Assessing the Impact of Land Use and Climate Change on River Ravi Flows: A GIS and Hydrological Modeling Approach

Sami Ullah
University of Engineering and Technology
Usman Ali
University of Engineering and Technology
Muhammad Rashid
University of Engineering and Technology
Saif Haider
ranasaifhaider@gmail.com

University of Engineering and Technology

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Abstract

In the present study, the impact of Land Use and climate change on the flows of River Ravi has been assessed through GIS remote sensing and applying the hydrological model at the catchment scale. A Soil and Water Assessment Tool (SWAT) model has been applied to simulate the hydrological response of River Ravi considering the current and future Land Use and climate changes. The model was calibrated and validated for the periods of 1999–2002 and 2003–2005, respectively. The good fit values of NSE, R^2, and PBIAS for the calibrated model are 0.85, 0.83, and 10.01 while for the validated model are 0.87, 0.89, and 7.2. By supervised classification techniques current and future Land Use maps were prepared for the study area using Landsat images and the TerrSet model for the prediction of future change in the built-up area. The result showed that the built-up area increased by 15.8% over the period 1990 to 2020 and the Future built-up area is expected to increase by 31.7% over the period 2020–2100. Climate change projections of precipitation and temperature under two Shared Socioeconomic Pathways SSP2 and SSP5 have been carried out, and statistical downscaling has been performed by the CMhyd model. The result indicated that over the period 2016–2100, precipitation is expected to increase by 10.9% under SSP2 and 14.9% under SSP5. Similarly, temperature is expected to increase by 12.2% under SSP2 and 15.9% under SSP5. The result of the SWAT model considering the increased precipitation over the period 2016–2100 shows the inflows of River Ravi are expected to increase by 19.4% by SSP2 and 25.4% by SSP5 in Scenario I. Similarly, the inflows of River Ravi are expected to increase by 22.4% by SSP2 and 28.4% by SSP5 in Scenario II. Based on the past observed data, it is found that average Groundwater depth decreased at a rate of 0.8 m per annum over the period from year 1996 to 2020.

1. Introduction

Two important elements that have a considerable impact on hydrological systems are climate change and changes in Land Use, particularly the flow patterns of rivers (Haider et al. 2023a, d; Hassan et al. 2023a, b; Masood et al. 2023b). The Ravi River, a vital tributary of the Indus River in Pakistan, plays a crucial role in supporting agriculture, providing drinking water, and sustaining ecosystems in the region (Hashmi et al 2012). However, in recent decades, the Ravi River has experienced fluctuations in flow patterns, attributed to the interplay between climate change and Land Use change (Ashraf et al. 2022; Aslam et al. 2022; Huda et al. 2023). This general introduction aims to shed light on the complex relationship between these two factors and their consequences concentrating on the catchment of River Ravi within Lahore City, to assess its response considering current and future Land Use and climate changes (Ashraf et al. 2018; Usman et al. 2018; Shafeeque et al. 2023). Water is essential to one's ability to live and can be put to several different uses. The consistent need for water is increasing throughout the world. To meet the human need for water, groundwater resources such as aquifers have been used as a source of water all over the world. At least one-fourth of the world's population depends on the supplies that come from the vast underground aquifer systems that hold nearly all of the world's liquid freshwater (Hiscock 2011; Qureshi 2020; Sohail et al. 2022). Other than Groundwater, there is also Surface water and both are interdependent. In 2015, almost 80 percent of all water used in the United States came from surface water (Bagstad et al. 2020).

Climate change profoundly influences hydrological systems by affecting precipitation, evaporation rates, and snowmelt patterns. These alterations directly impact river flows and their seasonal variability. Changes in precipitation can lead to both increased flooding and extended periods of drought, posing serious challenges to water resource management, agricultural productivity, and ecosystem health (Anandhi et al. 2011). Land Use change refers to the conversion of natural landscapes for human purposes, such as urbanization, agriculture, and deforestation. Human activities, driven by population growth and economic development, have significantly altered land cover across the globe (Meyer and Turner 1992). These changes disrupt the natural balance of ecosystems and often contribute to increased runoff and erosion. Altering land cover has a profound impact on the hydrological cycle. Forests, wetlands, and grasslands act as natural sponges that store and slowly release water, regulating river flows and reducing the risk of floods (Jonkman 2005; Kuenzer et al. 2013; Chohan et al. 2015; Mahmood et al. 2016; Garee et al. 2017; Yang et al. 2021; Huda et al. 2023). Conversely, urbanization and deforestation result in reduced infiltration of water into the ground, leading to increased surface runoff and accelerated erosion. This phenomenon can cause flash floods and adversely affect downstream river flow (Kundzewicz et al. 2013; Wu et al. 2019; Khan et al. 2020).

The Balloki region is strategically located along the Ravi River in Pakistan and is susceptible to the combined impacts of climate change and Land Use change (Haider et al. 2015; Ashraf et al. 2022; Huda et al. 2023). The region's agriculture heavily relies on the river's water, making it crucial for livelihoods and food security. Furthermore, the region's natural ecosystems and biodiversity are dependent on a stable and healthy river flow (Gaaloul et al. 2021; Pradipta et al. 2022; Raza et al. 2022; Rashid et al. 2023). Different Studies (Haider et al. 2020; Ashraf et al. 2022; Shabahat et al. 2022; Haider et al. 2023b, c; Huda et al. 2023; Masood et al. 2023c) indicate that climate change has influenced the Ravi River's flow patterns in recent decades. Changes in precipitation and snowmelt timing have resulted in alterations in the river's discharge (Masood et al. 2023a), leading to shifts in the seasonal distribution of water flow. For example, reduced snowmelt in the upstream Himalayas and increased variability in monsoon patterns have affected the Ravi River's flow regime [38,39,40]. Land Use changes, particularly urbanization and agricultural expansion, have significantly impacted the Balloki region's hydrology. The conversion of natural landscapes into built environments and intensive agricultural lands has increased surface runoff and soil erosion, affecting water infiltration and river flow. The removal of riparian vegetation and wetlands has further disrupted the river's ecological balance and its ability to regulate water flow.

A comprehensive strategy combining both mitigation and adaptation methods is required to address the effects of climate change and Land Use change on Ravi River flows at Balloki. To limit the severity of climate change, mitigation measures should concentrate on cutting greenhouse gas emissions. This requires transitioning to renewable energy sources, enhancing energy efficiency, and implementing afforestation and reforestation projects to sequester carbon dioxide (Mumtaz et al. 2023; Tariq et al. 2023). Adaptation strategies should aim to enhance the region's resilience to changing river flow patterns.

Implementing sustainable Land Use practices, preserving and restoring wetlands, and adopting water-efficient agricultural techniques are essential steps to mitigate the effects of changing land usage (Maroufpoor et al. 2019; Loures et al. 2020; Abioye et al. 2022; Raza et al. 2022). Additionally, the development of flood and drought early warning systems can enhance readiness and reaction to extreme occurrences. The effects of Land Use change and climate change on river flow patterns Ravi River at Balloki are evident and demand urgent attention (Shen et al. 2009). Climate change is one of the prevailing factors affecting the water of rivers in the world as well as in Pakistan. Lahore is one mega city of Pakistan that is affected along with other major cities by climate change and urbanization, resulting in groundwater depletion (Kanwal et al. 2015; Basharat 2016). Therefore, there is the utmost need to manage this prevailing problem to counter the future shortage of water resources. Addressing these challenges requires a holistic approach that integrates efforts to mitigate climate change, conserve natural landscapes, and enhance adaptive capacity.

Pakistan is affected by significant Land Use and climate change phenomena which in turn has affected both surface and groundwater resources in the country. This effect is more pronounced in major cities like Lahore where the aquifer has been under threat for the past few years due to less recharge and more abstractions. Therefore, it is important to determine how much Land Use and climate change in Lahore has occurred in the past what will be their trend in the future, and their impacts on water resources.

So, in this study, the Land Use and climate change of Lahore have been quantified considering the past and future scenarios and their impact on the flows of river Ravi at Balloki have also been assessed. The following goals are to be attained by this study: (a) To find the current and future Land Use and climate change trends in the study area. (b)To assess river Ravi hydrology and groundwater depletion rate of Lahore using the observed data. (c) To investigate the impact of Land Use and climate change on the flows of river Ravi. (d) The scope of the study is to find the current and future Land Use and climate change trends in the study by considering the past and future scenarios and their impact on the flows and hydrology of river Ravi at Balloki. Additionally, the variation in Groundwater depth in Lahore City has also been estimated by observing past data.

2. Materials and Methods

2.1. Study Area

Lahore, Pakistan's second-largest city after Karachi, is the capital of the Punjab province and is distinguished by a hot, semi-arid climate. Geographically, it is located between 31°15' and 31°45' N latitude and 74°01' and 74°39' E longitude. It is bordered on the north and west by the Sheikhupura District, on the east by Wagah, and the south by the Kasur District. On the district of Lahore's western side, the Ravi River runs. The Ravi River, one of the five major rivers of the Punjab region, flows through the northern part of Lahore, providing a crucial water source for the city's inhabitants, agriculture, and industries. The city's landscape is predominantly urbanized, characterized by a mix of residential, commercial, and industrial areas, as well as green spaces and historical landmarks. Surrounding Lahore are agricultural lands that contribute to the region's food production and economy.

One of Pakistan's most significant and rapidly expanding metropolitan hubs is Lahore. According to population statistics, the city district had 2,984,000 residents in 1981, 5,133,000 by 1998, and 8,091,000 by 2009. Lahore's population has surpassed 13.09 million, according to the census of 2021. 13,095,000 people called Lahore's metro region home in 2021, an increase of 3.58 percent from 2020. However, if the city's population growth keeps up at the current rate, it will soon rank among the biggest cities in the world. Lahore is expected to have 25 million residents by 2050. Lahore's yearly average temperature is 35°C, with monthly extremes of 22°C in January and 45°C in June. The climate in Lahore is classified as subtropical and has a warm summer and pleasant winter. The city experiences 600 mm of yearly rainfall during the monsoon season, with July and August often seeing the largest amounts (Qureshi 2012), while the rest of the year is quite dry. In Fig. 1, map of study area is shown.

Every research project has a specific work schedule that must be adhered to from start to completion. Figure 2 gives a detailed methodology of the study. It involves gathering data, analyzing the data, and extracting GIS characteristics and urban regions using SRTM 90m DEM and Landsat imagery (Durga Rao et al. 2009; O'Loughlin et al. 2016). It also involves downscaling projected climate data using statistical methods and setting up a hydrological model, which entails preparing input data, calibrating the model, and validating the model.

2.2. Data Collection

A crucial component of scientific study is the selection of appropriate data and the acquisition of that data from pertinent sources. The collected data and resources as shown in Table 1. The Meteorological data included Precipitation, Temperature, Relative Humidity, Sunshine Duration, and Wind Speed data collected from the Pakistan Meteorological Department (PMD), from 1990 to 2020 were gathered for the study area. Data on daily inflows at Balloki from 1990–2020 was obtained from the Programme Monitoring & Implementation Unit (PMIU). Canals data was obtained from the Irrigation Department. The study area's ASTER (DEM) with a 30m resolution was obtained and Landsat images of the study region were obtained as Tiff files.

Table 1
Description of Sources of Data Collected

TYPES	DATA-SET	SOURCE
Meteorological	Precipitation, Temperature, Sunshine Duration, Wind Speed (1990–2020)	Pakistan Meteorology Department (PMD) https://www.pmd.gov.pk/en/
Hydrological	Discharge (1990–2020)	Programme Monitoring & Implementation Unit (PMIU) & Irrigation Department https://irrigation.punjab.gov.pk/
Ground Water Level	Depth of Ground Water Table (1996–2020)	Water & Sanitation Agency (WASA) https://wasa.punjab.gov.pk/
Topography	DEM (Spatial Resolution 30 m)	Shuttle Radar Topographic Mission (version 4) https://earthexplorer.usgs.gov/
Landcover	Landsat (4–5,8) Images (Spatial Resolution 30 m)	USGS https://earthexplorer.usgs.gov/

2.3. GCM Data Downscaling

Global climate models (GCMs) are intricate mathematical representations of the principal parts of the climate system and how they communicate (Groppelli et al. 2011; Candela et al. 2012; Ahmadalipour et al. 2015; Babur et al. 2016; Azmat et al. 2018; Chunn et al. 2019). The world's air into network boxes, frequently with an accuracy of 100–200 km. On every matrix, conditions portraying barometrical elements are addressed. Because of the way that surface geology is additionally settled at similar spatial scales (100–200 km), a few critical actual cycles and meteorological phenomena can't be precisely addressed. Consequently, downscaling of the GCM simulated data uses the data for study on finer scales. Downscaling is the transformation of large-scale data to small-scale data (i.e. global climate data to regional climate data). It introduces new information into GCM output based on Observed Meteorological Data or High-Resolution Modeling of Physical Processes. In this study, statistical downscaling simulated by GCM (MPI-ESM1-2-HR) maximum and minimum temperature and precipitation is done using the CMhyd (Climate Model data for hydrologic modeling) model. Statistical downscaling is a process used to estimate local or regional climate variables based on larger-scale climate information.

For the intended area for the years 1995, 2000, 2010, 2015, 2018, and 2020, we obtained the free Landsat pictures. Two distinct Landsat image tiles covered the research area. So, for each of the aforementioned years these four tiles, which cover the catchment, were downloaded. These tiff-format tiles were stacked using the Erdas Imagine software. Following the stacking procedure in the image processing program, the Landsat tiles were mosaicked to produce a single image. The catchment was extracted once the downloaded tiles had been mosaicked. This was finished by opening the mosaicked picture document in

ArcGIS and utilizing the program's bulk feature extraction function. The same method was used for the Landsat images from 1995, 2000, 2010, 2015, 2018, and 2020.

2.4. Land Use Changes analysis

The creation of land cover maps for the present and earlier years included the utilization of regulated picture order. Downloaded Landsat pictures from quite a while were handled in ArcGIS before being identified using the maximum probability method. The most used supervised image classification methods. The combination of bands and their attribute is shown in Table 2.

Table 2
Landsat Band Combination to Extract Information

Visible Attribute	Band Combination
Color Infrared (vegetation)	5 4 3
False Color (urban)	7 6 4
Natural Color	4 3 2
Agriculture	6 5 2
Shortwave Infrared	7 5 4
Healthy Vegetation	5 6 2
Land/Water	5 6 4

2.5. Future Land Use Changes Analysis

Future Land Use change was predicted by using the TerrSet CA (Cellular Automata) - Markov model. The quantitative and geographical aspects of Land Use in the future were simulated using it. The CA-Markov module was used to simulate various combinations of multiple-category land-use changes (Subedi et al. 2013; Nouri et al. 2014; Omeno et al. 2021; Shikary Somnath 2022; Tariq Faisal 2022; Tariq et al. 2022; Hua and Gani 2023). This facilitates the creation of a matrix that compares the transitions between earlier land-use maps and calculates the likelihood that these transitions occur in future Land Use change predictions (Kumar et al. 2016; Baig et al. 2022; Mehmood et al. 2023). A future Land Use methodology flowchart represented in Fig. 3.

The Lahore city’s ASTER 30m DEM was used to extract GIS data, including information on the establishment of a river network at Balloki, the demarcation of the watershed, the evaluation of the catchment slope, as well as the length and timing of the concentration. The mentioned area's DEM 30 m tile was taken from the DEM 30 m of South Asia.

2.6. River Network and Watershed Delineation

The river network for the Ravi River at Balloki was made using the ASTER DEM 30 m in ArcGIS software version 10.5 with Arc Hydro tools. The research area's DEM file was initially opened in the ArcGIS program as an ASCII file. The data was resampled to a grid resolution of 100 m, and the coordinates of the information document were transformed from a geographic direction framework to UTM organizes. From that point forward, various stages including fill sink definition, stream amassing, stream definition, stream division, catchment network depiction, catchment polygon handling, and seepage line handling were done. These steps are all described in Arc Hydro tools.

After the construction of river networks, watersheds are formed by first applying seepage point handling, then, at that point, watershed handling, and in conclusion by determining the bunch point or point inclusion for the watershed's flight by giving its scope and longitude. The River Ravi's watershed was established around the outflow point after the point coverage of the outlet point was done (Sadrolashrafi et al. 2008; Nickman Steve W.; 2016; Tassew Mulugeta A.; Miegel, K. 2019).

The flows of River Ravi enter Pakistan from India. Figure 4 shows the upper part of India and the lower part of Pakistan, the working area was Balloki Headword to Ravi Syphon and the upper portion was subtracted. In this work, hydrological modeling of the Ravi River near Balloki was carried out for the years 1990–2100 to assess the impacts of climate and Land Use on the Balloki region water supplies. The discharge data of the Upper Chenab Link Canal and Qadirabad Balloki Link Canal is subtracted from Ravi Syphon discharge data

2.6. Hydrological Modelling

The SWAT hydrological model setup, which was used for the current investigation. Daily rainfall data for the Lahore rain gauge from 1990 to 2020 are included in the input data set for the model, as well as inflow data for the Ravi River at Balloki from 1990 to 2020 (Cheema Walter W.; Bastiaanssen, Wim G.M. 2013; Babur et al. 2016; Zhang et al. 2016; Zhang Yi; Sun, Lin 2016; Saddique et al. 2019; Ahmed et al. 2020; Khan et al. 2020; Saifullah et al. 2021; Masood et al. 2023d). To acquire the best values for sensitive parameters, model calibration was done. For model calibration, SWAT 2012 offers a manual calibration approach. To slightly adjust the parameters for this study, manual calibration was first carried out. First, manual calibration was used to tweak several model parameters. In this method, parameter values were balanced by altering a few parameters at once while staying within the acceptable ranges, either by changing the starting value or by adding to it, multiplying it, or replacing it altogether. SWAT-CUP, an auto-calibrating tool, was next employed. The auto calibration feature, present in SWAT 2009 is not available in SWAT 2012 (Shafeeque et al. 2022). SWAT-CUP is now used for auto-calibration. The calibration was performed using streamflow measurements, in monthly time steps at the Balloki between 1999 and 2002. Auto calibration was carried out for parameters including values for extremely high, high, and medium sensitivity. An SCE-UA (Shuffled Complex Evolution Algorithm) and a single goal function form the foundation of the calibration process (Ghaffari et al. 2010; Shafeeque et al. 2022). A multi-objective, automated calibration process that was created by Karim C. Abbaspour called SUFI-2 was employed in this study. This approach was chosen because it may be used with both straightforward and intricate hydrological models. The intended optimization parameters, the observed data file, and the calibration techniques were then chosen. As a result, many flow parameters were taken into account throughout the calibration procedure. After the automatic calibration, SWAT was run with the best parameter values. The selected Calibration and Validation parameters as shown in Table 3.

Table 3
Calibration and Validation Parameters selected for Hydrological Modelling

Categories	Parameters	Parameters Detail
Groundwater Parameters	REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)
	GW_DELAY.gw	Groundwater delay (days)
	GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)
Hydrologic Response Unit Parameters	ESCO.hru	Soil evaporation compensation factor
	HRU_SLP.hru	Average slope steepness
	SLSUBBSN.hru	Average slope length
	OV_N.hru	Manning's "n" value for overland flow
	CANMX.hru	Maximum canopy storage
Routing Parameters	CH_K2.rte	Effective hydraulic conductivity in main channel alluvium
	CH_N2.rte	Manning's "n" value for the main channel
Watershed Parameters	SURLAG.bsn	Surface runoff lag time
Management Parameters	CN2.mgt	SCS runoff curve number
Soil Parameters	SOL_BD(..).sol	Moist bulk density
	SOL_K(..).sol	Saturated hydraulic conductivity
	SOL_AWC(..).sol	Available water capacity of the soil layer
Sub-Basin Parameters	CH_N1.sub	Manning's "n" value for the tributary channels

2.7. Performance Indicators

Three tests were undertaken to determine how well the hydrological model worked: the root mean square mistake, the Nash-Sutcliffe coefficient, and the coefficient of determination (R^2). It is a statistical parameter that indicates the variation in the dependent variable predictable from the independent variable. It is used to check the goodness fit of the model. A model is a good fit if the difference between observed values and those predicted by the model is small. R^2 gives a measure of the distance of data to the fitted regression line. In other words, it is the square of the correlation between observed and model-predicted values. The value of R^2 ranges from 0–1. 0% indicates that the model failed to explain the variability of data around the average. 100% indicates that the model successfully explained all the variability of data around its average. Generally, the closer the R^2 values to 1, the better the fit is the model.

The mathematical expression for R^2 is shown in Eq. (1):

$$R^2 = \{ \sum((xi - \bar{x}) * (yi - \bar{y}))\ N * (\sigma x * \sigma y) \}^2 \quad (1)$$

Where; N is the number of observations, I denote the observation, and xi and yi denote the observation's corresponding x and y values. X is the typical incentive for X, and Y is the typical incentive for Y. X addresses the standard deviation of X, and Y addresses the standard deviation of Y. Nash Sutcliffe is the hydrological model efficiency coefficient and its value indicates how good the model prediction is. Its values range from - ∞ to 1. When efficiency E = 1, the modeled discharge is the best match to observed values. When E = 0, the average of observed values matches the accuracy of modeled predictions. When E < 1 or a negative value, the predictions of the model don't even match with the average of observed values, and the mean of observed values is a better predictor. The closer the values of Ns to 1, the more accurate the model is.

The mathematical expression (2) for the Ns coefficient:

$$E = 1- \sum(Qo - Qm)^2 \sum(Qo - Q\bar{o})^2 \quad (2)$$

Where; Qo is observed discharge values, Qm has modeled values of discharge and shows an average of observed flows. Root Mean Square Error or Deviation is another statistical parameter used to find the difference between modeled values and observed values. It shows the standard deviation of the difference between observed data and corresponding predicted/modeled values. It is a simple method to test the accuracy of model predictions and to check the predicted errors of different models. It aggregates the magnitude of errors in modeled values for various calculations into a single measure of predictive power. This parameter is sensitive to outliers.

The mathematical expression for RMSE is shown in Eq. (3):

$$RMSE = \sqrt{} \sum (xo, - xm, i)^2\ i=1\ n\ n \quad (3)$$

Where: Xo is the observed ith value, xm is the corresponding modeled ith value, and n is the total number of observations.

2.8. Groundwater Depth

Figure 5 shows data for groundwater depth (Pre & Post Monsoon) that has been gathered from the Lahore Irrigation and WASA Departments for 25 years (1996–2020) to create the temporal groundwater maps for the City district of Lahore. Then cleaned data by removing the dead points on the map showing values of zero '0 m', and plotted the remaining point showing values on the Lahore shape file in the ArcGIS software. The collected water table data for the years 1996 to 2020 were then stored in Geo-database and processed using ArcGIS software version 10.5. The areas included Mathran Wala, Chora Langar, Chokhian wala, Bonga Gillan, Pipal wala, Keelay, Kakar Gill, Dera jarman wala, Lalkay, Warn, Kot Mahand bukhsh, chak shah pur, Mirza virkan, Jahangir pur,, Hardev, Qila Gian singh, Pindi Machhain, Kotli Virk, Ghang, Kharian wala, Targay wali, Shehzada, Chandrai, Mogalpura, Ram Ka Khuh, Raiwind, Muhammad Abad, Mal along, Bhai Kot Along, Raiwind, Basti Ramzan Wali, Mir Kot Kohna, Vir Ka Kohna, sham kot, Chak khurpa, Rao khan wala, Chadday wan, Hundal, sheru kahan, Chena Arla, jhuggian Makhan singh, Talaw, chak No-59, sher grah, chak 29/D,Kalian wala, Havaili Lakha, Dera Touran Da, Rajowal, Gulsher.

After going through all these steps, Interpolation Technique i.e., Inverse Distance Weighting (IDW) to estimate the groundwater fluctuation was applied. Inverse Distance Weighted (IDW) is a method of interpolation that estimates cell values by averaging the values of sample data points in the neighborhood of each processing cell. The closer a point is to the center of the cell being estimated, the more influence, or weight, it has in the averaging process. This method assumes that the variable being mapped decreases in influence with distance from its sampled location.

3. Results and Discussion

3.1. Climate Change Projections

3.1.2. Projections of Precipitation under Climate Change

Precipitation increased in summer, winter, autumn, and spring, according to the analysis of seasonal variation. This modification was presented by dividing the months of the year into four classes: winter (November, December, and January), spring (February, March, and April), summer (May, June, and July), and fall (August, September, and October).

Winter precipitation increased under SSP2 and SSP5 from 11.26 mm to 12.61 mm and 13.06 mm, as shown in Fig. 6. Precipitation in the late spring and autumn pursued a comparative direction yet with a more emotional ascent, going from 96.54 mm to 108.12 mm and 112 mm under SSP2 and SSP5, separately, in the mid-year and from 90.75 mm to 101.64 mm and 105.3 mm under SSP2 and SSP5, in the autumn season. Like this, under SSP2 and SSP5, the springtime precipitation at Lahore is expected to ascend from 34.11 mm to 38.21 mm and 39.57 mm, separately (Buhay et al. 2022; Hassan et al. 2023a; Masood et al. 2023d).

3.1.2. Projections of Maximum Temperature under Climate Change

The examination of the temperature changes uncovered that the most extreme temperature expanded across the year's four seasons. This modification was presented by dividing the months of the year into four classes: winter (November, December, and January), spring (February, March, and April), summer (May, June, and July), and autumn (August, September, and October).

As shown in Fig. 7, under SSP2 and SSP5, the colder time of year most extreme temperature climbed from 23.3 ^{O}C to 26.4 ^{O}C and 27.3 ^{O}C. Summer's greatest temperatures expanded from 38.7 ^{O}C to 43.7 ^{O}C and 45.2 ^{O}C under SSP2 and SSP5, individually; spring's most extreme temperatures expanded from 27.7 ^{O}C to 31.3 ^{O}C and 32.4 ^{O}C under SSP2 and SSP5, separately; and autumn most extreme temperatures expanded from 34.3 ^{O}C to 38.8 ^{O}C and 40.2 ^{O}C under SSP2 and SSP5, individually.

3.1.3. Projections of Minimum Temperature under Climate Change

The examination of temperature changes uncovered that the base temperature expanded across the year's four seasons.

As shown in Fig. 8, under SSP2 and SSP5, the colder time of year least temperature climbed from 8.7 ^{O}C to 9.4 ^{O}C and 10.1 ^{O}C. Summer's greatest temperatures expanded from 26.2 ^{O}C to 28.6 ^{O}C under SSP2 and 30.4 ^{O}C under SSP5, while autumn's most extreme temperatures expanded from 22.7 ^{O}C to 24.7 ^{O}C and 26.3 ^{O}C under SSP2 and SSP5, individually. Spring's greatest temperatures additionally expanded from 22.7 ^{O}C to 24.7 ^{O}C and 26.3 ^{O}C under SSP2 and SSP5, respectively.

3.2. Land Use Dynamics

Using the image classification tool in ArcGIS, the supervised image classification of the mosaicked Landsat 1995, 2000, 2010, 2015, 2018, and 2020 was completed. In Fig. 9, classified maps of the study area are shown. Five categories—Water, Bare Soil, Vegetation, and built-up area—were used to group the photographs.

The analysis revealed that from 1995 to 2020, Lahore's vegetation, forest, and bare soil fell by 11.1%, 0.3%, and 12.3%, respectively. There has been a sharp growth in the built-up area and water surface by amounts of 15.8% and 7.8%, respectively. Figure 10 shows this shift in Land Use classes.

3.3. Future Land Use Maps

Using TerrSet’s Land Change Modeler, future Land Use maps for 2030, 2060, and 2100 were created. In Fig. 11, classified maps of the study area are represented.

According to the findings, Lahore's built-up area and water body areas would grow by 31.7% and 4.3%, respectively, between 2020 and 2100. Amount of water bodies increased due to the inclusion of flooded

Landsat images. Other types of Land Use, such as forests, vegetation, and bare soil, have dropped by magnitudes of 0.1%, 21.9%, and 14.1%, respectively. The change in Land Use classes are shown in the Fig. 12.

3.3. Calibration and Validation of Hydrological Model

On the Ravi River at Balloki, model validation and calibration are carried out. The calibrated parameters and optimized values. The process of calibration includes finding the ideal arrangement of boundaries that best matches the noticed and mimicked release. The model was at first run in everyday time ventures before being aligned for 1999–2002 and validated for 2003–2005.

The day-to-day and month-to-month releases were precisely replicated by the model. In Figs. 13 and 14, the SWAT model's validation and calibration processes showed that the observed and simulated discharges were reasonably consistent. Table 4, contains the values for the PBIAS and the Nash-Sutcliffe coefficient of determination R^2 for calibration and validation.

Table 4
Statistics Evaluation Hydrological Model

	Calibration	**Validation**
NSE	0.85	0.87
R^2	0.83	0.81
RMSE	10.01	7.2

3.4. Impact Assessment

Two situations are presented: Situation A (Hydrological Reaction under Future Climate and Current Land Use) and Situation B (Hydrological Reaction under Future Climate and Future Land Use).

Scenario A: Hydrological Response under Future Climate and Current Land Use

The maximum temperature has increase by 13% and 17% under SSP2 and SSP5, separately, precipitation has expanded by 12% and 16%, while the base temperature has expanded by 9–16%. The streams are expected to increment from 803.25 cumecs in the standard period (1990–2015) to 959.08 cusecs (an increment of 19.4%) and 1007.28 cumecs (an increment of 25.4%).

Later on, time frame (2016–2100) under SSP2 and SSP5, when these scenarios of Land Use and climate are constrained into the adjusted SWAT model under current Land Use conditions. To evaluate the temporal changes in the mean month-to-month flows at Balloki, Fig. 15 shows, mean month-to-month flows for the benchmark time frame (1990–2015) with those for the future time frame under the SSP 2 and 5 situations. Both SSPs expect an expansion in the flow during the whole year.

Scenario-B: Hydrological Response under Future Climate and Future Land Use.

Land Use patterns showed that from 2020 to 2100, Lahore's built-up area and water body areas will increase by 31.7% and 4.3%, respectively. The amount of bare soil, forest, and other types of vegetation has declined by amounts of 0.1%, 21.9%, and 14.1%, respectively, compared to other Land Use groups. The streams are supposed to increment from 803.25 cumecs in the standard period (1999–2015) to 983.18 cumecs (an increment of 22.4%) and 1021.37 cumecs (an increment of 28.4%). Later on, time skyline (2016–2100) under SSP2 and SSP5, when these progressions in Land Use and climate are constrained into the adjusted SWAT model under future Land Use conditions.

To examine the transient changes in the mean month-to-month flows at Balloki, Fig. 16 shows that mean month-to-month flows for the baseline time frame (1990–2015) with those for the expected flows under change Land Use. By and then, the pattern of flows expanded over the whole year.

3.5. Contemporary Situation of Groundwater in Lahore

The maps depicting the fluctuation in water depth over the research period were compared and analyzed. Figures 17, depicts groundwater fluctuation maps for the years 1996 and 2020.

3.6. Changes in Ground Water Depth

Changes in groundwater depth were assessed based on the data collected from different areas of Lahore for 1996 and 2020. The results plotted on the map as shown in the Table 5. The analysis illustrates that the water table has changed all over the study area over time.

Table 5
Depth of Water Table Variations (1996–2020)

Locations	Coordinates		Depth of Water Table	
	Latitude	Longitude	Year (1996) (m)	Year (2020) (m)
Bonga Gillan	30°49'7.00" E	73°55'16.00" N	24.92	34.38
Chadday Wan	31°8'4.90" E	74°9'4.90" N	11.88	21.96
Chora Langar	31°15'1.70" E	74°6'5.00" N	19.09	25.50
Dera Jarman Wala	31°8'3.90" E	74°9'5.50" N	25.72	32.83
Hardev	31°10'4.30" E	74°21'6.00" N	13.81	16.83
Jahangir Pur	31°8'3.30" E	74°15'49.00" N	15.46	19.58
Jhuggian Makhan Singh	31°15'2.90" E	74°20'22.00" N	14.58	14.17
Mogalpura	30°56'4.80" E	74°6'2.20" N	27.16	39.50
Keelay	30°49'1.00" E	74°6'2.10" N	13.08	24.67
Kharian Wala	30°39'1.20" E	73°55'53.00" N	34.42	38.13
Kotli Virk	30°50'3.20" E	74°4'3.40" N	19.42	25.24
Lalkay	30°47'3.50" E	73°46'56.00" N	17.70	24.08
Mathran Wala	31°11'4.70" E	74°24'36.00" N	17.17	17.58
Mir Kot Kohna	30°49'3.50" E	74°55'26.00" N	20.20	25.50
Qila Gian Singh	31°15'5.80" E	74°9'3.50" N	17.50	6.29
Raiwind	30°23'4.90" E	73°48'34.00" N	10.53	25.00
Ram Ka Khuh	30°45'5.90" E	73°39'48.00" N	15.88	24.29
Targay Wali	31°13'4.90" E	74°6'8.30" N	18.63	23.33
Warn	31°10'2.20" E	74°8'2.80" N	20.96	21.66

Because of the excessive drawdown of water, a continuous decrease in groundwater levels was observed. Levels fell by 10–14 m from 1996 to 2020 as shown in Fig. 18. The water level estimated at various locations was averaged to obtain a single value for the year 2020

The average estimated groundwater depth for 2020 was 29.43 m. The Average Ground Water Depletion Rate is about 0.8 m per year represented in Fig. 19. Ground Water Depletion Rate varies from 0.4 m to 0.9 m. An increase of 28.3% in built-up area over three decades (1995–2020) is enormous. Most of the changes have occurred at the expense of vegetation, which decreased by approximately 18.6% during the period 1995–2020. Because of the decrease in vegetated areas, environmental problems can also occur. Also, because of the highly built-up areas in Lahore, there is significant variation in Land Use. The temporal change in built-up area for the years 1995,2000, 2010, 2015, 2018, and 2020, shown in Fig. 9. By comparing research M. Afzal (2013) it is found groundwater level is dropping by 1.27 meters per year.

5. Conclusions

- The Current Land Use change (1990–2020) for the study area is found to be 15.8% and is expected to increase by 31.7% in the future (2020–2100).
- Precipitation, Maximum Temperature, and Minimum Temperature are expected to increase by 10.9%, 12.2%, and 7.8% respectively by the SSP2 Scenario and 14.87%, 15.97%, and 9.71% by the SSP5 Scenario.
- SWAT Model has been successfully applied for the assessment of the impact of future Land Use and climate change on flows on river Ravi with best-fit values of NSE, R2, and PBIAS for the calibrated model are 0.85, 0.83, and 10.01 while for the validated model are 0.87, 0.89, and 7.2.
- Considering the current Land Use and future climate change, the flows of river Ravi are expected to increase by 19.4% and 25.4%, and considering the future Land Use and future climate change, the flows of river Ravi are expected to increase by 22.4% and 28.4%. Weather patterns are being disrupted by climate change, which is causing extreme weather events, uncertain water supply, increased water shortages, and contaminated water sources.
- Based on the observed data from the year 1996 to the year 2020 it is found that average groundwater depth has increased by 10.58 ft and the groundwater depletion rate is 0.8 m/year.

The current study shows that the future flows of River Ravi at Balloki may increase because of Land Use and Climate change, therefore, the concerned departments need to consider the increased water resources in future planning. The study may further be improved by considering Landsat images of better resolution and considering other SSP Scenarios.

Declarations

Conflicts of Interest:

The authors declare no conflict of interest.

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N/A

Author Contribution

All authors were involved in the intellectual elements of this paper. S.U., U.A., and M.R. designed the research. S.H. and M.R. conducted the research and wrote the manuscript. S.H. and U.A. helped in the data arrangement and analysis. All authors have read and agreed to the published version of the manuscript. All authors prepared the figures and agreed on them.

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Data Availability Statement:

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References

1. Abioye Oliver; Esau, Travis J.; Elijah, Olakunle; Abidin, Mohamad Shukri Zainal; Ayobami, Ajibade Sylvester; Yerima, Omosun; Nasirahmadi, Abozar EAH (2022) Precision Irrigation Management Using Machine Learning and Digital Farming Solutions. AgriEngineering 4:70–103. https://doi.org/10.3390/agriengineering4010006
2. Ahmadalipour Arun; Moradkhani, Hamid; Sharma, Ashish AR (2015) Multi-Criteria Evaluation of CMIP5 GCMs for Climate Change Impact Analysis. Theor Appl Climatol 128:71–87. https://doi.org/10.1007/s00704-015-1695-4
3. Ahmed Firas; Zhang, Jin; Yang, Wenyu; Saddique, Naeem; Krebs, Peter EAJ (2020) Hydrologic Assessment of TRMM and GPM-Based Precipitation Products in Transboundary River Catchment (Chenab River, Pakistan). Water 12:1902-NA. https://doi.org/10.3390/w12071902
4. Anandhi Allan; Pierson, Donald C.; Schneiderman, Elliot M.; Zion, Mark S.; Lounsbury, David G.; Matonse, Adao H. AF (2011) Examination of change factor methodologies for climate change impact assessment. Water Resour Res 47:NA-NA. https://doi.org/10.1029/2010wr009104
5. Ashraf A, Ahmad Z, Akhter G (2018) Monitoring Groundwater Flow Dynamics and Vulnerability to Climate Change in Chaj Doab, Indus Basin, Through Modeling Approach BT - Groundwater of South Asia. In: Mukherjee A (ed). Springer Singapore, Singapore, pp 593–611
6. Ashraf S, Ali M, Shrestha S, et al (2022) Impacts of climate and land-use change on groundwater recharge in the semi-arid lower Ravi River basin, Pakistan. Groundw Sustain Dev 17:100743. https://doi.org/https://doi.org/10.1016/j.gsd.2022.100743

7. Aslam RA, Shrestha S, Usman MN, et al (2022) Integrated SWAT-MODFLOW Modeling-Based Groundwater Adaptation Policy Guidelines for Lahore, Pakistan under Projected Climate Change, and Human Development Scenarios. Atmosphere (Basel) 13:2001
8. Azmat M, Qamar MU, Huggel C, Hussain E (2018) Future climate and cryosphere impacts on the hydrology of a scarcely gauged catchment on the Jhelum river basin, Northern Pakistan. Sci Total Environ 639:961–976. https://doi.org/10.1016/j.scitotenv.2018.05.206
9. Babur Mukand S.; Shrestha, Sangam; Kawasaki, Akiyuki; Tripathi, Nitin K. MNB (2016) The Impact of Climate Change on Reservoir Inflows Using Multi Climate-Model under RCPs' Including Extreme Events—A Case of Mangla Dam, Pakistan. NA NA:NA-NA
10. Babur M, Babel MS, Shrestha S, et al (2016) Assessment of Climate Change Impact on Reservoir Inflows Using Multi Climate-Models under RCPs—The Case of Mangla Dam in Pakistan. Water 8
11. Bagstad KJ, Ancona ZH, Hass J, et al (2020) Integrating physical and economic data into experimental water accounts for the United States: Lessons and opportunities. Ecosyst Serv 45:101182. https://doi.org/https://doi.org/10.1016/j.ecoser.2020.101182
12. Baig Muhammad Raza Ul; Baig, Imran; Takaijudin, Husna Binti; Zeshan, Muhammad Talha MFM (2022) Assessment of Land Use Land Cover Changes and Future Predictions Using CA-ANN Simulation for Selangor, Malaysia. Water 14:402. https://doi.org/10.3390/w14030402
13. Basharat M (2016) Chapter 8 - Groundwater Environment in Lahore, Pakistan. In: Shrestha S, Pandey VP, Shivakoti BR, Thatikonda SBT-GE in AC (eds). Butterworth-Heinemann, pp 147–184
14. Buhay Bucton Sangam; Kc, Saurav; Mohanasundaram, S; Virdis, Salvatore G P; Chaowiwat, Winai BGS (2022) Impacts of climate and land use change on groundwater recharge under shared socioeconomic pathways: A case of Siem Reap, Cambodia. Environ Res 211:113070. https://doi.org/10.1016/j.envres.2022.113070
15. Candela L, Tamoh K, Olivares G, Gomez M (2012) Modelling impacts of climate change on water resources in ungauged and data-scarce watersheds. Application to the Siurana catchment (NE Spain). Sci Total Environ 440:253–260. https://doi.org/10.1016/j.scitotenv.2012.06.062
16. Cheema Walter W.; Bastiaanssen, Wim G.M. MJMI (2013) Spatial quantification of groundwater abstraction in the irrigated indus basin. Ground Water 52:25–36. https://doi.org/10.1111/gwat.12027
17. Chohan Sajid Rashid; Islam, Zia ul; Adrees, Muhammad KA (2015) Riverine Flood Damage Assessment of Cultivated Lands along Chenab River Using GIS and Remotely Sensed Data: A Case Study of District Hafizabad, Punjab, Pakistan. J Geogr Inf Syst 7:506–526. https://doi.org/10.4236/jgis.2015.75041
18. Chunn Monireh; Smerdon, Brian D.; Alessi, Daniel S. DF (2019) Application of an Integrated SWAT–MODFLOW Model to Evaluate Potential Impacts of Climate Change and Water Withdrawals on Groundwater–Surface Water Interactions in West-Central Alberta. Water 11:110-NA. https://doi.org/10.3390/w11010110

19. Dewan TH (2015) Societal impacts and vulnerability to floods in Bangladesh and Nepal. Weather Clim Extrem 7:36–42. https://doi.org/10.1016/j.wace.2014.11.001
20. Durga Rao KH V, Bhanumurthy V, Roy PS (2009) Application of satellite—based rainfall products and SRTM DEM in hydrological modelling of Brahmaputra basin. J Indian Soc Remote Sens 37:587–600
21. Gaaloul N, Eslamian S, Katlance R (2021) Impacts of Climate Change and Water Resources Management in the Southern Mediterranean Countries. Water Product J 1:51–72
22. Garee Xi; Bao, Anming; Wang, Yu; Meng, Fanhao KC (2017) Hydrological Modeling of the Upper Indus Basin: A Case Study from a High-Altitude Glacierized Catchment Hunza. Water 9:17-NA. https://doi.org/10.3390/w9010017
23. Ghaffari Saskia; Ghodousi, Jamal; Ahmadi, Hassan GK (2010) SWAT-simulated hydrological impact of land-use change in the Zanjanrood basin, Northwest Iran. Hydrol Process 24:892–903. https://doi.org/10.1002/hyp.7530
24. Groppelli B, Bocchiola D, Rosso R (2011) Spatial downscaling of precipitation from GCMs for climate change projections using random cascades: a case study in Italy. Water Resour Res 47:
25. Haider Muhammad; Liu, Shiyin; Saifullah, Muhammad; Usman, Muhammad; Chauhdary, Junaid Nawaz; Anjum, Muhammad Naveed; Waseem, Muhammad HZ (2020) Appraisal of Climate Change and Its Impact on Water Resources of Pakistan: A Case Study of Mangla Watershed. Atmosphere (Basel) 11:1071-NA. https://doi.org/10.3390/atmos11101071
26. Haider H, Singh P, Ali W, et al (2015) Sustainability Evaluation of Surface Water Quality Management Options in Developing Countries: Multicriteria Analysis Using Fuzzy UTASTAR Method. Water Resour Manag 29:2987–3013. https://doi.org/10.1007/s11269-015-0982-2
27. Haider S, Masood MU, Rashid M, et al (2023a) Simulation of the Potential Impacts of Projected Climate and Land Use Change on Runoff under CMIP6 Scenarios. Water 15:3421
28. Haider S, Masood MU, Rashid M, et al (2023b) Evaluation of the effects of climate and land use variations on the groundwater dynamics of the Bari Doab Canal System in Punjab , Pakistan. 3390
29. Haider S, Masood MU, Rashid M, et al (2023c) Assessment of rainwater harvesting potential for urban area under climate and land use changes using geo-informatics technology. Urban Clim 52:101721
30. Haider S, Masood MU, Rashid M, Alshehri F (2023d) Simulation of the Potential Impacts of Projected Climate and Land Use Change on Runoff under CMIP6 Scenarios
31. Hashmi Qazi Tallat Mahmood; Ghumman, Abdul Razzaq; Kamal, Mumtaz Ahmed; Mughal, Habib ur Rehman HNS (2012) A critical analysis of 2010 floods in Pakistan. AFRICAN J Agric RESEEARCH 7:1054–1067. https://doi.org/10.5897/ajarx11.036
32. Hassan S, Masood MU, Haider S, et al (2023a) Investigating the Effects of Climate and Land Use Changes on Rawal Dam Reservoir Operations and Hydrological Behavior. Water 15
33. Hassan S, Masood MU, Haider S, et al (2023b) Hydrological Response and Reservoir Operation Study under Climate and Landuse Landcover Changes of Rawal Dam. 3390

34. Hiscock K (2011) Groundwater in the 21st Century – Meeting the Challenges. pp 207–225
35. Hua AK, Gani P (2023) Urban Sprawl Prediction Using Ca-Markov Model: a Case Study of Melaka River Basin, Malaysia. Appl Ecol Environ Res 21:157–171. https://doi.org/10.15666/aeer/2101_157171
36. Huda N, Mahmood S, Sajjid R, Ahamad MI (2023) Spatio-temporal analysis of river channel pattern in lower course of River Ravi using GIS and remote sensing. Appl Geomatics 15:759–772. https://doi.org/10.1007/s12518-023-00519-6
37. Jonkman SN (2005) Global Perspectives on Loss of Human Life Caused by Floods. Nat Hazards 34:151–175. https://doi.org/10.1007/s11069-004-8891-3
38. Kanwal S, Gabriel HF, Mahmood K, et al (2015) Lahore's groundwater depletion-A review of the aquifer susceptibility to degradation and its consequences. Univ Eng Technol Taxila Tech J 20:26
39. Khan Bibi S.; Bowling, Laura C. AN (2015) Separating snow, clean and debris covered ice in the Upper Indus Basin, Hindukush-Karakoram-Himalayas, using Landsat images between 1998 and 2002. J Hydrol 521:46–64. https://doi.org/10.1016/j.jhydrol.2014.11.048
40. Khan Manfred; Tahir, Adnan Ahmad AJK (2020) Impacts of Climate Change on the Water Availability, Seasonality and Extremes in the Upper Indus Basin (UIB). Sustainability 12:1283-NA. https://doi.org/10.3390/su12041283
41. Khan TA, Alam MM, Shahid Z, Su'Ud MM (2020) Investigation of flash floods on early basis: A factual comprehensive review. IEEE Access 8:19364–19380
42. Kuenzer Huadong; Huth, Juliane; Leinenkugel, Patrick; Li, Xinwu; Dech, Stefan CG (2013) Flood Mapping and Flood Dynamics of the Mekong Delta: ENVISAT-ASAR-WSM Based Time Series Analyses. Remote Sens 5:687–715. https://doi.org/10.3390/rs5020687
43. Kumar K. Padma; Bhaskar, P. Udaya KSK (2016) Application of Markov chain & cellular automata based model for prediction of Urban transitions. 2016 Int. Conf. Electr. Electron. Optim. Tech. NA:4007–4012
44. Kundzewicz Shinjiro; Seneviratne, Sonia I.; Handmer, John; Nicholls, Neville; Peduzzi, Pascal; Mechler, Reinhard; Bouwer, Laurens M.; Arnell, Nigel W.; Mach, Katherine J; Muir-Wood, Robert; Brakenridge, R.; Kron, Wolfgang; Benito, Gerardo; Honda, Yasushi ZW. K (2013) Flood risk and climate change: global and regional perspectives. Hydrol Sci J 59:1–28. https://doi.org/10.1080/02626667.2013.857411
45. Loures L, Chamizo A, Ferreira P, et al (2020) Assessing the effectiveness of precision agriculture management systems in mediterranean small farms. Sustain 12:1–15. https://doi.org/10.3390/su12093765
46. Lutz Walter W.; Shrestha, Arun Bhakta; Bierkens, Marc F. P. AF. I (2014) Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nat Clim Chang 4:587–592. https://doi.org/10.1038/nclimate2237
47. Mahmood R, Jia S, Babel MS (2016) Potential Impacts of Climate Change on Water Resources in the Kunhar River Basin, Pakistan. Water 8

48. Maroufpoor S, Shiri J, Maroufpoor E (2019) Modeling the sprinkler water distribution uniformity by data-driven methods based on effective variables. Agric Water Manag 215:63–73. https://doi.org/10.1016/j.agwat.2019.01.008
49. Masood MU, Haider S, Rashid M, et al (2023a) The Effect of the El Nino Southern Oscillation on Precipitation Extremes in the Hindu Kush Mountains Range. Water 15
50. Masood MU, Haider S, Rashid M, et al (2023b) Quantifying the Impacts of Climate and Land Cover Changes on the Hydrological Regime of a Complex Dam Catchment Area. Sustainability 15:15223
51. Masood MU, Haider S, Rashid M, et al (2023c) Assessment of Hydrological Response to Climatic Variables over the Hindu Kush Mountains, South Asia. Water 15:3606
52. Masood MU, Khan NM, Haider S, et al (2023d) Appraisal of Land Cover and Climate Change Impacts on Water Resources: A Case Study of Mohmand Dam Catchment, Pakistan. Water (Switzerland) 15:. https://doi.org/10.3390/w15071313
53. Mehmood Adnanul; Sajjad, Muhammad; Song, Jinxi; Zafar, Zeeshan; Shiyan, Zhai; Yaochen, Qin MSR (2023) Evaluating land use/cover change associations with urban surface temperature via machine learning and spatial modeling: Past trends and future simulations in Dera Ghazi Khan, Pakistan. Front Ecol Evol 11:NA-NA. https://doi.org/10.3389/fevo.2023.1115074
54. Meyer WB, Turner BL (1992) Human Population Growth and Global Land-Use/Cover Change. Annu Rev Ecol Syst 23:39–61
55. Mumtaz Jing; Liu, Qinhuo; Tariq, Aqil; Arshad, Arfan; Dong, Yadong; Zhao, Jing; Bashir, Barjeece; Zhang, Hu; Gu, Chenpeng; Liu, Chang FL (2023) Impacts of Green Fraction Changes on Surface Temperature and Carbon Emissions: Comparison under Forestation and Urbanization Reshaping Scenarios. Remote Sens 15:859. https://doi.org/10.3390/rs15030859
56. Nickman Steve W.; Jansson, Per-Erik; Olofsson, Bo AL (2016) Simulating the impact of roads on hydrological responses: examples from Swedish terrain. Hydrol Res 47:767–781. https://doi.org/10.2166/nh.2016.030
57. Nouri J, Gharagozlou A, Arjmandi R, et al (2014) Predicting Urban Land Use Changes Using a CA–Markov Model. Arab J Sci Eng 39:5565–5573. https://doi.org/10.1007/s13369-014-1119-2
58. O’Loughlin FE, Paiva RCD, Durand M, et al (2016) A multi-sensor approach towards a global vegetation corrected SRTM DEM product. Remote Sens Environ 182:49–59
59. Omeno Ying; Fan, Wenyi; Lubalega, Tolerant; Chen, Chen; Kaiko, Claude Kachaka Sudi MOY (2021) Analysis of the Impact of Land-Use/Land-Cover Change on Land-Surface Temperature in the Villages within the Luki Biosphere Reserve. Sustainability 13:11242-NA. https://doi.org/10.3390/su132011242
60. Pradipta Pantelis; Kourgialas, Nektarios; Doula, Maria; Dokou, Zoi; Makkawi, Mohammad; Alfarhan, Mohammed; Tawabini, Bassam; Kirmizakis, Panagiotis; Yassin, Mohamed AS (2022) Remote Sensing, Geophysics, and Modeling to Support Precision Agriculture—Part 2: Irrigation Management. Water 14:1157. https://doi.org/10.3390/w14071157

61. Qureshi AS (2012) Groundwater management in Pakistan: The question of balance. Centen Celebr (1912–2012), Pap 207–217
62. Qureshi AS (2020) Groundwater Governance in Pakistan: From Colossal Development to Neglected Management
63. Rashid M, Haider S, Masood MU, et al (2023) Sustainable Water Management for Small Farmers with Center-Pivot Irrigation: A Hydraulic and Structural Design Perspective. Sustainability 15:16390
64. Raza H, Jaffry AH, Waseem M, et al (2022) A comparative study of different optimization techniques for agricultural water allocations. 8670
65. Saddique N, Usman M, Bernhofer C (2019) Simulating the Impact of Climate Change on the Hydrological Regimes of a Sparsely Gauged Mountainous Basin, Northern Pakistan. Water 11
66. Sadrolashrafi Thamer A.; Mahmud, Ahmad R.B.; Kholghi, Majid K.; Samadi, Amir SS. M (2008) Integrated Modeling for Flood Hazard Mapping Using Watershed Modeling System. Am J Eng Appl Sci 1:149–156. https://doi.org/10.3844/ajeassp.2008.149.156
67. Saifullah M, Adnan M, Zaman M, et al (2021) Hydrological Response of the Kunhar River Basin in Pakistan to Climate Change and Anthropogenic Impacts on Runoff Characteristics. Water 13
68. Shabahat S, Raza A, Haider S, et al (2022) Investigating the Groundwater Recharge Potential in the Upper Rechna Doab. 100–107
69. Shafeeque Abid; Basit, Abdul; Mohamed, Abdelmoneim Zakaria; Rasheed, Muhammad Waseem; Khan, Muhammad Usman; Buttar, Noman Ali; Saddique, Naeem; Asim, Mohammad Irfan; Sabir, Rehan Mehmood MS (2022) Quantifying the Impact of the Billion Tree Afforestation Project (BTAP) on the Water Yield and Sediment Load in the Tarbela Reservoir of Pakistan Using the SWAT Model. Land 11:1650. https://doi.org/10.3390/land11101650
70. Shafeeque M, Hafeez M, Sarwar A, et al (2023) Quantifying future water-saving potential under climate change and groundwater recharge scenarios in Lower Chenab Canal, Indus River Basin. Theor Appl Climatol. https://doi.org/10.1007/s00704-023-04621-y
71. Shamir Sharon B.; Carrillo, Carlos M.; Castro, Christopher L.; Chang, Hsin I.; Chief, Karletta; Corkhill, Frank E.; Eden, Susanna; Georgakakos, Konstantine P.; Nelson, Keith M.; Prietto, Jacob EM (2015) Climate change and water resources management in the Upper Santa Cruz River, Arizona. J Hydrol 521:18–33. https://doi.org/10.1016/j.jhydrol.2014.11.062
72. Shen Yongwei; Li, Yan; Hong, Qian; Xu, L.; Liu, Ruimin ZG (2009) A comparison of WEPP and SWAT for modeling soil erosion of the Zhangjiachong Watershed in the Three Gorges Reservoir Area. Agric Water Manag 96:1435–1442. https://doi.org/10.1016/j.agwat.2009.04.017
73. Shikary Somnath CR (2022) Urban growth Prediction for Sustainable Urban Management Using Markov Chain Model: A Study on Purulia Municipality, West Bengal, India. J Indian Soc Remote Sens 50:2229–2244. https://doi.org/10.1007/s12524-022-01596-7
74. Sohail MT, Hussan A, Ehsan M, et al (2022) Groundwater budgeting of Nari and Gaj formations and groundwater mapping of Karachi, Pakistan. Appl Water Sci 12:267. https://doi.org/10.1007/s13201-022-01795-0

75. Subedi P, Subedi K, Thapa B (2013) Application of a Hybrid Cellular Automaton �C Markov (CA-Markov) Model in Land-Use Change Prediction: A Case Study of Saddle Creek Drainage Basin, Florida. Appl Ecol Environ Sci 1:126–132. https://doi.org/10.12691/aees-1-6-5
76. Tariq Faisal AM (2022) Modeling spatio-temporal assessment of land use land cover of Lahore and its impact on land surface temperature using multi-spectral remote sensing data. Environ Sci Pollut Res Int 30:23908–23924. https://doi.org/10.1007/s11356-022-23928-3
77. Tariq Jianguo; Mumtaz, Faisal AY (2022) Land change modeler and CA-Markov chain analysis for land use land cover change using satellite data of Peshawar, Pakistan. Phys Chem Earth, Parts A/B/C 128:103286. https://doi.org/10.1016/j.pce.2022.103286
78. Tariq Yan; Li, Qingting; Gao, Jianwei; Lu, Linlin; Soufan, Walid; Almutairi, Khalid F; Habib-Ur-Rahman, Muhammad AJ (2023) Modelling, mapping and monitoring of forest cover changes, using support vector machine, kernel logistic regression and naive bayes tree models with optical remote sensing data. Heliyon 9:e13212–e13212. https://doi.org/10.1016/j.heliyon.2023.e13212
79. Tassew Mulugeta A.; Miegel, K. BG. B (2019) Application of HEC-HMS Model for Flow Simulation in the Lake Tana Basin: The Case of Gilgel Abay Catchment, Upper Blue Nile Basin, Ethiopia. Hydrology 6:21-NA. https://doi.org/10.3390/hydrology6010021
80. Usman M, Liedl R, Zhang F, Zaman M (2018) Groundwater Irrigated Agriculture Evolution in Central Punjab, Pakistan BT - Sustainable Agriculture Reviews 33: Climate Impact on Agriculture. In: Lichtfouse E (ed). Springer International Publishing, Cham, pp 259–294
81. Wu Haixing; Wei, Guozhen; Song, Tianyu; Zhang, Chi; Zhou, Huicheng JL (2019) Flash flood forecasting using Support Vector Regression model in a small mountainous catchment. Water 11:1327-NA. https://doi.org/10.3390/w11071327
82. Yang D, Yang Y, Xia J (2021) Hydrological cycle and water resources in a changing world: A review. Geogr Sustain 2:115–122. https://doi.org/https://doi.org/10.1016/j.geosus.2021.05.003
83. Zhang Xin; He, Chansheng; Zhang, Baoqing; Zhang, Xifeng; Li, Jinlin; Zhao, Chen; Tian, Jie; DeMarchi, Carlo LJ (2016) Comparison of SWAT and DLBRM for Hydrological Modeling of a Mountainous Watershed in Arid Northwest China. J Hydrol Eng 21:4016007. https://doi.org/10.1061/(asce)he.1943-5584.0001313
84. Zhang Yi; Sun, Lin YL (2016) Quantifying future changes in glacier melt and river runoff in the headwaters of the Urumqi River, China. Environ Earth Sci 75:1–14. https://doi.org/10.1007/s12665-016-5563-z

Figures

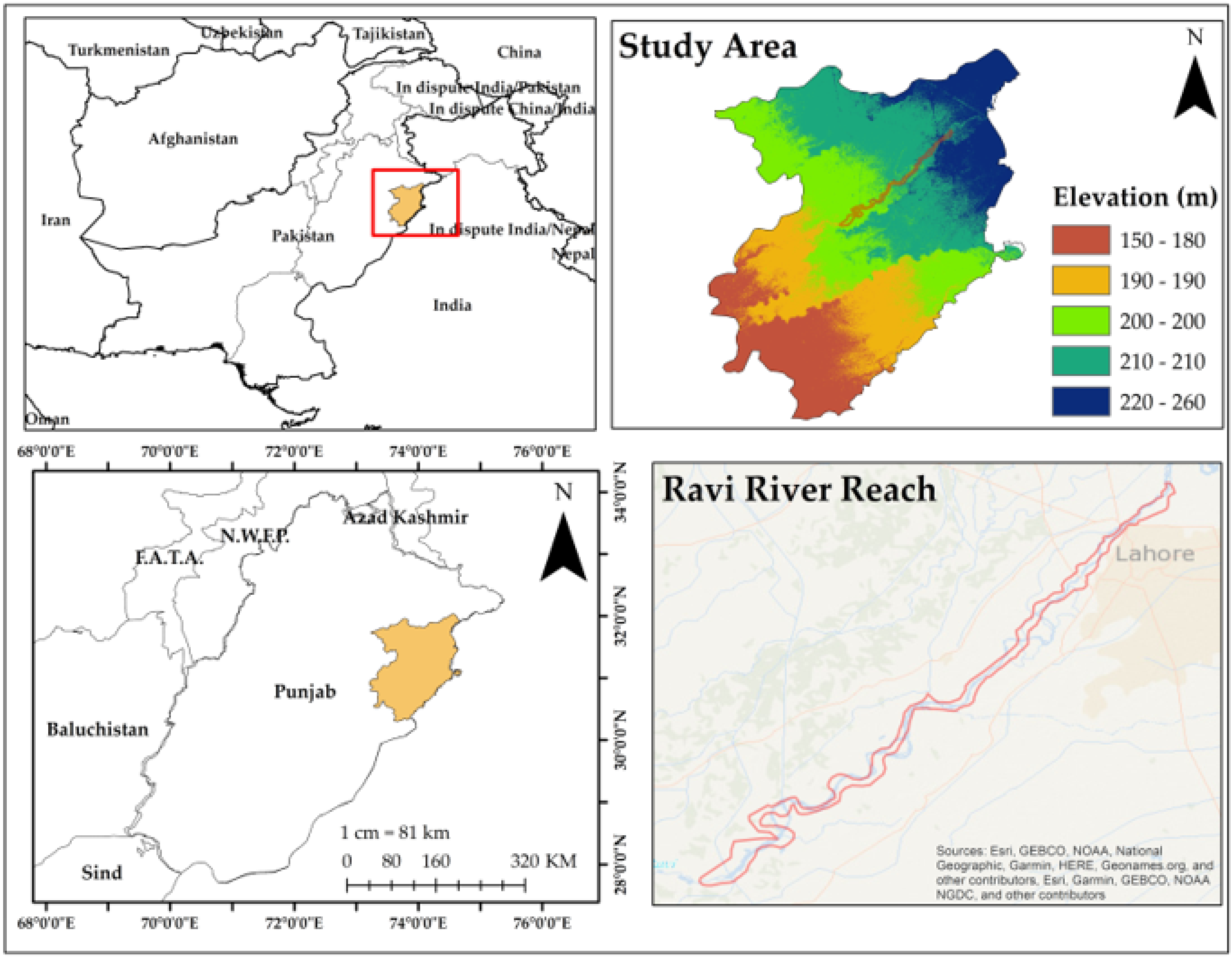

Figure 1

Map of the Study Area

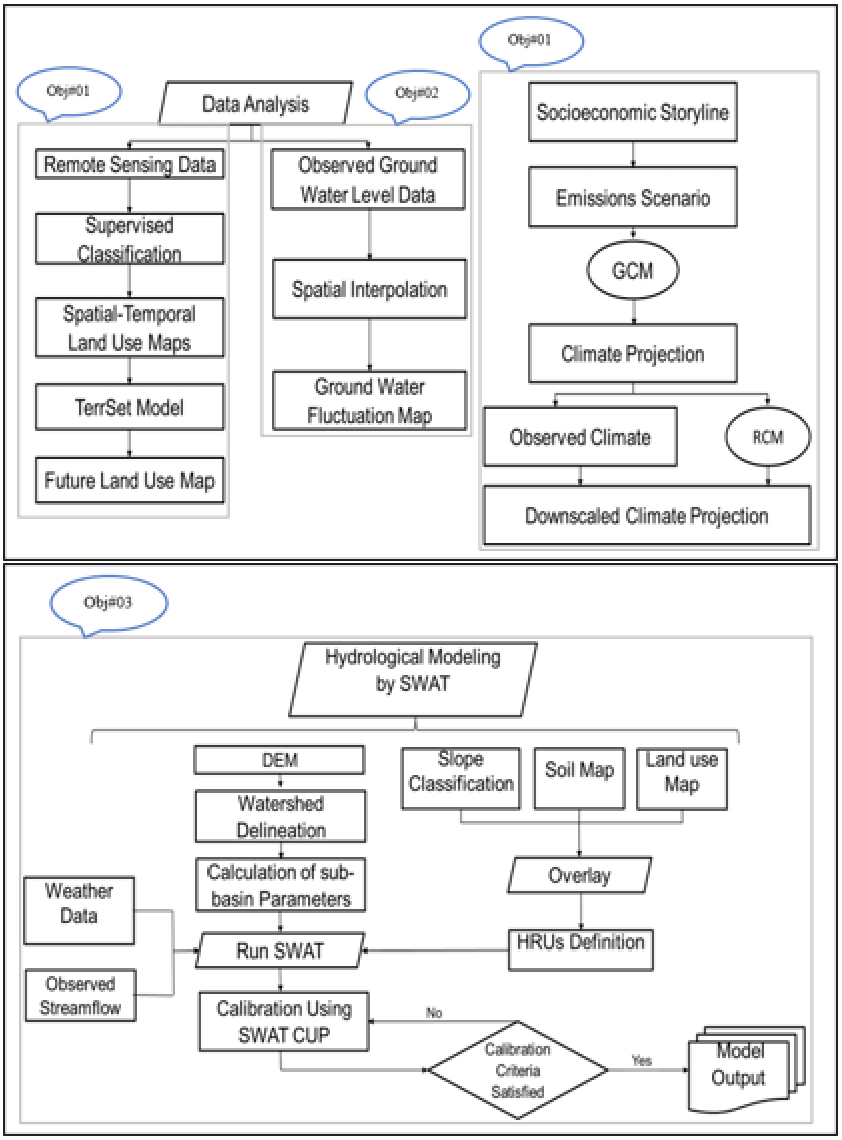

Figure 2

Methodology Flowchart of the current study

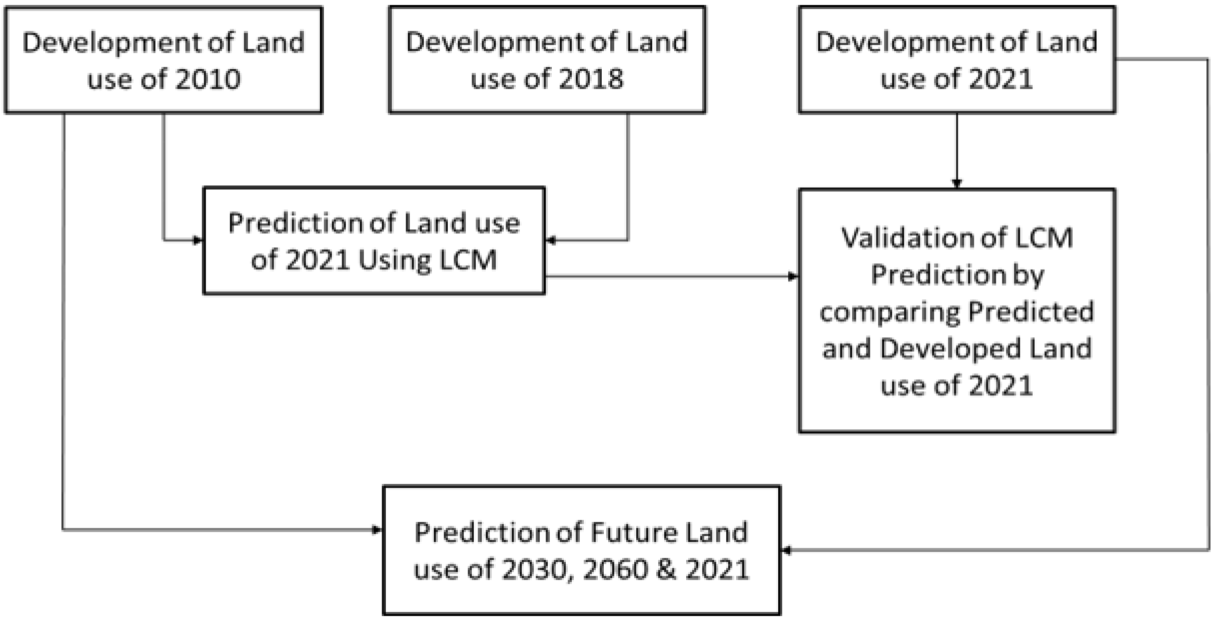

Figure 3

Future Land Use Methodology Flowchart

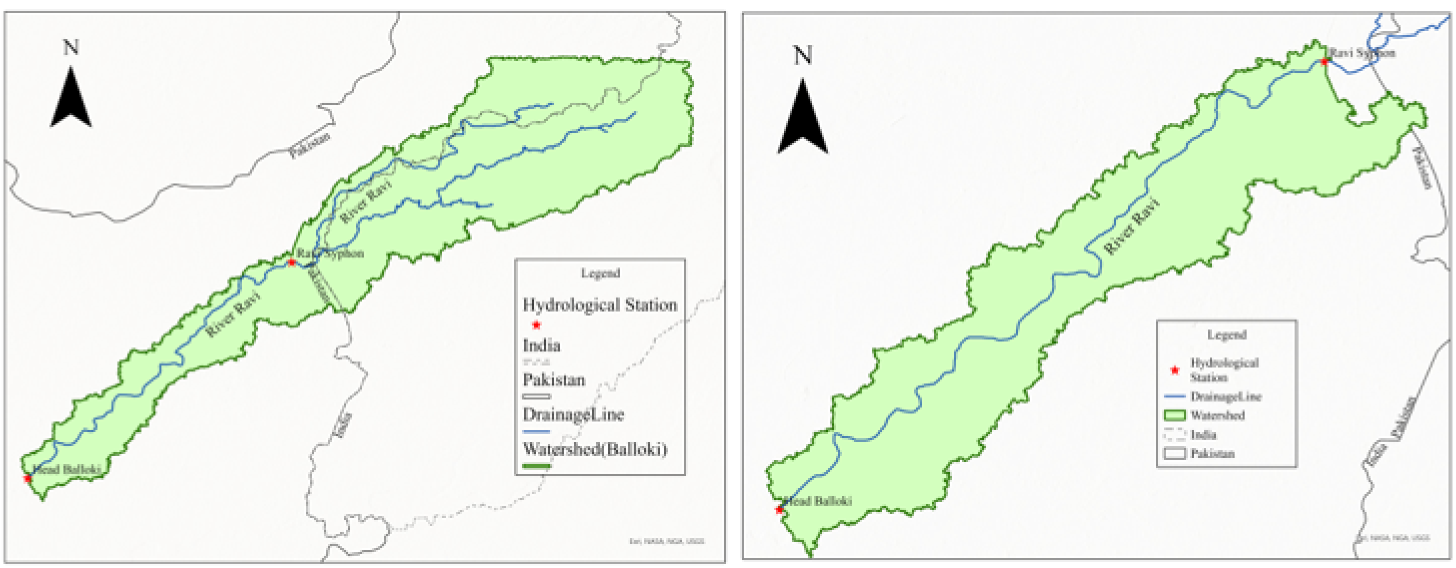

Figure 4

Watershed Delineated Model of River Ravi and from Ravi Syphon to Balloki Headworks

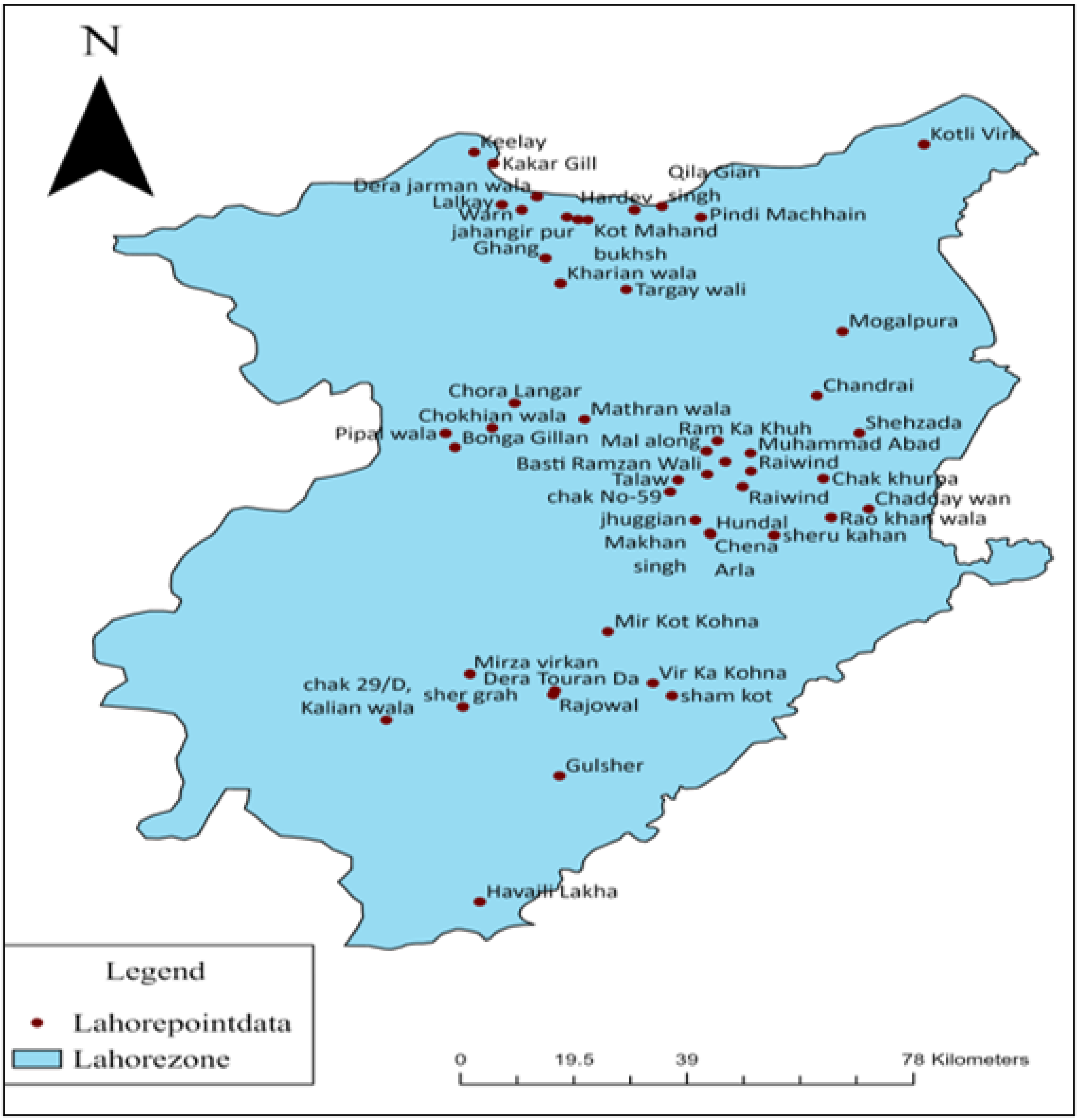

Figure 5

Past Observed Ground Water Level Points Distribution

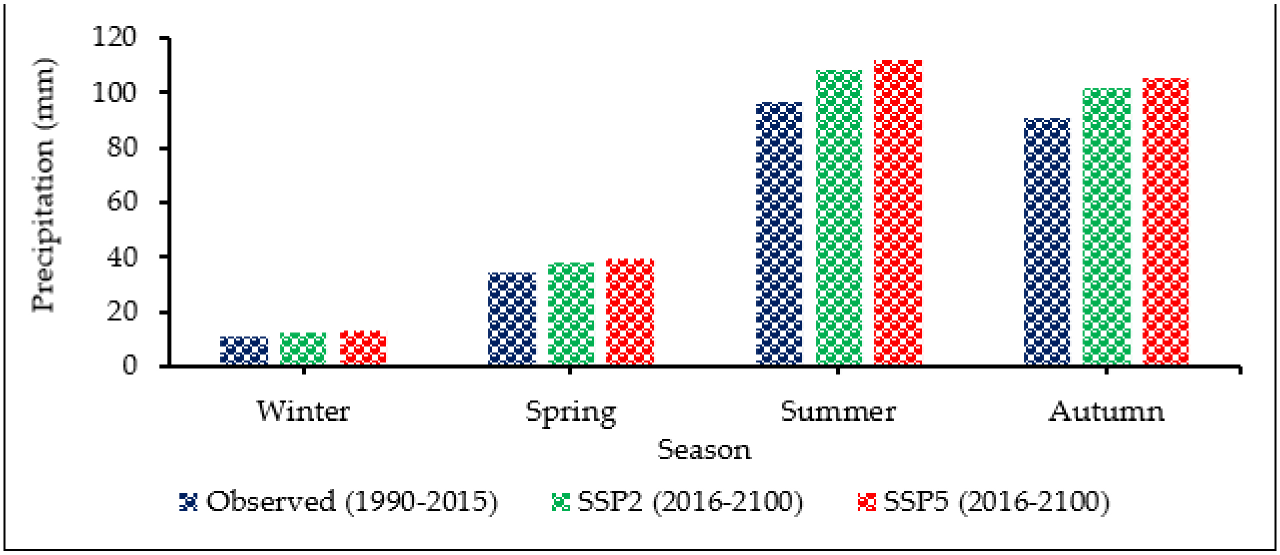

Figure 6

Comparison of Seasonal Precipitation at Lahore under Climate Change Scenarios SSP2 and SSP5

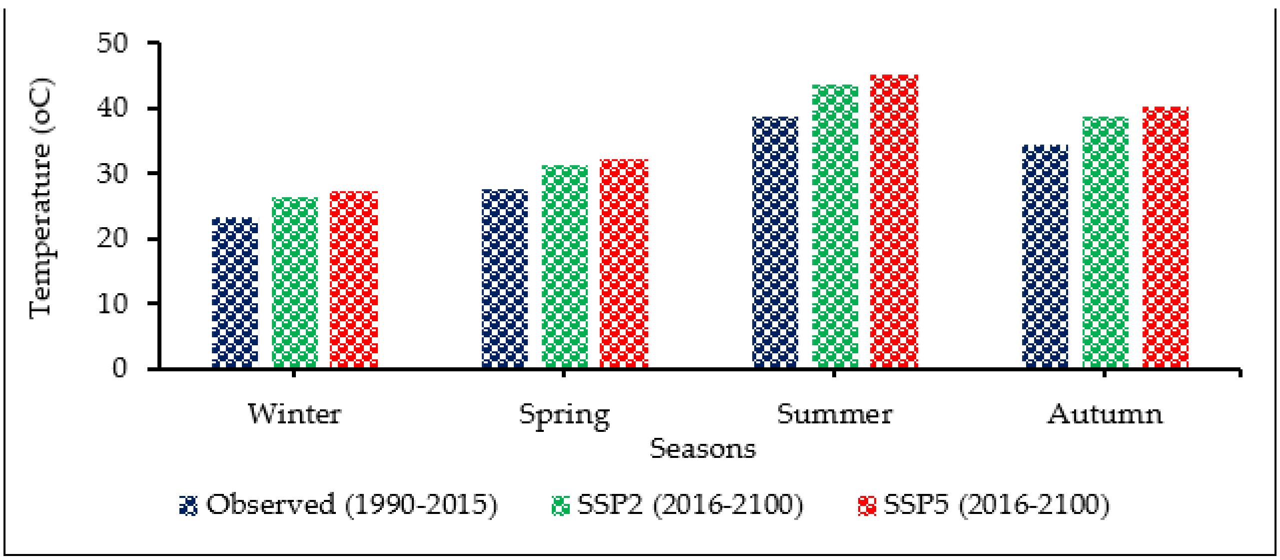

Figure 7

Comparison of Seasonal Maximum Temperature at Lahore under Climate Change Scenarios SSP2 and SSP5

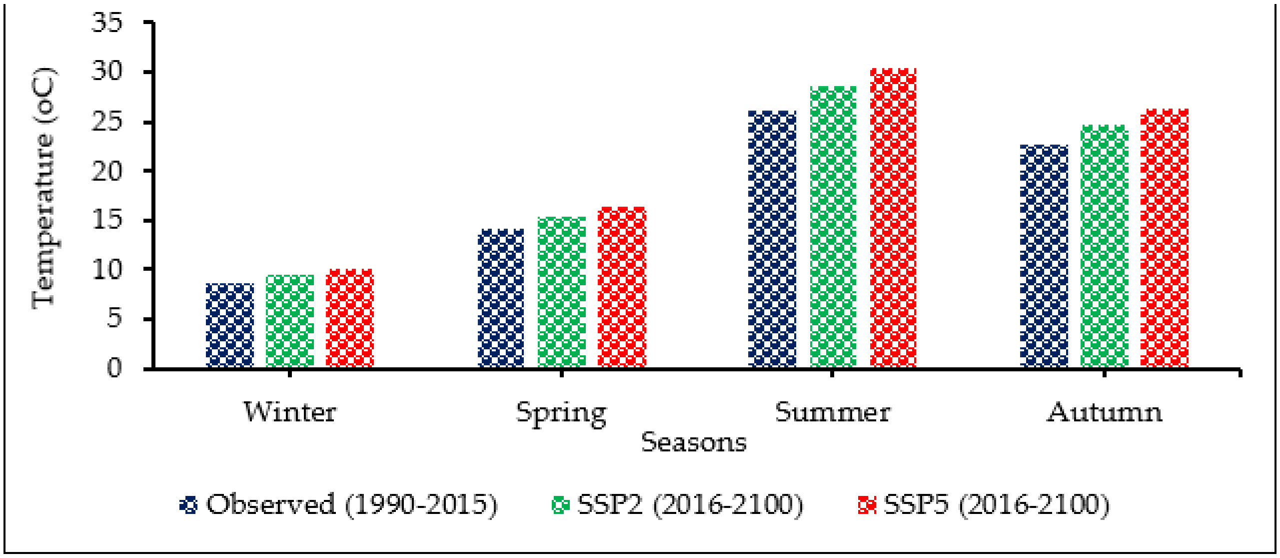

Figure 8

Comparison of Seasonal Minimum Temperature at Lahore under Climate Change Scenarios of SSP2 and SSP5

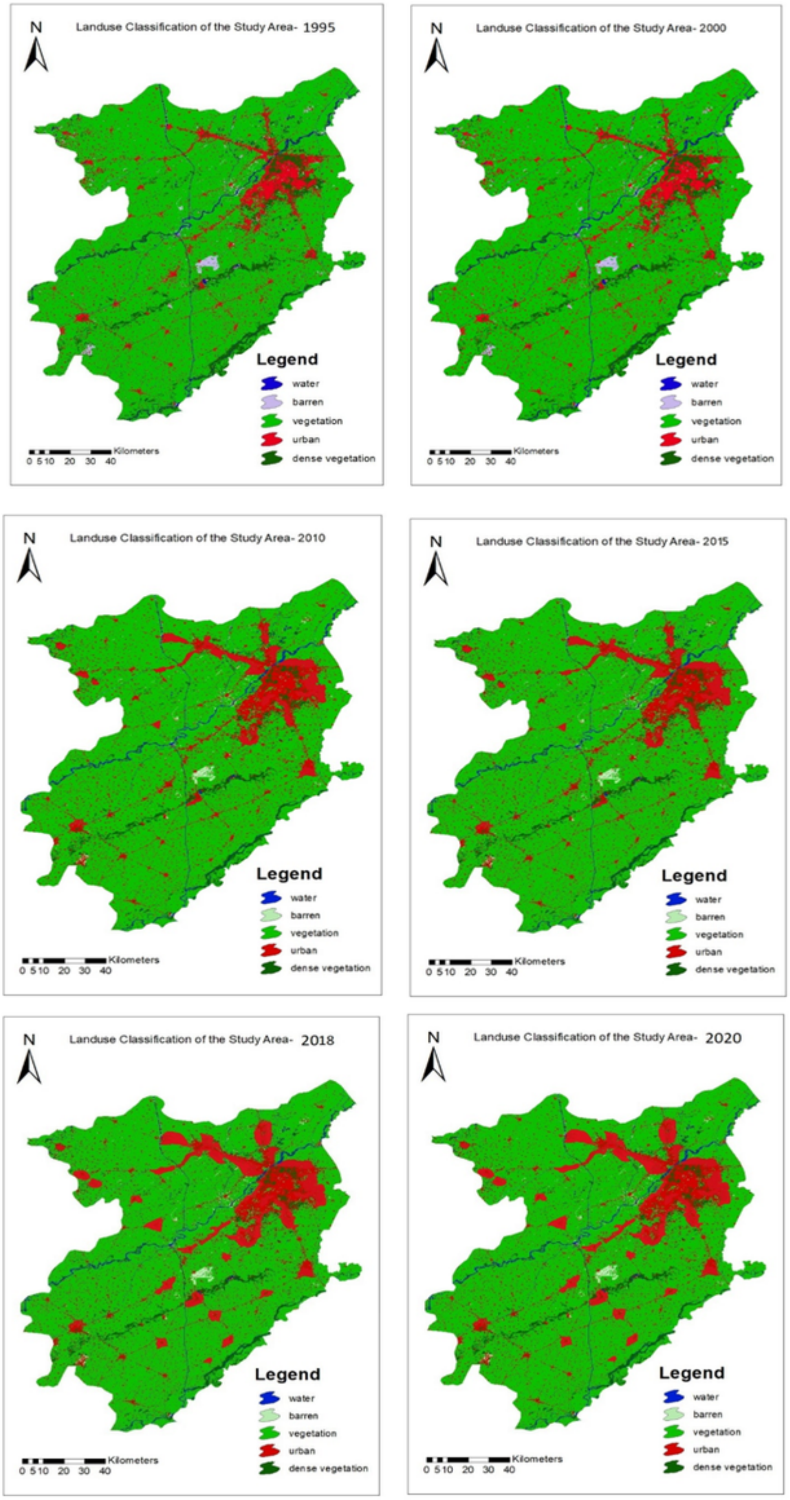

Figure 9

Landuse maps of different years from 1995 to 2020

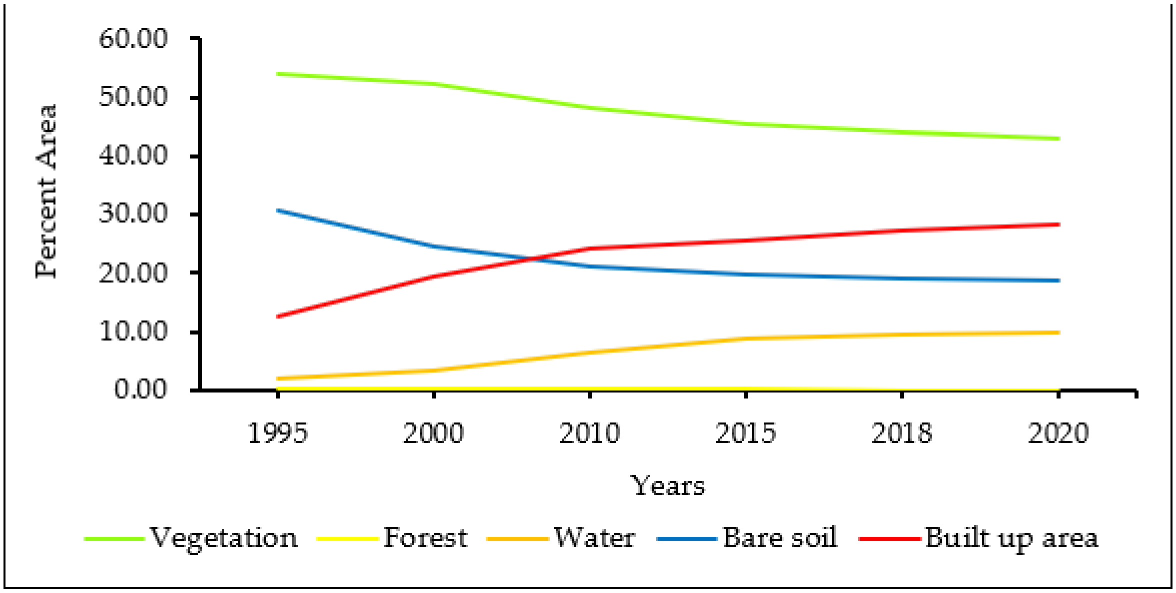

Figure 10

Trends of Land Use Change from 1995 to 2020

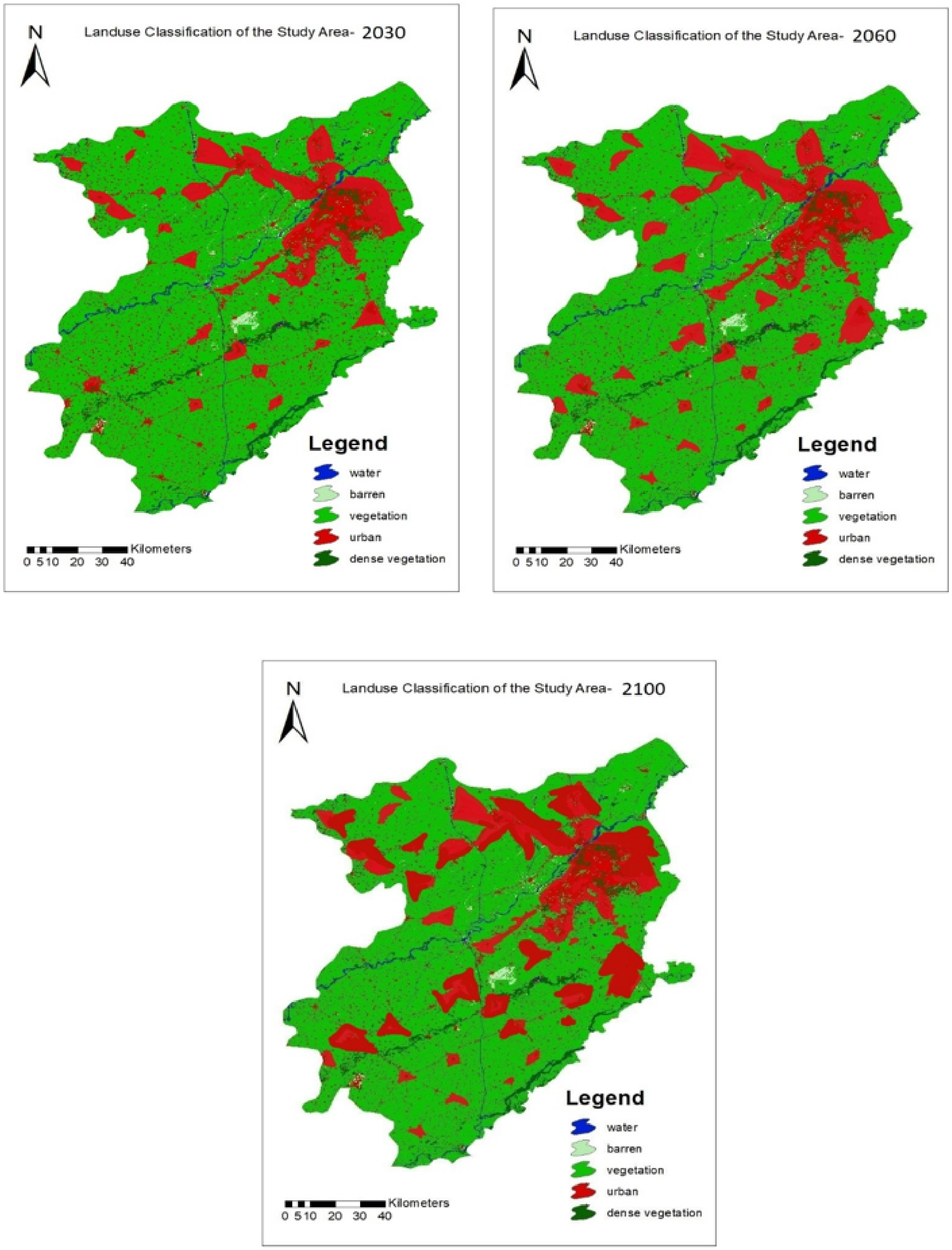

Figure 11

Future landuse maps of 2030, 2060 and 2100

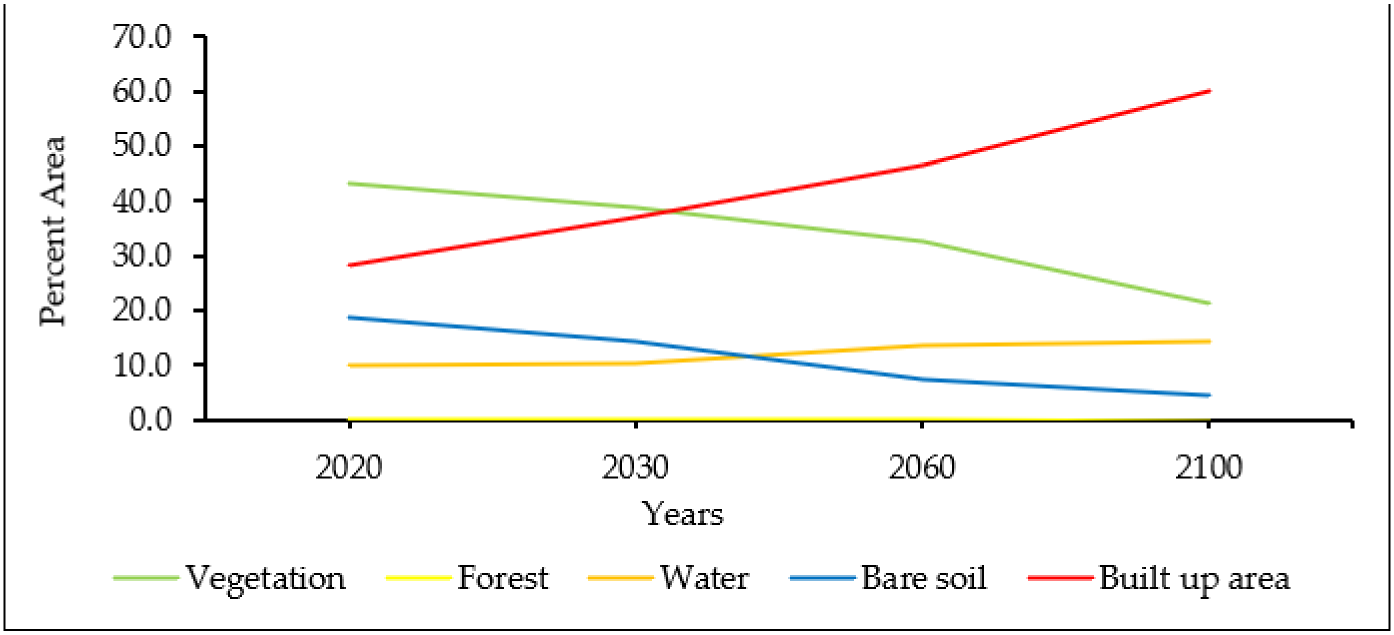

Figure 12

Trends of Land Use Change from 2020 to 2100

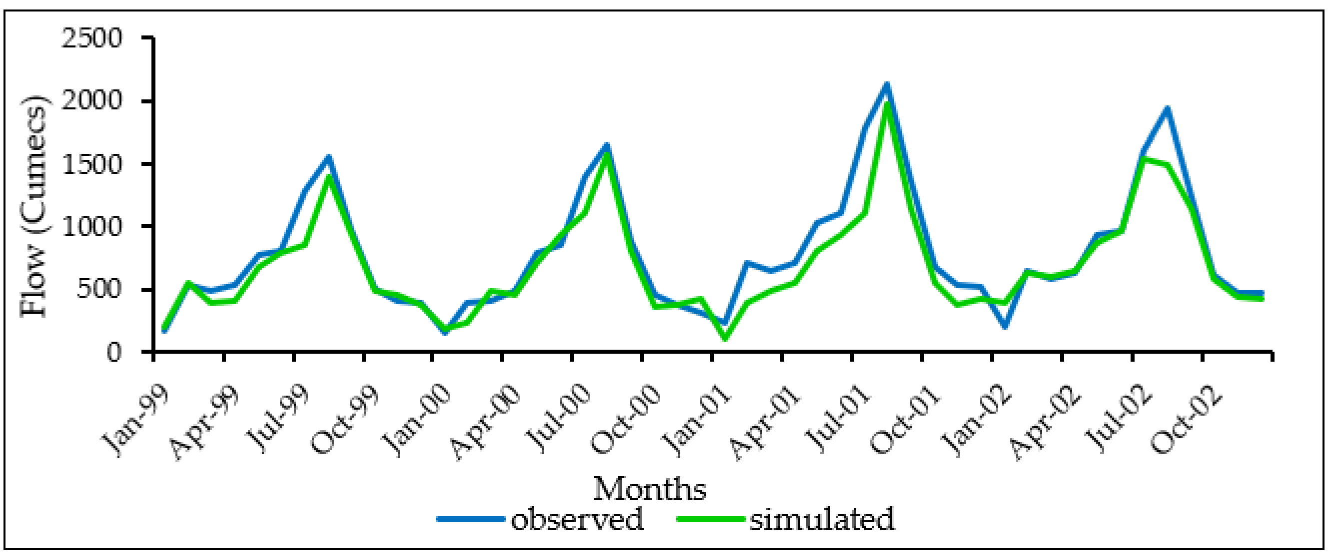

Figure 13

Simulated and Observed Flows for Calibration Period 1999-2002

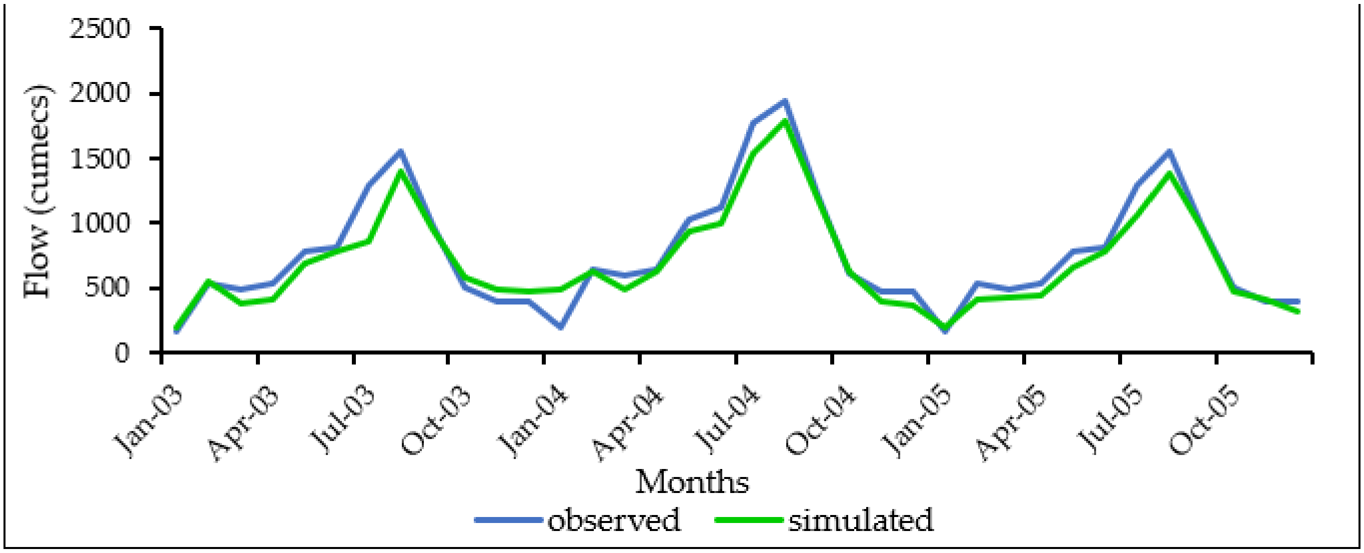

Figure 14

Simulated and Observed Flows for Validation Period 2003-2005.

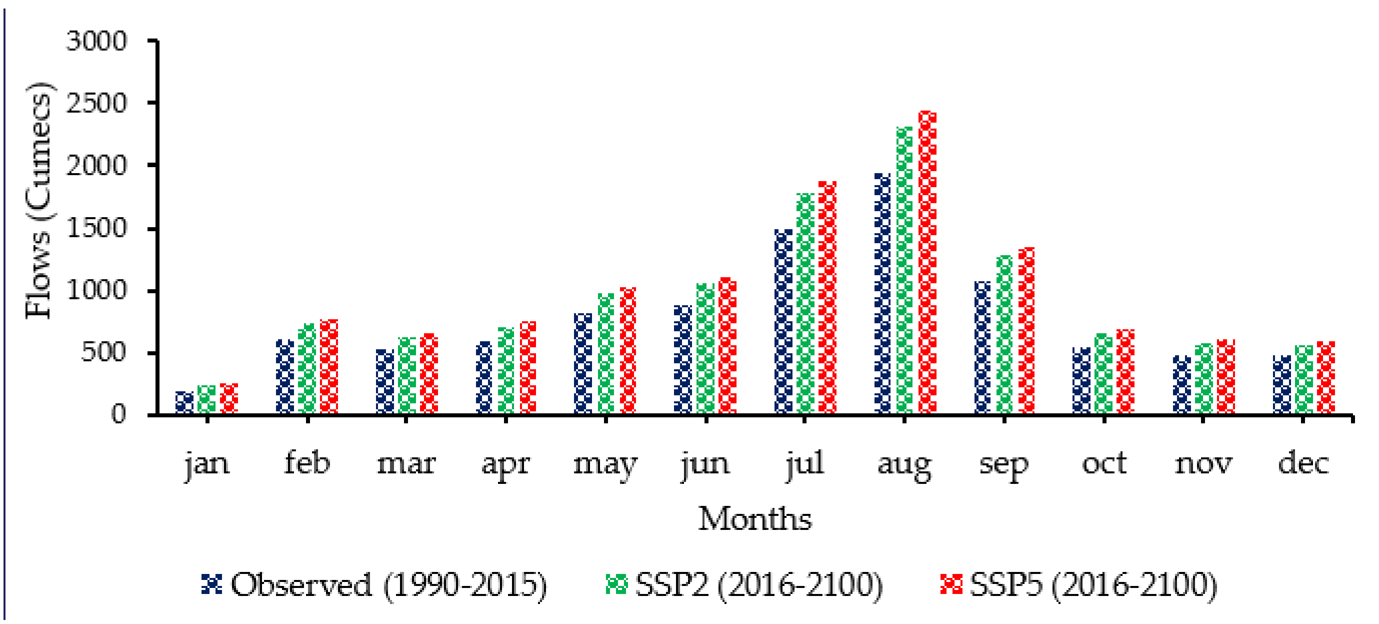

Figure 15

Comparison of Flows at River Ravi under Scenario A (i.e. Future Climate and Current Land Use)

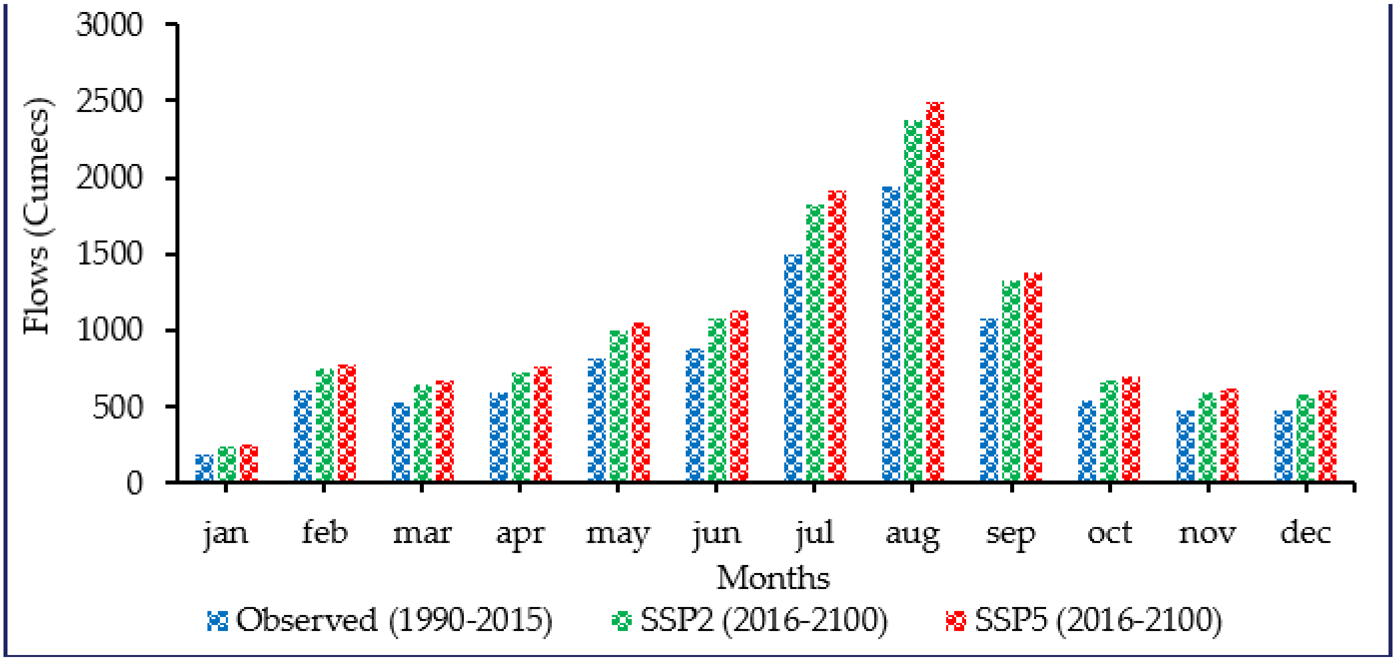

Figure 16

Comparison of Flows at River Ravi under Scenario B (i.e., Future Climate and Future Landuse)

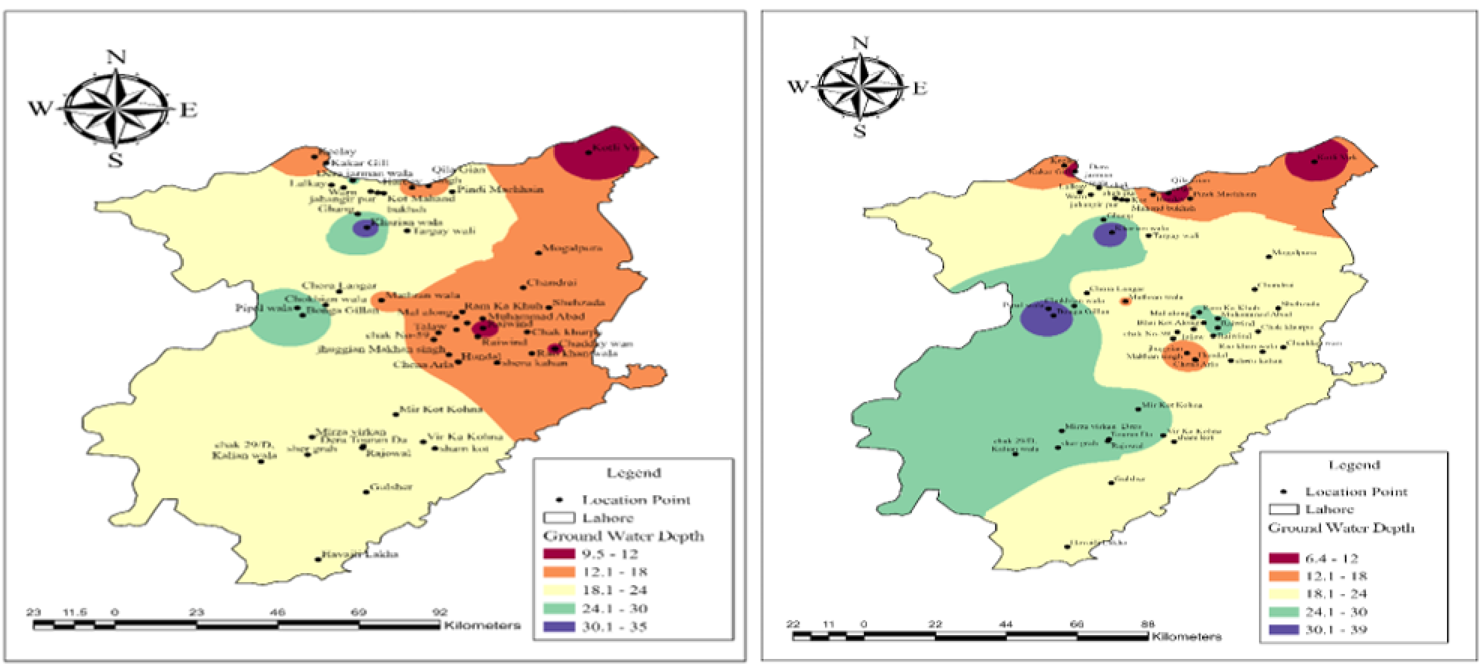

Figure 17

Groundwater depth variation of Lahore in 1996 and 2020

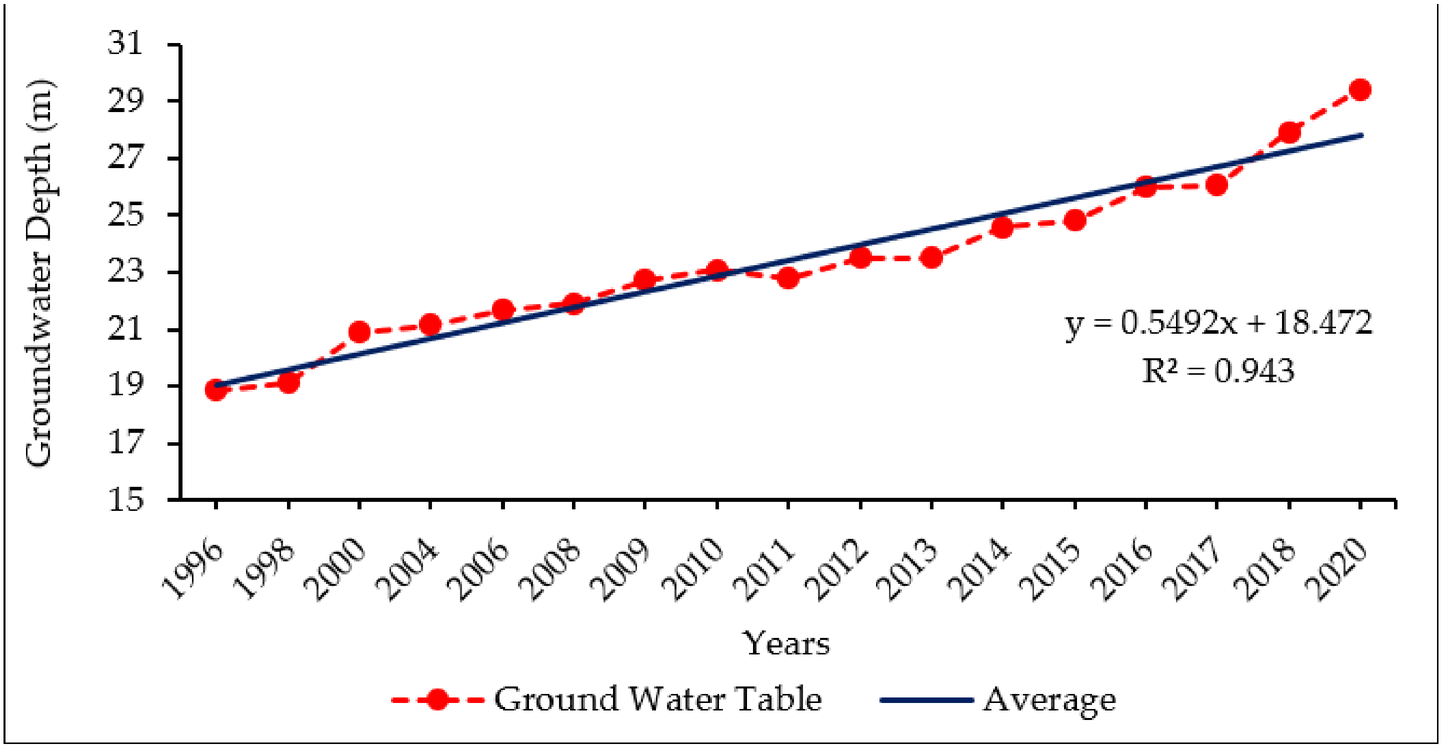

Figure 18

Trend of Depth to Groundwater Table of Lahore from 1996 to 2020

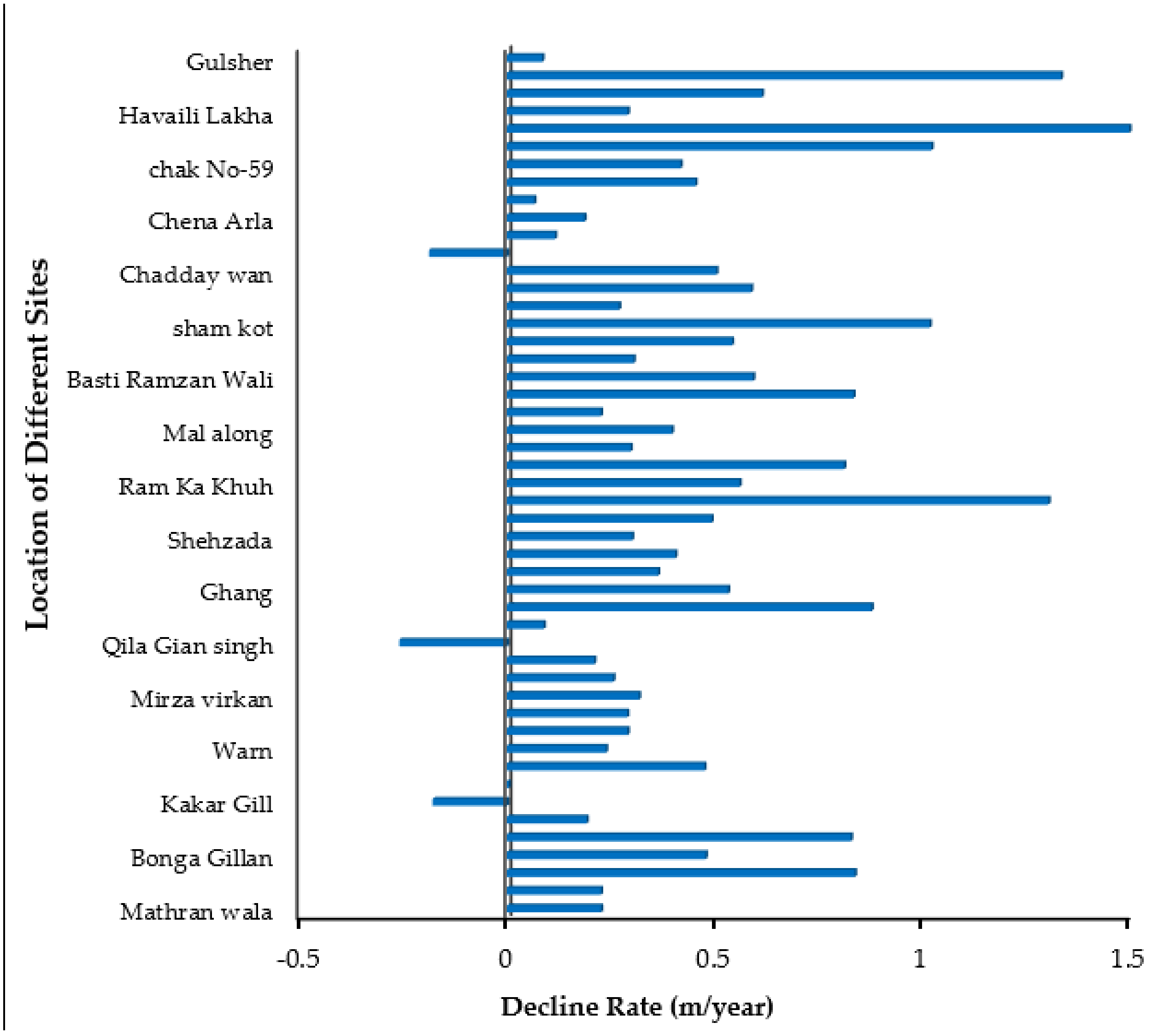

Figure 19

Groundwater Depletion Rate of Lahore