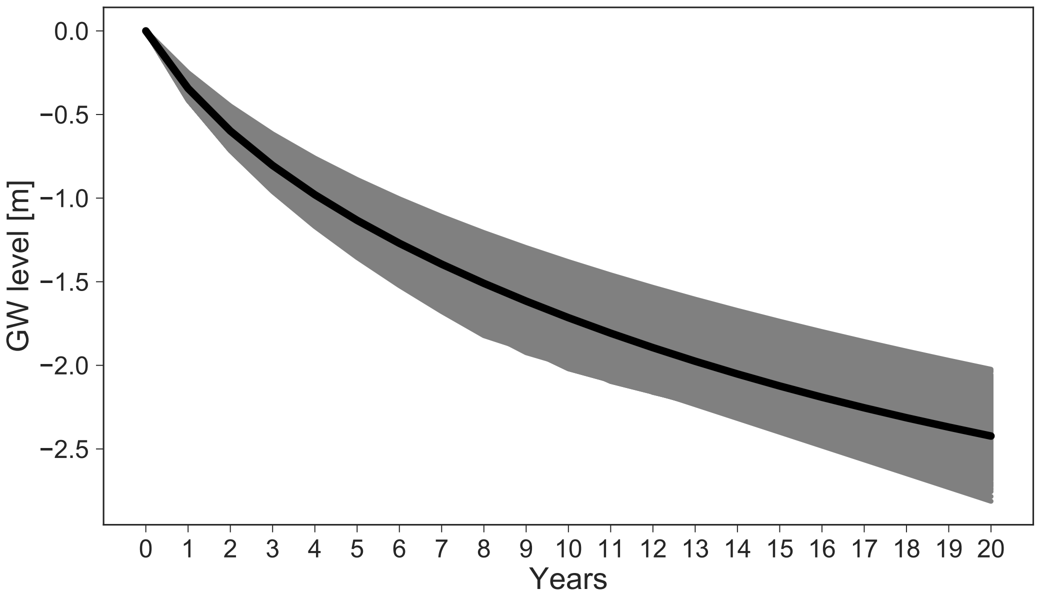

Figure 17: Ensemble modeling of drawdown where irrigation percentage = 50 %

The drawdown out of thousand of combinations of samples for 80 % irrigation abstraction resulted in maximum 30 meter decrease, whereas minimum was around 8 meters for 20 year time horizon.

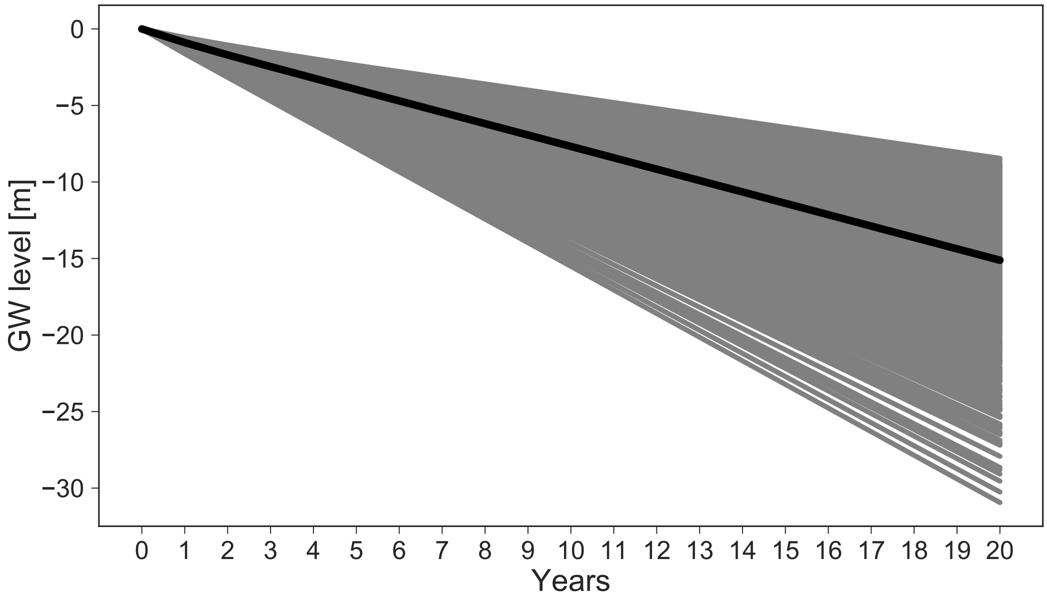

Figure 18: Ensemble modeling of drawdown where irrigation percentage = 80 %

Until this stage, the irrigation demand was for the main crop which is the winter wheat in Afghanistan. In contrast, the barley water demand (50 %) was simulated using Monte Carlo methods in figure 19).

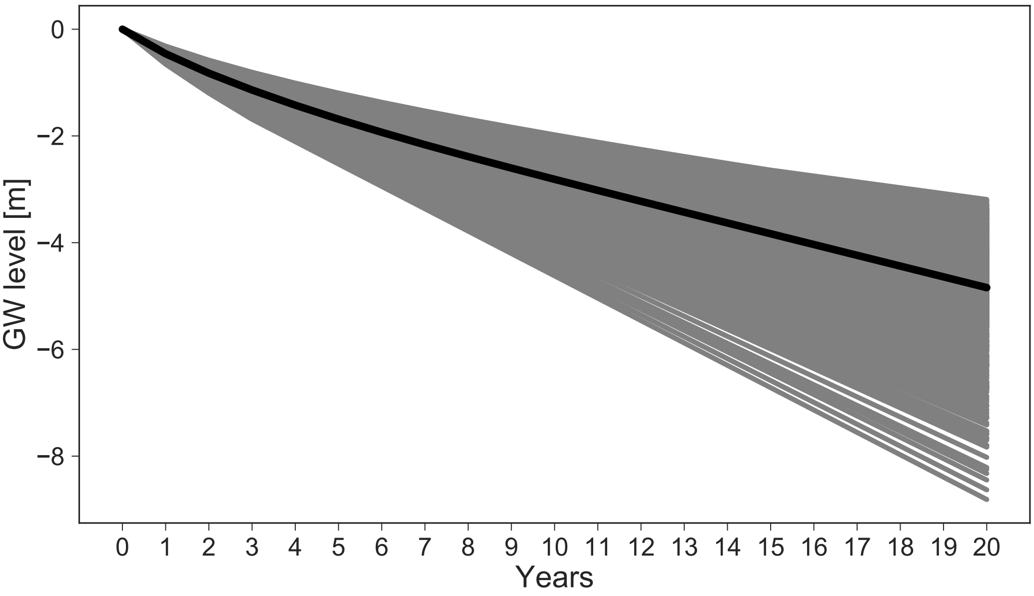

Figure 19: Ensemble modeling of drawdown where irrigation percentage of barley = 50 %

4.3 Spatially distributed simulations

For spatially distributed simulation, 1 km high resolution data was used. The data retrieved from global databases were pre and post processed. In figure 20 the annual precipitation is shown in the Kabul River Basin.

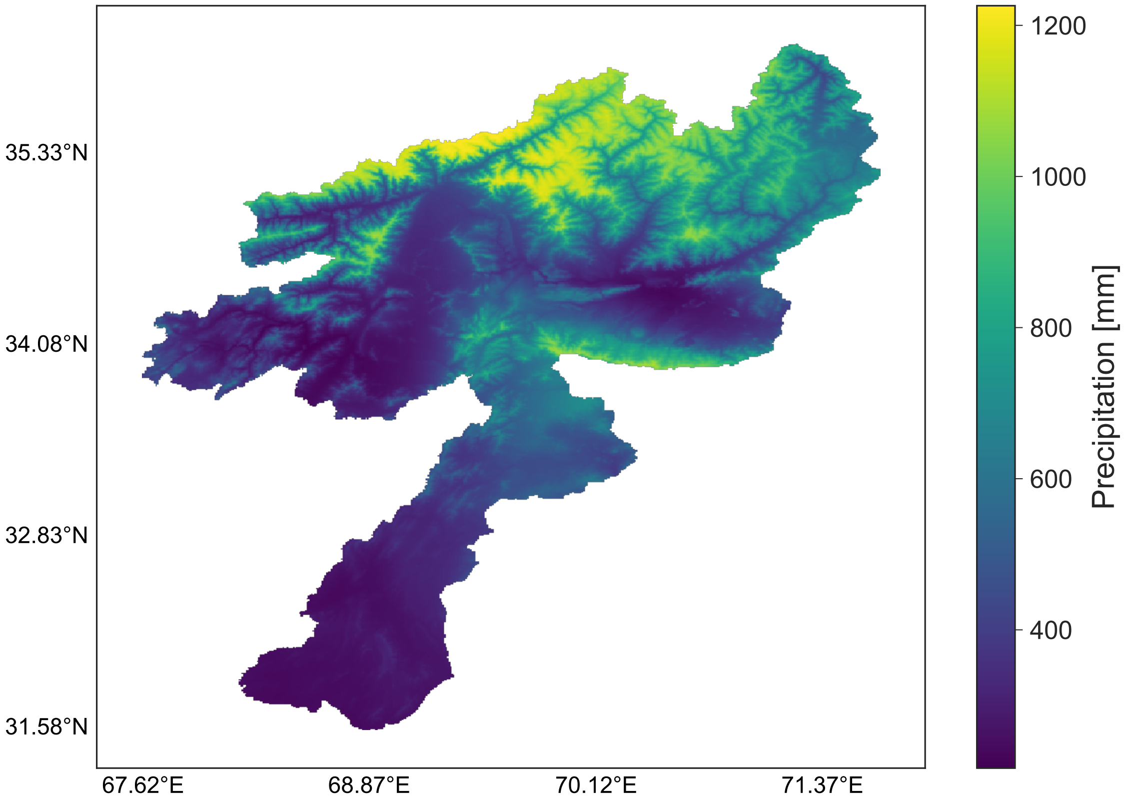

Figure 20: Annual precipitation

In the following figure (21) precipitation in the wettest month, April, is illustrated.

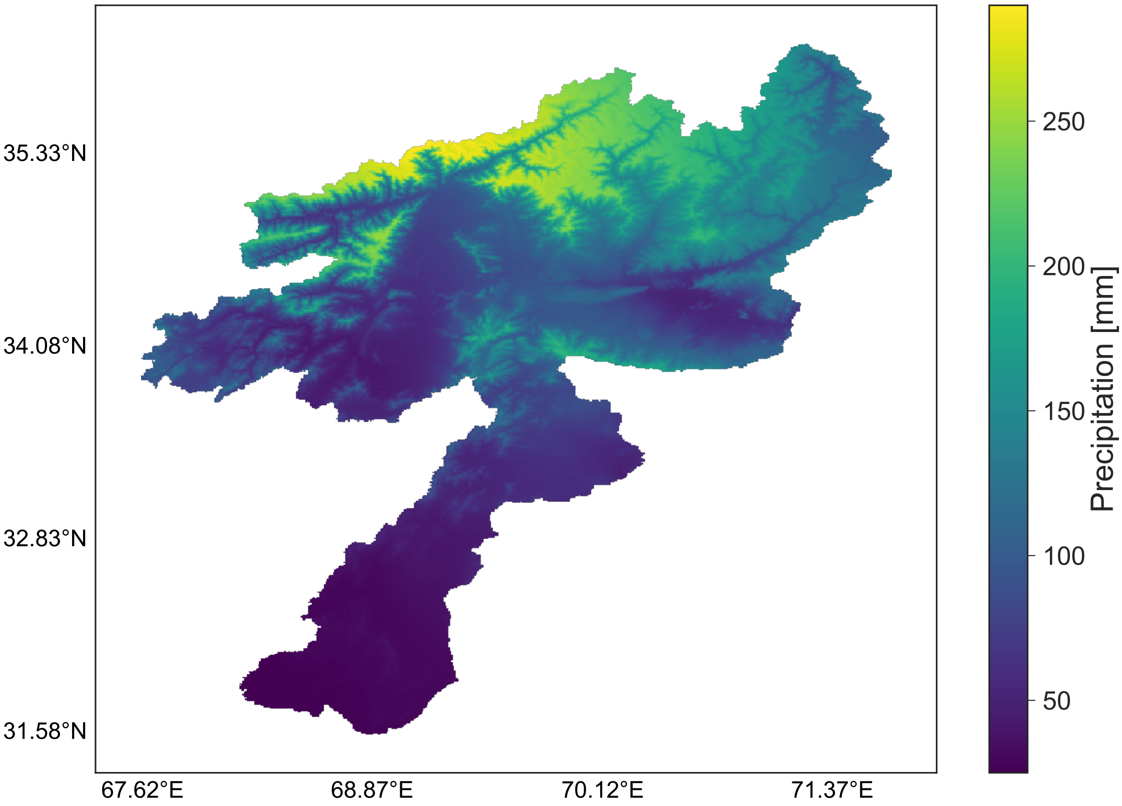

Figure 21: Precipitation in April

To compare and contrast, long term average precipitation of hottest month, July is also plotted in figure 22.

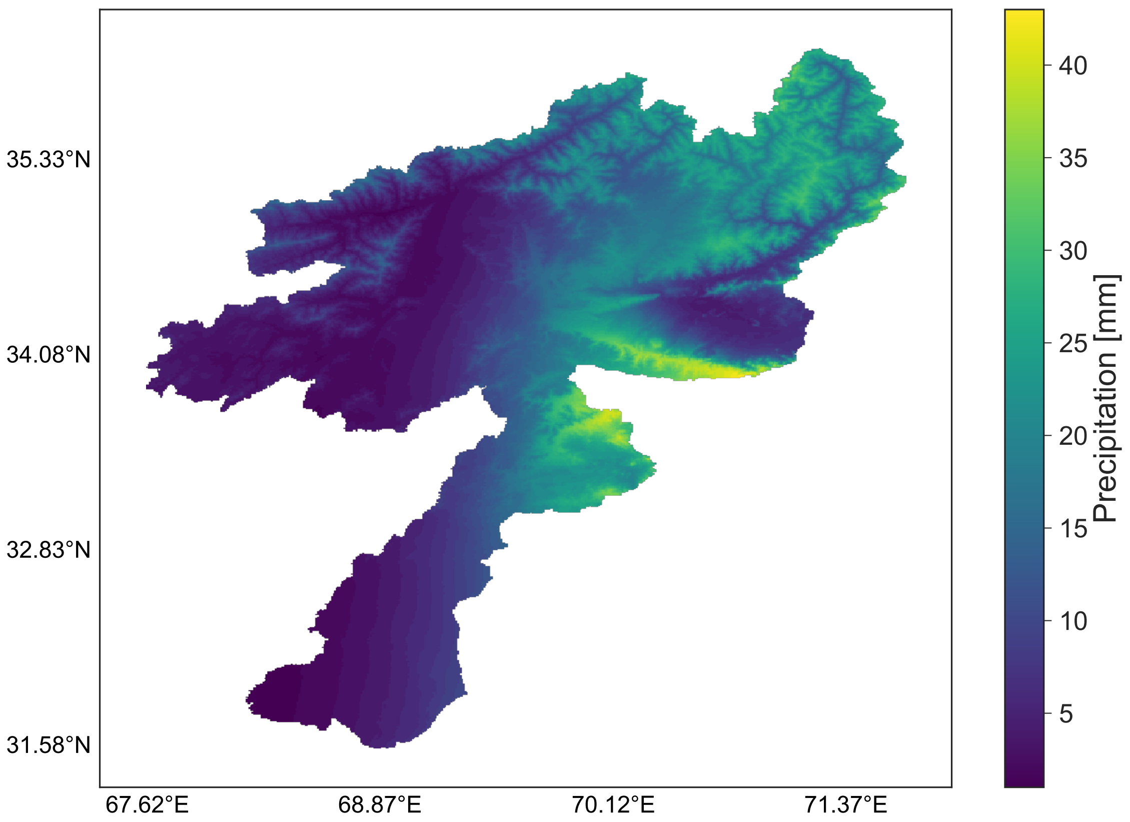

Figure 22: Precipitation in June

The model needs monthly data for calculating the evapotranspiration as a function of crop type and agro-management data. The temperature data for the wettest and hottest months are demonstrated in in figures 23 and 24.

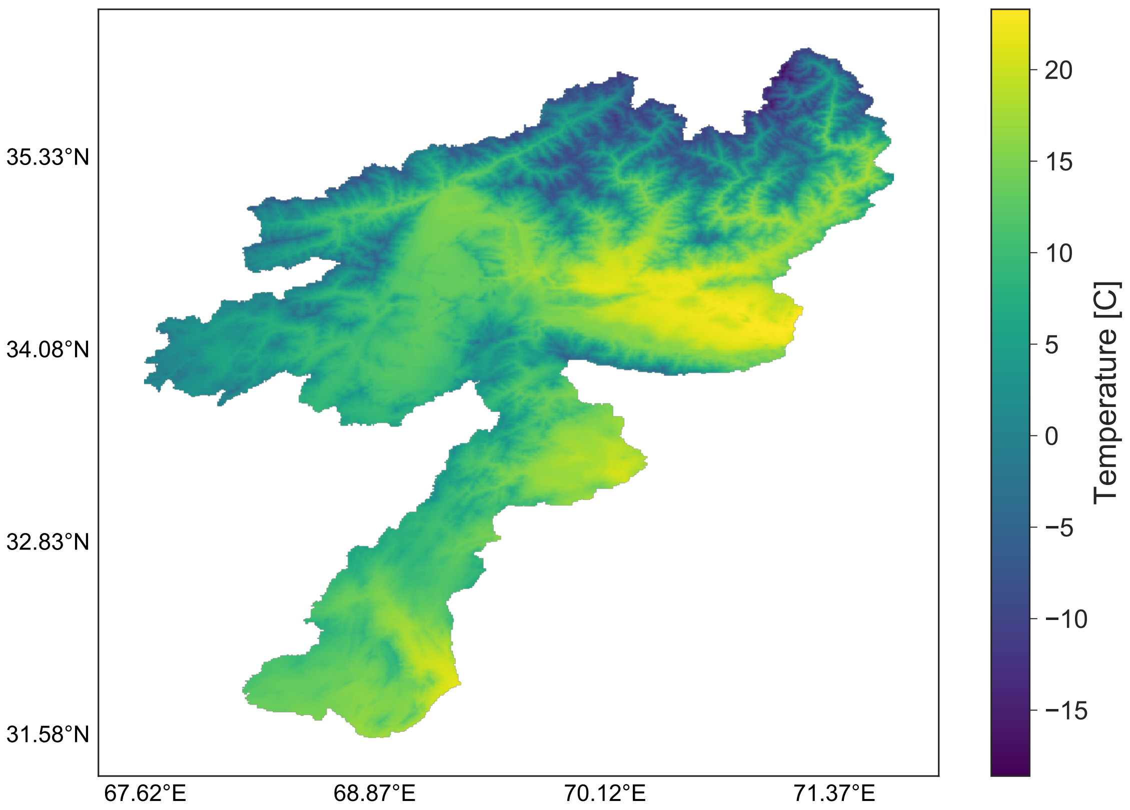

Figure 23: Average temperature in April

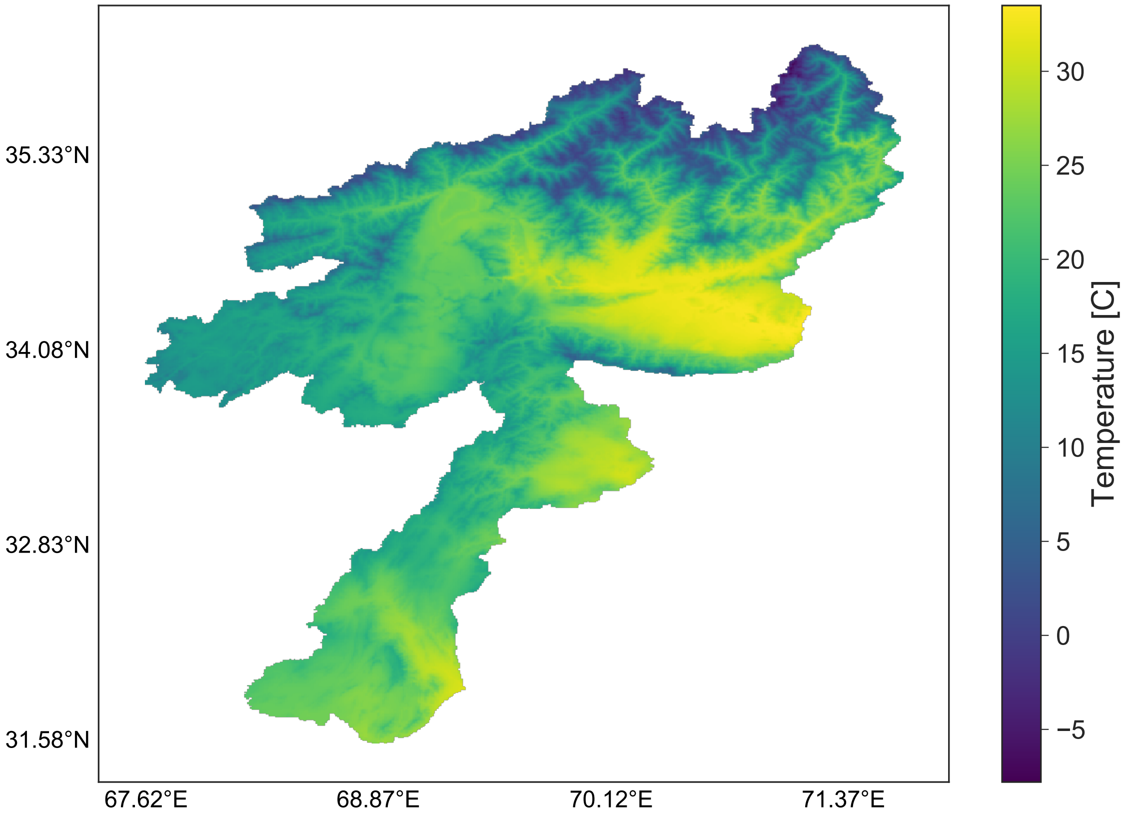

Figure 24: Average temperature in June

Geomorphological data is also required to the rainfall-runoff module of the model. Slope, land use and soil texture data is needed to calculate the infiltration rate to the groundwater. The slope is illustrated in figure 25 and land use data is in figure 26.

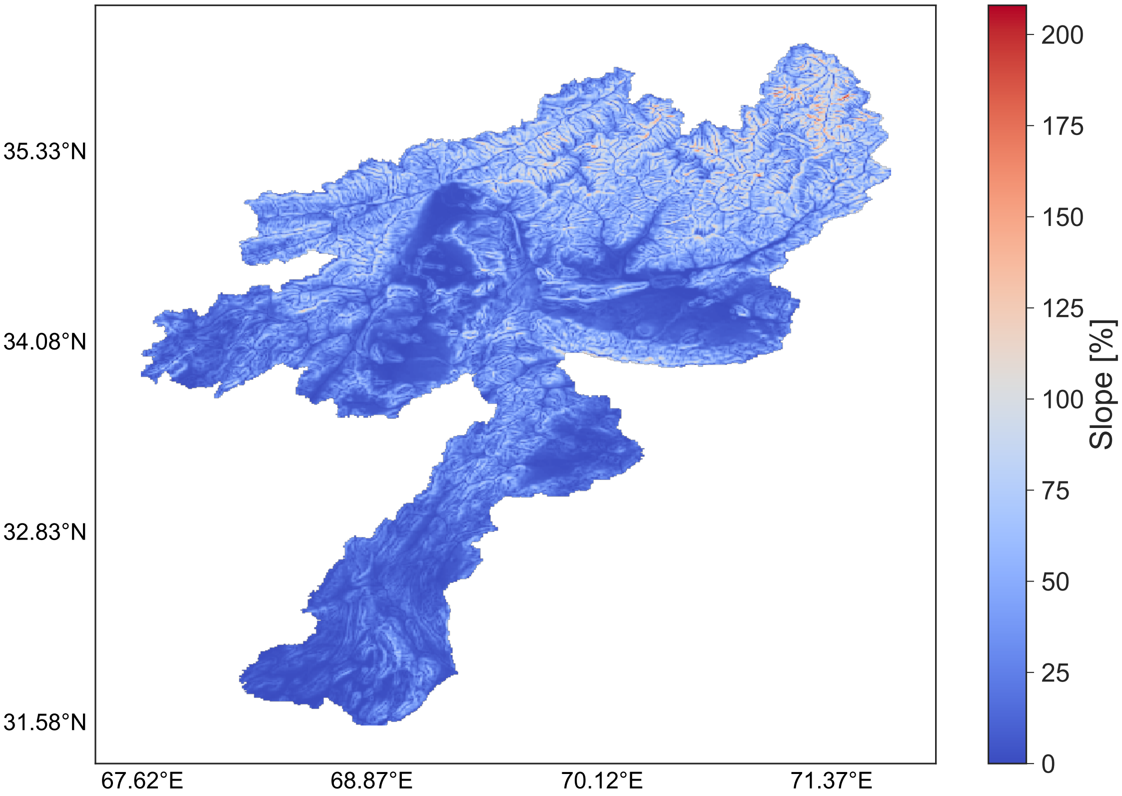

Figure 25: Slope

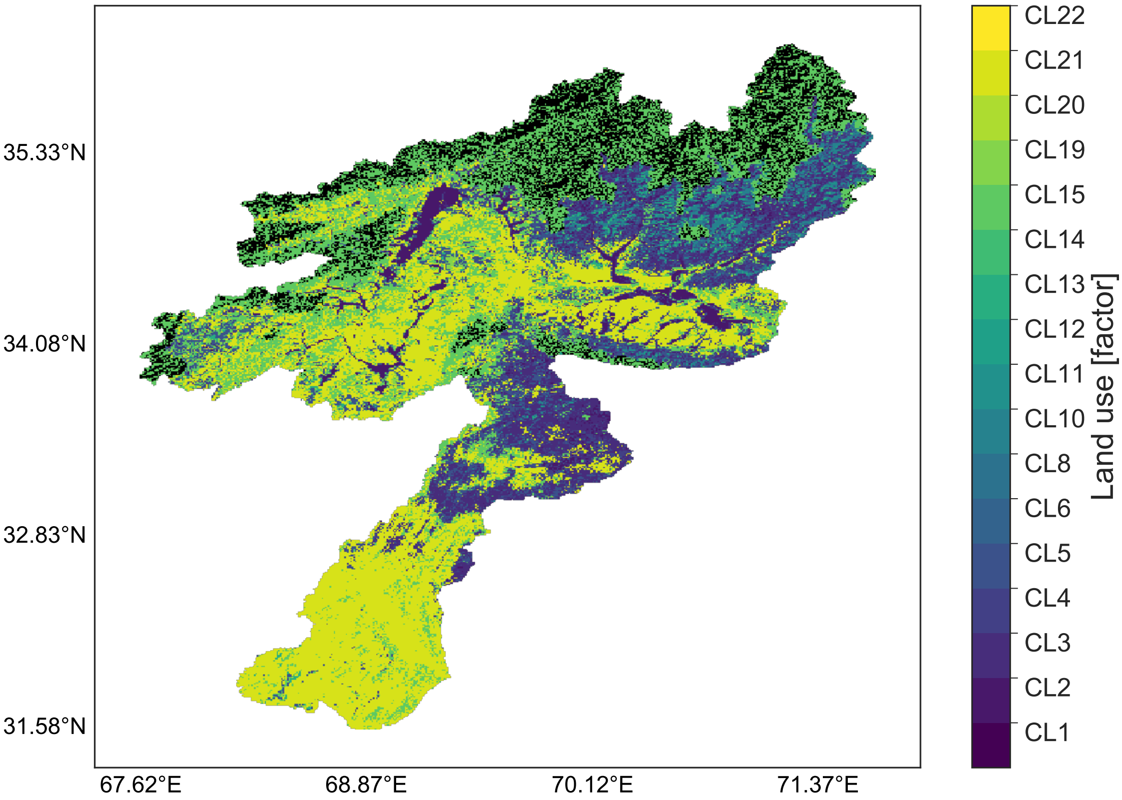

Figure 26: Land use

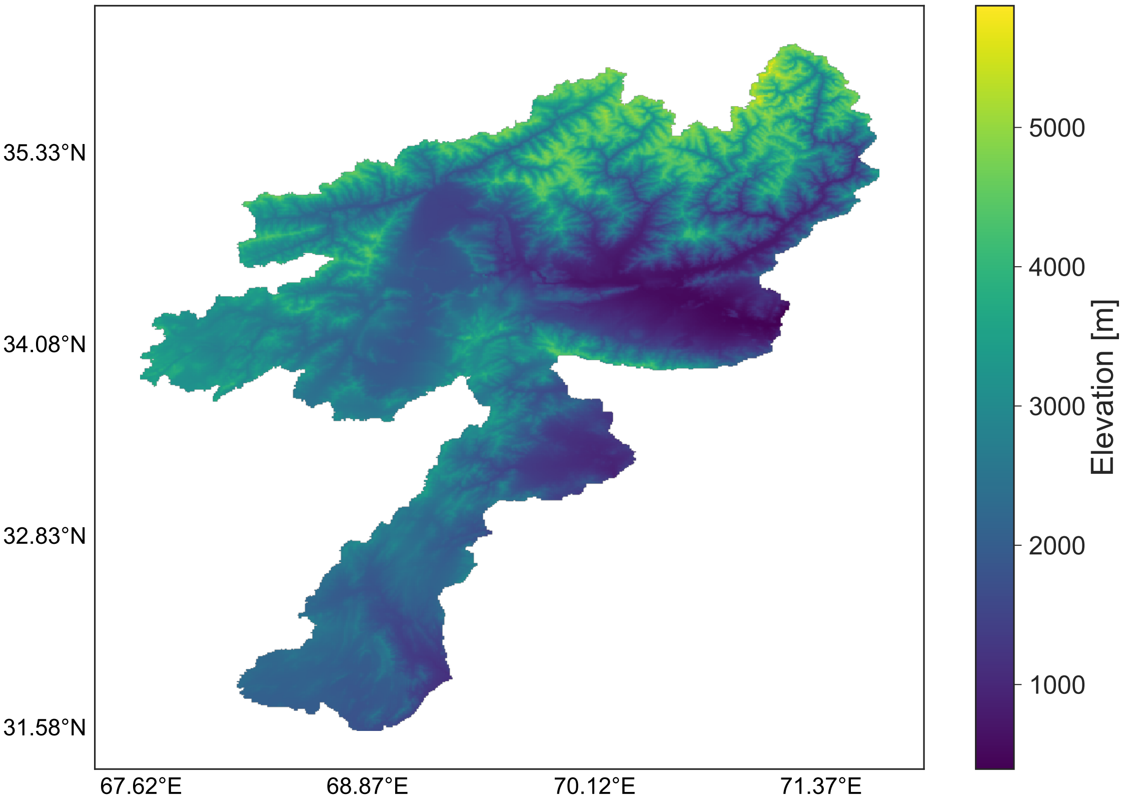

Figure 27: Elevation

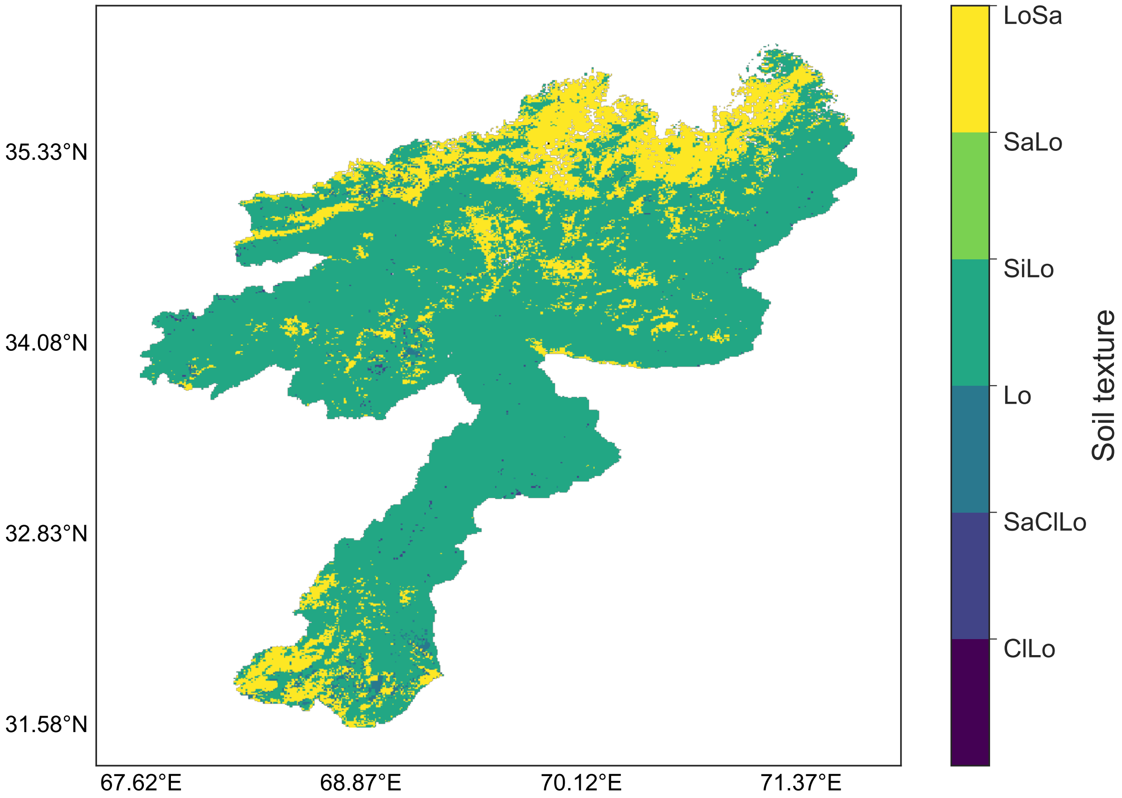

Figure 28: Soil texture

The pre and post processed spatially distributed input data was used to simulated the groundwater level in space and time. The results were mapped for the analysis of the drawdowns. In this section, only two time horizons were presented (20 and 50 year). However, the ratio of groundwater abstraction for irrigation were simulated ranging from 20 to 80 percents. The key parameter, porosity, was selected as static (20 %) for deterministic simulation and for the stochastic simulation porosity was selected from triangular distribution by means of Monte Carlo simulation.

In figure 29, the main crop, winter wheat simulation results are illustrated. The drawdown is relatively shallow in major areas when the irrigation ratio of groundwater is 20 %.

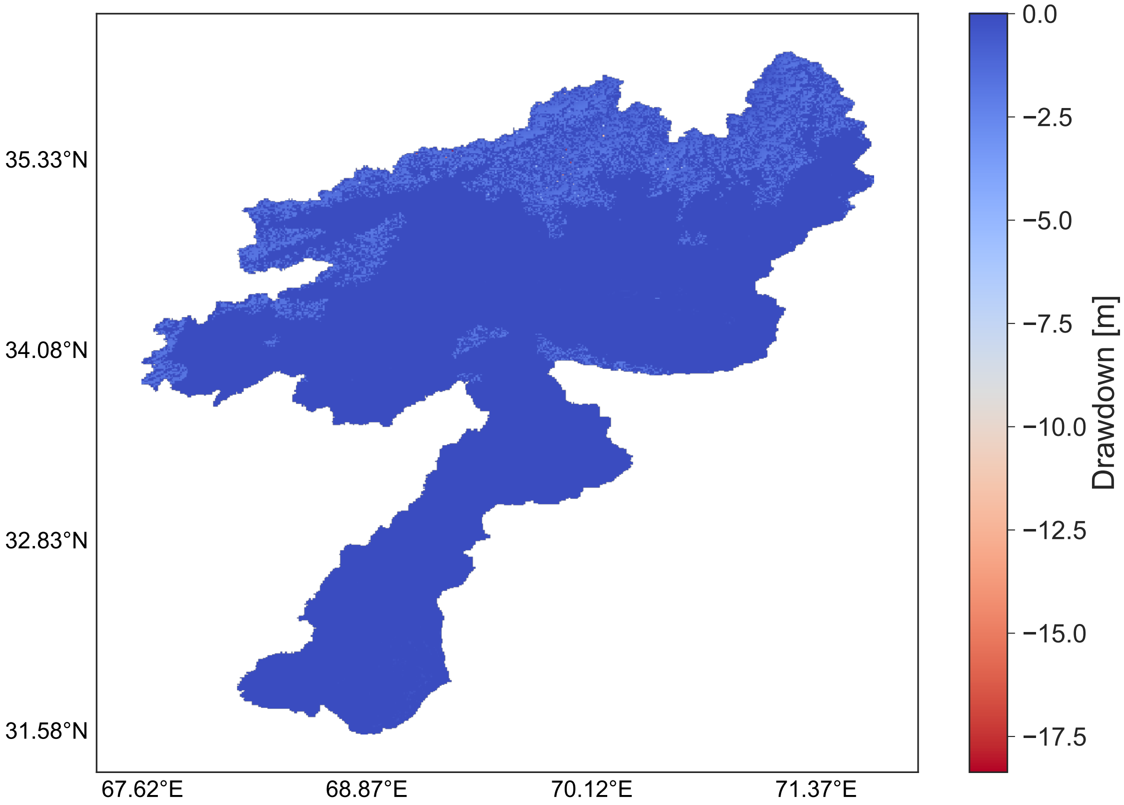

Figure 29: Drawdown of winter wheat cropping with 20 % irrigation from groundwater for 20 year time horizon

However, in figure 30 where irrigation ratio is 50 % the situation changes drastically. The highest drawdown is around 35 meters.

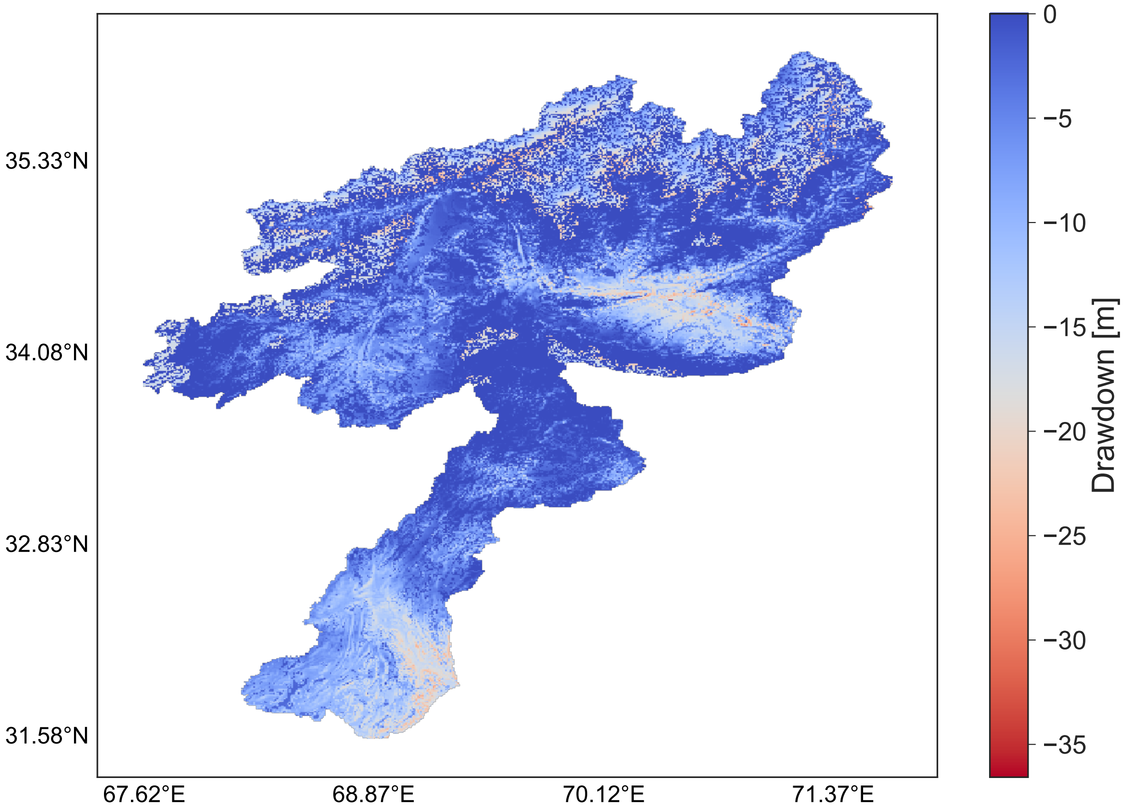

Figure 30: Drawdown of winter wheat cropping with 50 % irrigation from groundwater for 20 year time horizon

The worst case is analyzed increasing the irrigation demand from groundwater resources from 50 to 80 % (37). Only 30 % increase in groundwater irrigation demand significantly changes the drawdown up to 70 meters deep.

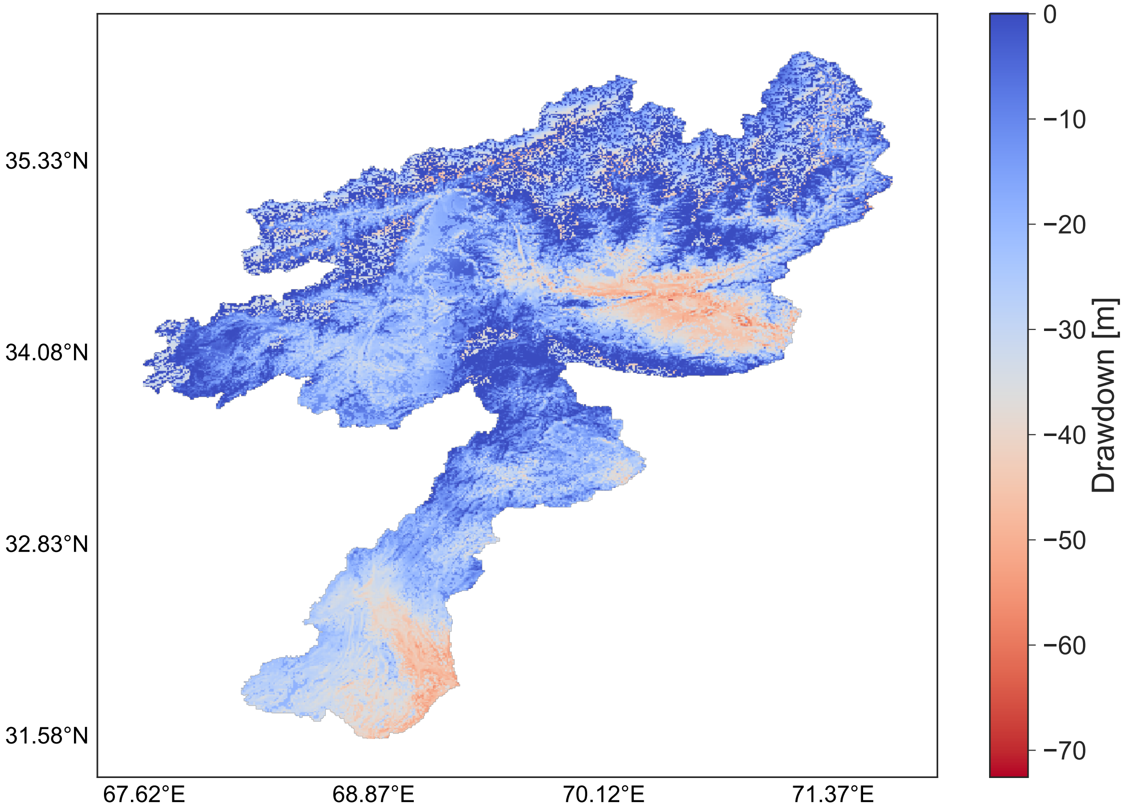

Figure 31: Drawdown of winter wheat cropping with 80 % irrigation from groundwater for 20 year time horizon

In the next section of the work, the time horizon was changed from 20 years to 50 year. So, if the same irrigation demand from groundwater is consumed, how the groundwater level situation will be in the next 50 years, assuming other factors will be constant. Figures 32, 33 and 34 show longer time horizon and more serious drawdown results.

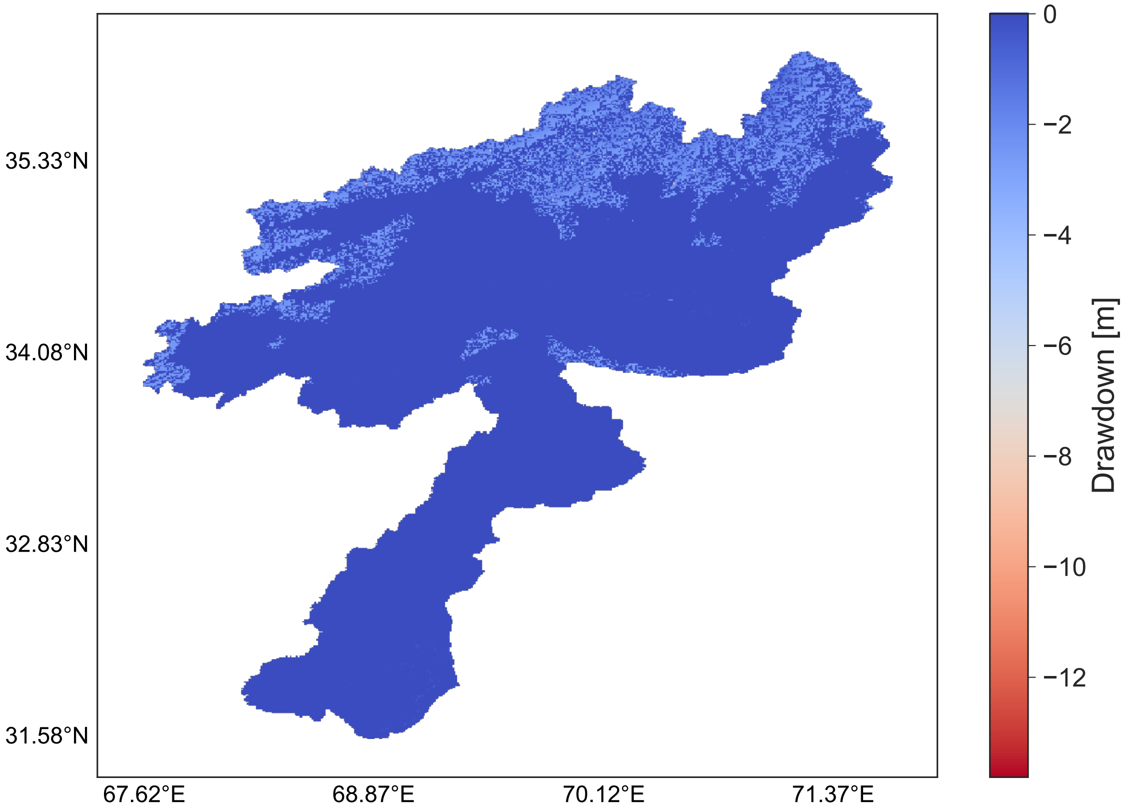

Figure 32: Drawdown of winter wheat cropping with 20 % irrigation from groundwater for 50 year time horizon

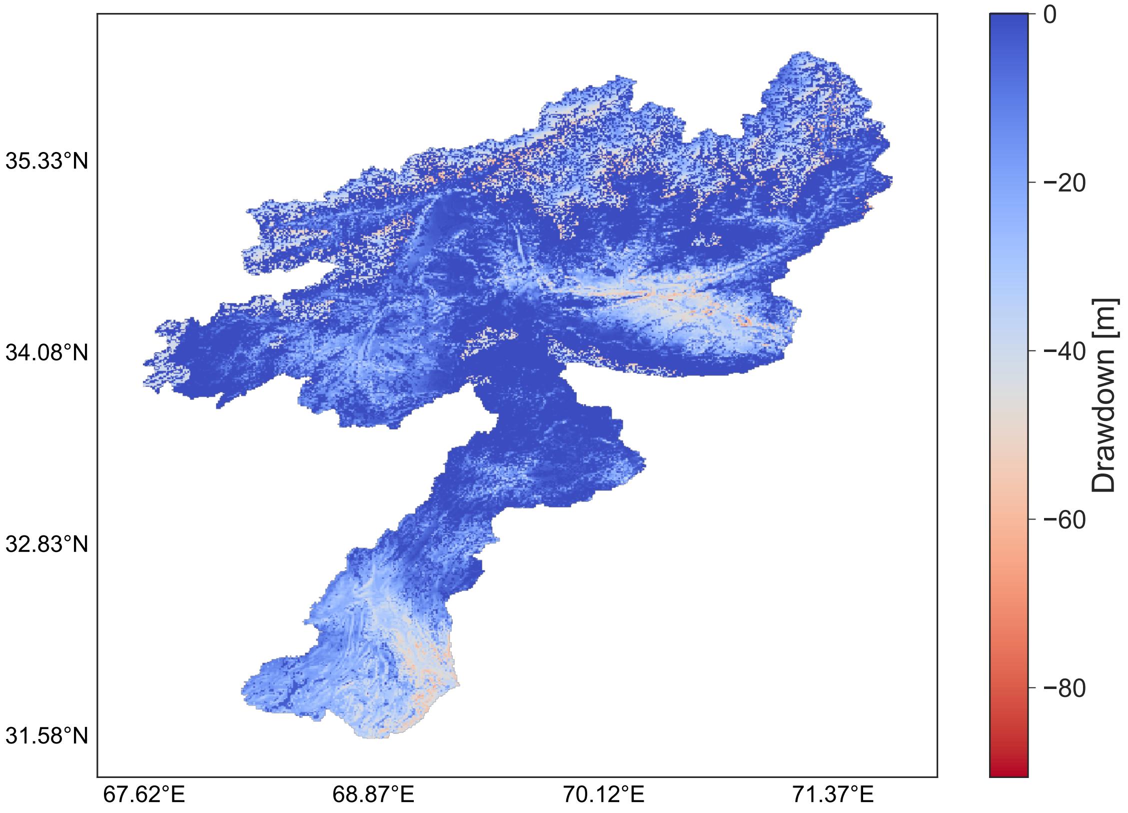

Figure 33: Drawdown of winter wheat cropping with 50 % irrigation from groundwater for 50 year time horizon

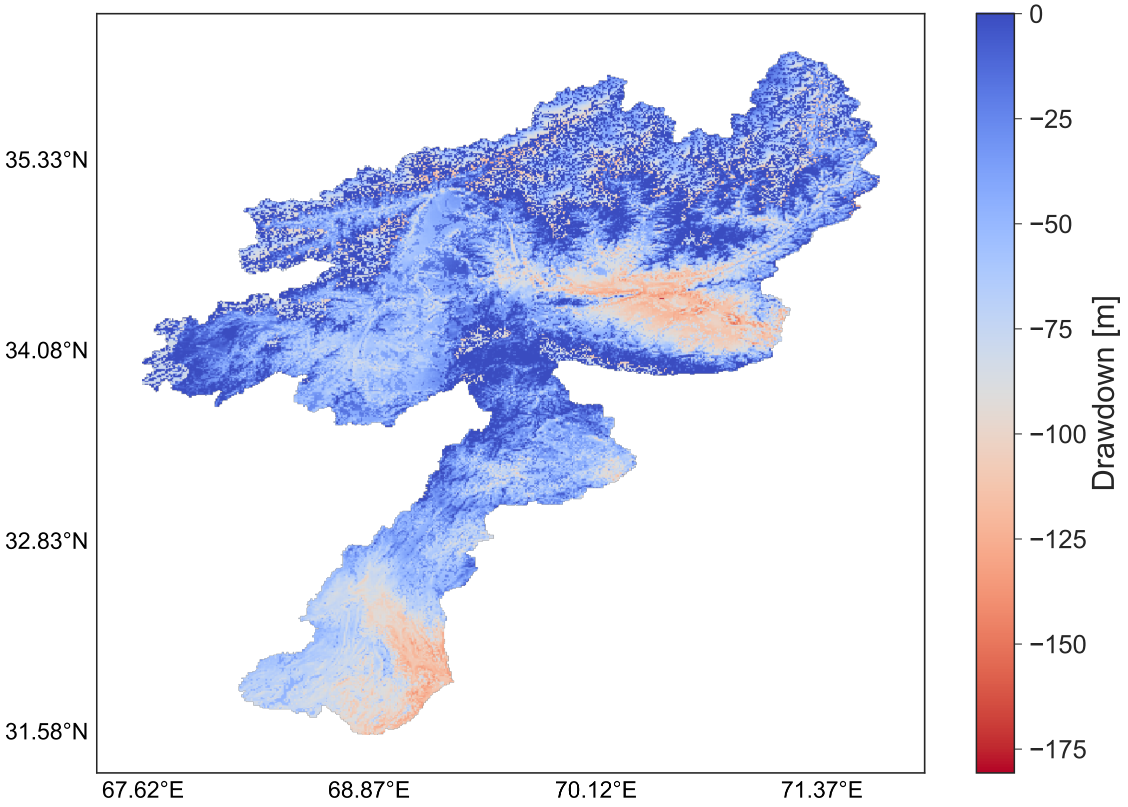

Figure 34: Drawdown of winter wheat cropping with 80 % irrigation from groundwater for 50 year time horizon

In addition, maize also was modeled as it is the second major crop grown in the Kabul River basin. The same scenarios were applied as in the case of winter wheat. The result of drawdown by maize cropping are demonstrated in figures 35 - 40.

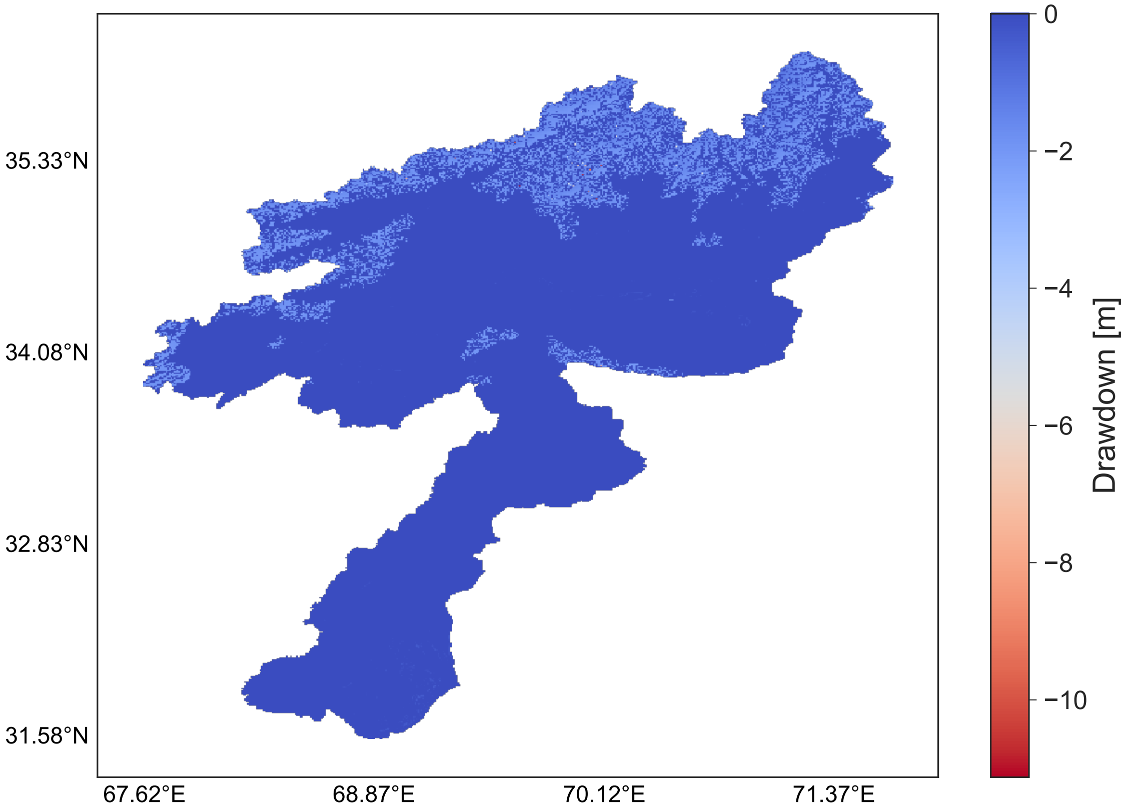

Figure 35: Drawdown of maize cropping with 20 % irrigation from groundwater for 20 year time horizon

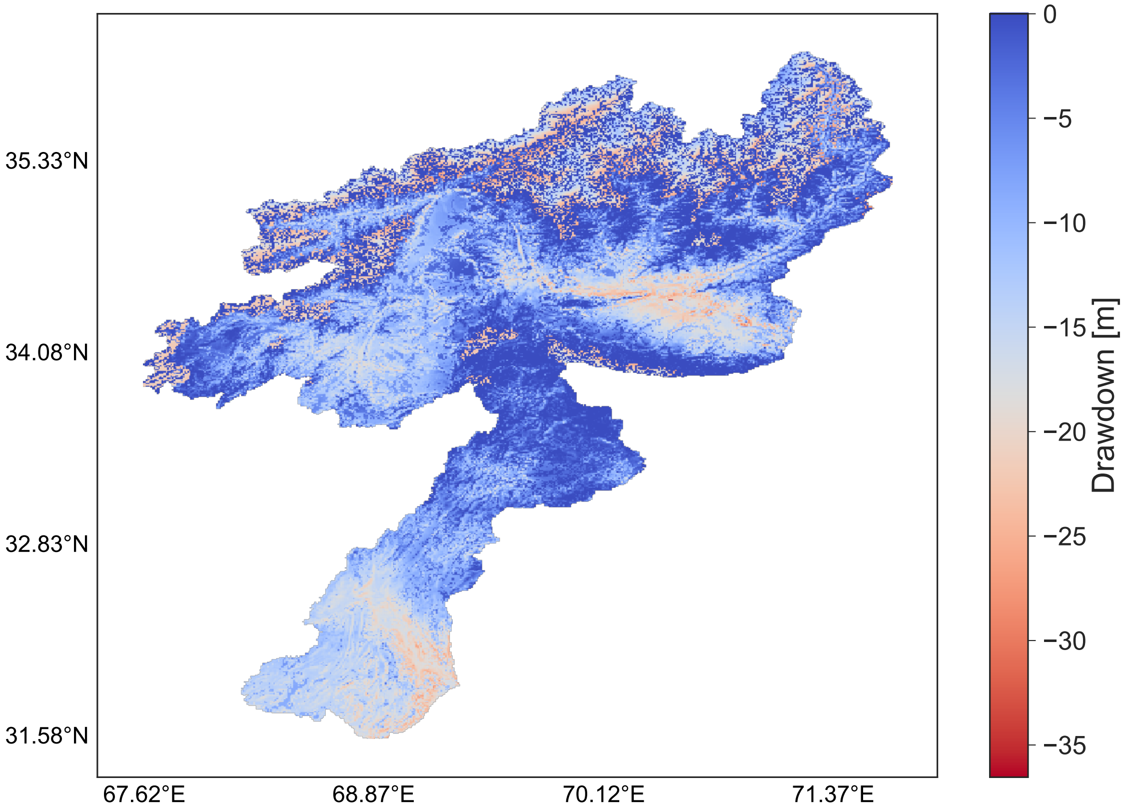

Figure 36: Drawdown of maize cropping with 50 % irrigation from groundwater for 20 year time horizon

In the same way as in winter wheat, the model was run for 50 year time horizon for maize production. Despite the fact that the same agricultural management with 20 % abstraction of groundwater, the drawdown happens only in the upstream regions (figure 35).

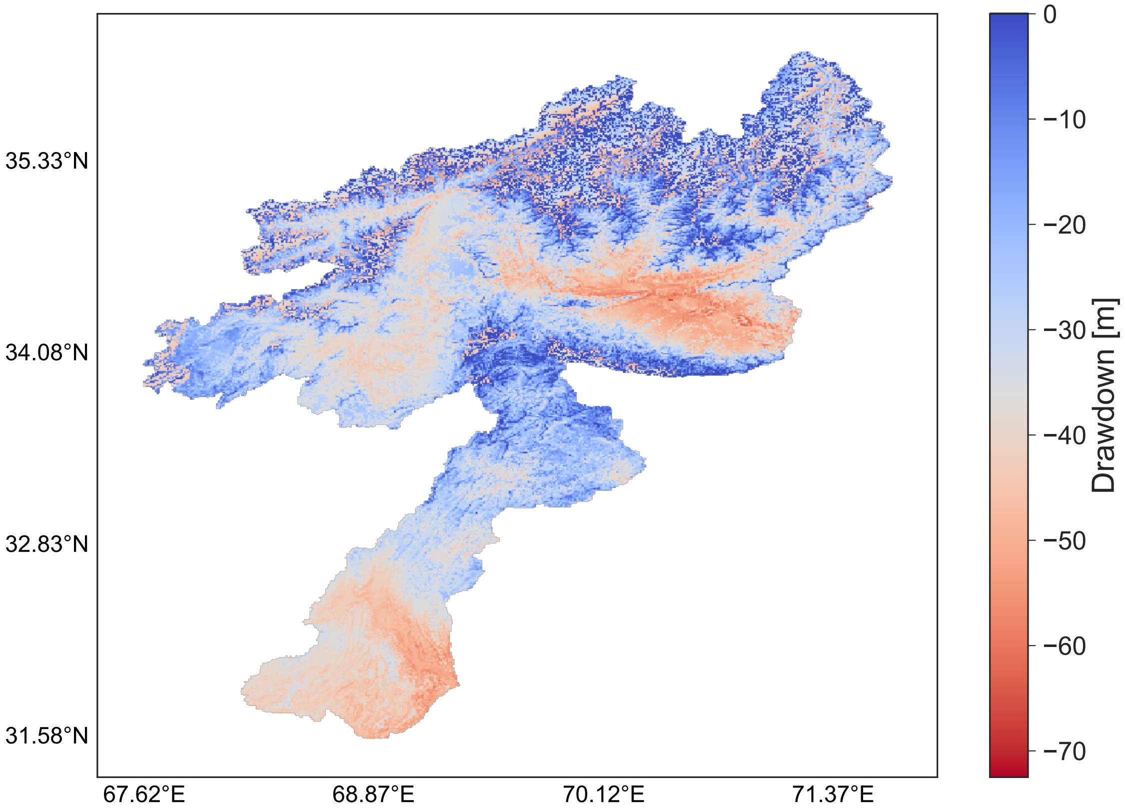

Figure 37: Drawdown of maize cropping with 80 % irrigation from groundwater for 20 year time horizon

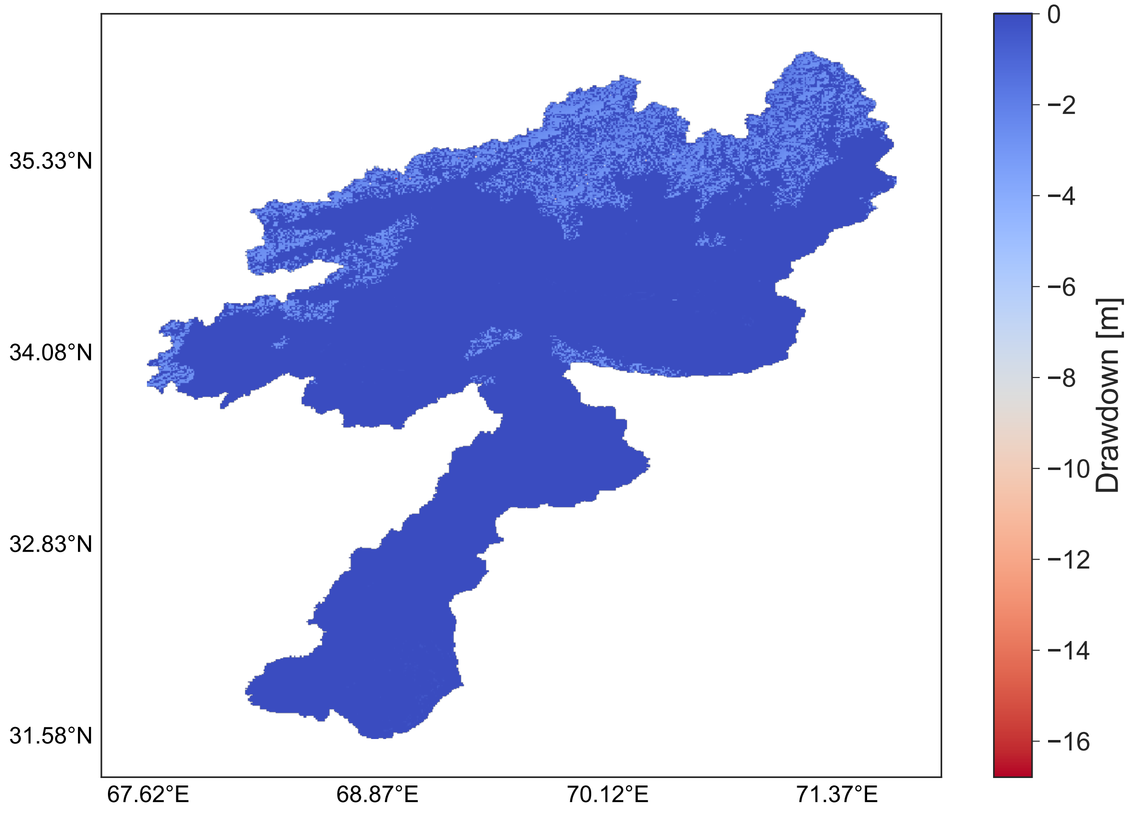

Figure 38: Drawdown of maize cropping with 20 % irrigation from groundwater for 50 year time horizon

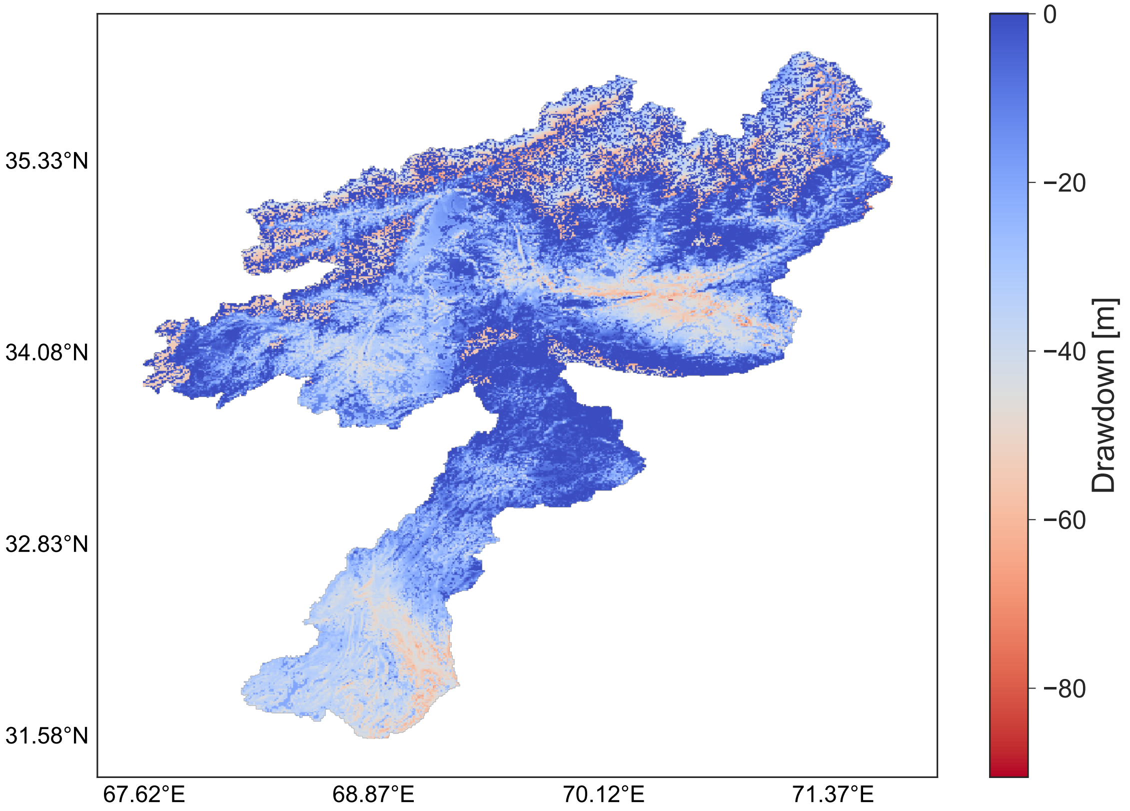

Figure 39: Drawdown of maize cropping with 50 % irrigation from groundwater for 50 year time horizon

Highest drawdown is observed when the irrigation from groundwater percent was 80 %. Particularly, maize production shows the wide spatial distribution of significant drawdowns ranging up to 175 meters covering bigger area than winter wheat production.

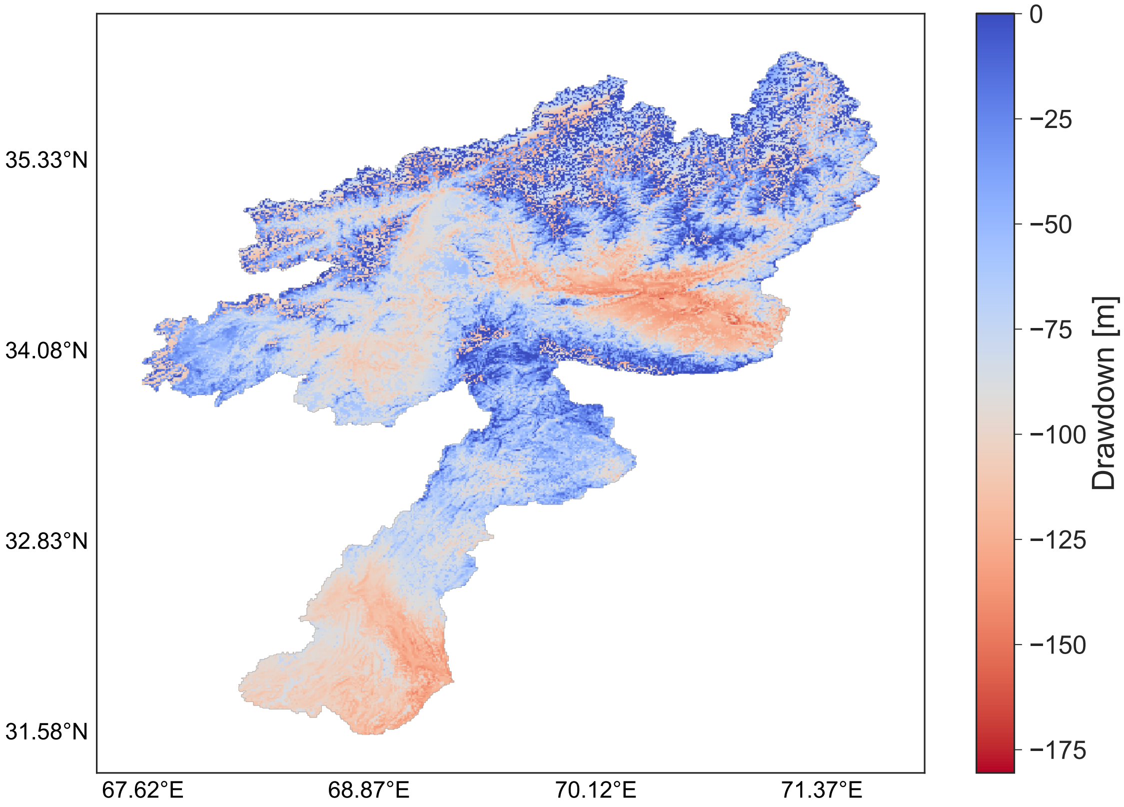

Figure 40: Drawdown of maize cropping with 80 % irrigation from groundwater for 50 year time horizon

5 Discussion

5.1 Point scale simulations

The model was run at point scales to see the performance of each modules. As the box model has three systems, each system was run separately for a detailed analysis. In the following chapter, systems and their performance is discussed.

5.1.1 Potential recharge system

Potential recharge system does not vary significantly. The main driving forces in this system are the total precipitation and phreatic evaporation. The total precipitation influences the groundwater level considerably because of high infiltration during the raining seasons (figure 1). The yearly groundwater drawdown gradually, in contrast, gets stable because of mass balance where input gets equal to output (figure 2). The stability of the recharge system depends of the porosity and the bottom elevation of the aquifer.

However, when the groundwater head gets high enough and closer to soils surface, the phreatic evaporation starts and removes the water pumped up by capillary forces. This phenomenon of dominant phreatic evaporation causes soil salinization, especially in arid and semi-arid regions. However, high groundwater level mainly happens during the irrigation seasons where irrigation type is inefficient such as flood irrigation. The influence of irrigation on phreatic evaporation in described in the agriculture system section.

5.1.2 Agricultural system

The agricultural system is the most important system as it is the main water consumer. Due to higher abstraction of groundwater resources more than its recharge capacity, the drawdown happens (figures 5 and 6). These plots show the impact of irrigation water demands of 40 and 50 % from groundwater resources for growing winter wheat.

If the percentage of irrigation abstraction gets higher than 50 %, the groundwater drawdown gets drastic. The figure 7 illustrates the drawdown for 80 % irrigation from groundwater. The water level decreases up to 17 meters in 20 years. If the same irrigation management is used for 100 year time horizon, the groundwater table decreases by around 80 meters (figure 8).

These scenarios demonstrate that irrigation can cause significant groundwater drawdowns if the irrigation management is inefficient.

5.1.3 Mixed system

The mixed system is the most complex system and requires more components in comparison with other systems. Particularly, the industrial and domestic water demands required which are highly uncertain. Those sectors' consumptions not only varies in space and time, but they also influenced by economic and social aspects within a region.

The data for industrial and domestic water consumptions is scarce and mostly does not exist for many river catchments in developing countries. Furthermore, if decision has to made for future, then some forecasted data also needed. Hence, using autoregressive models, which are probabilistic methods for time series forecasting, are used to predict the human population in Afghanistan (figure 10). By forecasting the human population, we can estimate the domestic water demand.

Industrial water demand also will be forecasted in later stages ...

5.1.4 Parameter sensitivity

As the box model is parsimonious, it has only few sensitive parameters. Porosity is the main and significant parameter in the model. Hence, the model was run for a range of porosity values to observe its sensitivity in term of groundwater head.

The figure 11 illustrates that porosity is very sensitive. When the porosity is very small the drawdown happens fast. Nevertheless, if the it is higher than 20 %, the drawdown gets stable. It indicates aquifers with small porosity need to calibrated i carefully so that box model performs properly. Otherwise, too small percentage of porosity might cause some numerical instabilities in the model.) In addition to porosity, the phreatic evaporation parameter was also tested. The phreatic evaporation only influences the model output if the groundwater table is higher than the evapotranspiration (ET0) extinction depth. For this reason, in figure 12 it can be observed that drawdown happens only when certain amount of water is stored in the aquifer system and level is higher than ET0 extinction depth. In other words, the higher the extinction parameter, the more evaporation happens. It turns on the phreatic evaporation at certain depth.

5.2 Uncertainty analysis

The groundwater parameters vary in space and time significantly and have complex distribution in nature. Nonetheless, some statistical methods can provide additional information for decision making such as confidence intervals. Rather than providing the single value of groundwater head, which can be highly uncertain, numerous statistics and confidence intervals can provided. For these reasons, Monte Carlo methods is used.

5.2.1 Monte Carlo simulation

As described in the section 4.2.1, the groundwater parameters varies in nature significantly and it is physically impossible to sample all over the river catchment those parameters. Furthermore, the higher the resolution of simulation, the more time consuming is the computation.

In order to deal with the complexity of parameter data collection and and its uncertainty, the continuous probability distributions were selected. In this study, triangular distribution was used to sample the parameters for each Monte Carlo run (figure 13 and 14).

In most cases, the groundwater parameters are assumed to be log-normally distributed. However, in this study, due to lack of data and samples, it was impossible to use log-normal distribution. The best approach is conducting some experiments and determining the parameter ranges, however, due to time and other constraints, Monte Carlo and ensemble modeling method was done to account for uncertainties.

5.2.2 Ensemble simulation

In figure 15 it can be seen that ensemble mean of the all Monte Carlo trajectories is relatively small. This indicates that if the irrigation abstraction is between 30 to 50 %, the ensemble mean drawdown is around 1 meter throughout the time horizon. When the irrigation percent is equal to 30 %, the drawdown is very small despite the varying porosity ranges.

If the irrigation percentage is higher than 50 %, the situation changes drastically and the variation of drawdown get significantly higher, especially at the end of the time horizons. It should be also noted that irrigation and crop type also plays an important role. For example, barley which grows within spring and summer season show significantly different results than winter wheat which is planted in autumn (figure 19).

5.3 Spatially distributed simulations

One of the advantages of the spatially distributed models is that it does not require complex calibration processes. The parameters are mostly physically meaningful and can be derived from the input data. The main disadvantage is the fact that it requires input data with high accuracy and resolution in space and time.

One of the most important input, the annual precipitation is visualized in figure 20. The downscaled 1 km resolution data shows significantly detailed high resolution distribution of precipitation in space for Kabul river basin. Consequently, the output data of the model will be highly detailed.

Another sensitive parameter is the slope (figure 25). Slope influences the infiltration model significantly, hence it is the sensitive input data. However, high slope percentages are distributed mainly in high elevation regions, especially in mountainous areas in the north and north-east side of the Kabul River basin. Despite the fact that high slope results in lower infiltration, due to the high precipitation in those areas, infiltration do not get too low.

After preparing the input data, the spatially distributed version of the box model was run. However, the model was run only for recharge and agriculture systems, because the mixed system requires domestic and industrial water demands which are not widely spread in space. Domestic and industrial sectors are analyzed in point scale chapter.

In the results section, only the main two crops, winter wheat and maize are illustrated. The other crops results and maps can be found in the appendix. The winter wheat drawdown results are shown in figures 29 - 34. As the winter wheat grows from late Autumn to late Spring, it does not results higher drawdown than other crops. The recharge during the Autumn and Spring are high due to high precipitation.

On the other hand, maize cropping shows more significant drawdown results than winter wheat (figures 35 - 40). The reason is the fact that maize grows in the summer season when the evapotranspiration rate is at its maximum level. In addition, the precipitation is very low or zero in summer season as the region is arid and semi-arid. Nonetheless, the highest drawdown regions are the lower elevation plain areas in the catchment. In the mountainous areas, the results show very diverse results due to land use type.

There are some areas where the drawdown is extremely high. It happens when the land use type is impervious (cities for example).

6 Conclusion

The results of the study show that the groundwater is sensitive in plain areas of the Kabul River basin if abstracted to irrigation purposes. Especially, for summer crops, the drawdown gets drastically higher due to higher evapotranspiration. If the percent of groundwater abstraction for irrigation higher than 50 %, the results of drawdown becomes significant. The results this research can be useful for decision making purposes, especially for the long term water resources planning or in planning the drought prevention measures.

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