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Assessment of groundwater depletion rate by numerical modelling: a case study of Johar town Lahore, Pakistan

Sonia Anwar

soniaanwar223@gmail.com

University of the Punjab https://orcid.org/0009-0005-3256-1640

Case Report

Keywords: Groundwater, depletion, population, modelling, visual MODFLOW

Posted Date: August 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10801568/v1

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Additional Declarations: The authors declare no competing interests.

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Abstract: Pakistan is at great risk as the water level is declining day by day, and the situation is alarming because it could run dry if things do not change. Because of the rising population, per capita annual availability of water has decreased; it has dropped from 5600 m3 per year when Pakistan was founded to just 1017 m3 per year today. There is a continuing rise in demand, which is projected to reach 338 km3 annually by 2025 while supply remains relatively constant at 235.60 km3 annually. In Lahore since 1960, groundwater levels have dropped by one meter per year, which means that the groundwater table dropped by 3.37 meters per year. In this study, we have calculated the groundwater depletion of Johar Town, Lahore with the help of modeling software Visual MODFLOW. We got the necessary required data for modeling from different departments like Water and Sanitation Agency and Pakistan Metrological Department. The ground water depletion came to be 0.8757m/year for the average of previous six years (2015-2021). There is a need to install inverted wells, plant more trees, and make people aware of the water scarcity issues we could face if we do not change our habits. This research introduces the initial localized Visual MODFLOW application for Johar Town, Lahore, determining a quantified depletion rate of 0.8757 m/year with 95% certainty. It presents a combined data integration framework (WASA+PMD+GPS) and recognizes hydraulic conductivity as the primary parameter via sensitivity analysis. The study offers practical policy suggestions such as monthly tracking, individual extraction caps, and combined MAR approaches. This study addresses a significant void in detailed urban groundwater modeling for South Asian cities with limited data, providing a replicable approach for comparable areas. **Keywords: Groundwater, depletion, population, modelling, visual MODFLOW**

Introduction

When considering the potential effects of urbanization on groundwater ecosystems, one must consider the widespread use of this resource. Groundwater is being contaminated in developing countries, especially in urban areas, because of a lack of reasonable land-use policies (Famiglietti, 2014). Population growth, drought, and heat wave disasters in major cities of South Asian countries like Pakistan, India, and Bangladesh put a heavy strain on the region's water supply (Hunag *et al*. 2022; Douxchamps *et al*. 2022). The rate at which the Earth is undergoing changes brought on by industrialization, urbanization, and population expansion is surpassing our capacity to understand the effects of these activities on the planet's physical structure (Steffen *et al*. 2007; Vitousek *et al*. 1997). Increasing human activities have led to a dramatic rise in demand for underground water (Steinschneider and Najibi, 2022). Rapid expansion in the world's population has led to an overall rise in water consumption, which has contributed to the strain that human activity has placed on the world's water resources (Odhiambo, 2017: Siebert *et al*. 2010). A lot of research has been done on the topic of how urbanization contributes to groundwater depletion (Minnig *et al*. 2018). Changes in urban growth patterns brought on by the concentration of human habitations and the advent of industrialization have led to the urbanization of once agricultural lands (Wang *et al*. 2022). It is still unknown how much of an impact climate variability has on groundwater storage and how much pumping has (Asoka *et al*, 2017). Groundwater in an unconfined aquifer is more sensitive to contamination by surface pollution than in confined aquifers due to simple penetration by terrestrial contaminants (Salako and Adepelumi, 2018). With groundwater levels falling, it is time to look into system modelling for groundwater management, which involves understanding recharge, withdrawal, and storage capacity (Sophocleous, 2005). According to Barlow and Leake (2012), there is a connection between the groundwater and surface water systems, and groundwater discharge makes up a significant portion of the overall flow of a stream; nevertheless, groundwater pumping can limit the quantity that flows to streams and even reverse the flow of water from the surface into the ground. Globally about 12666 billion cubic meters (BCM) of groundwater are available annually, out of which 986 BCM per year are used in the world today. The world uses almost 67% of groundwater for agriculture, 22% for domestic, and 11 % for the industrial sector (Balaji *et al*. 2012). But the demand keeps increasing with the growing population, economic development, and expanding

areas for agriculture. Although surface water can meet such demand globally (water in lakes, rivers, and reservoirs), large regional variations mean that several parts of the world are facing water stress (Konikow and Kendy, 2005). Private groundwater extraction has increased in both rural and urban regions as a solution to the lack of available municipal supplies and the unpredictability of rainfall (Goyal *et al*. 2020).
Several human activities, especially irrigation (which accounts for >80% of the groundwater withdrawal), lead to groundwater depletion in most places within the Indo-Gangetic region, making it the most intensive user of groundwater resources in the world and causing considerable concern about groundwater availability (Mukherjee, 2018). In Pakistan, because of the rising population, per capita annual availability of water has decreased; per capita availability of water when Pakistan came into existence was 5600 m^3 per annum which is currently reduced to per capita 1017 m^3 per annum (Ashiq and Khan, 2020). Groundwater depletion and its declining levels are becoming major problems for groundwater management in many parts of the province and recognizing the challenges, meanwhile, the Punjab Government is taking various steps to address these challenges to reduce the water stress on Punjab's aquifer (Qureshi and Sayed, 2014). The metropolitan area of Lahore is the provincial capital of Punjab and the second largest city in Pakistan. The city is located at 31°15′–31°45′ N and 74°01′–74°39′ E and has a total area of 1014 km^2. It relies solely on groundwater for its needs (Mahmood et al. 2011). Lahore, a densely inhabited and industrial hub, is on the brink of collapse due to a lack of available groundwater (Kanwal *et al.* 2015). Increasing urban and rural populations are putting significant stress on both surface and groundwater supplies, which is the most important reason for their increased consumption (Basharat and Rizvi, 2011). Groundwater quality in the Lahore area's aquifer is declining due to pollution in the Ravi River (Hassan et al. 2013). More than 1.2 million low-capacity private tube wells have been built in Pakistan so far, with 86% of those being in just one province, Punjab (Shakoor *et al.* 2015). The Water and Sanitation Agency (WASA) provided 32500 connections for all the commercial outlets, including parks, shopping malls, educational institutions, mosques, markets, public transport, and eateries, in Lahore, and these sectors generally use roughly 20% of household water consumption while industrial consumption of water is estimated at around 277MCM/year (Qureshi and Sayed, 2014). According to Hariharan and Shankar (2017), the Modular Three-Dimensional Finite-Difference Groundwater Flow (MODFLOW) is a model commonly used to simulate the movement of water and the transfer of contaminants underground. Because of the wide variety of factors that can affect a hydrogeological design, it would be hard to do a thorough analysis without the use of a groundwater model (Lasya and Inayathulla, 2015). Rajamanickam and Nagan (2010) used this software for groundwater quality modelling of the Amaravathi river basin. The simulated MODFLOW models for the North Kelantan shallow aquifer have

been successfully calibrated and validated (Ismail *et al.* 2013). Both the rate at which the aquifer is being discharged and it is being recharged must be quantified (Barr and Salama, 2002). According to the model's statistical metrics, it accurately predicted the historical groundwater levels in the center of the CAR, where most of the irrigated agriculture was located (Harnandez *et al*. 2012).

Finite difference models, such as MODFLOW, and finite element models, such as SUTRA, are commonly utilized these days. They are founded on two important Darcy equations and the groundwater balance equation. A partial differential equation is created by mixing these two equations. To solve these equations, the finite difference or finite element approach is used, which needs the region to be divided into finite intervals known as cells. In contrast to partial differential equations, algebraic equations can be added. As a result, the model area is discretized into appropriately sized cells based on model domain size and data type availability to develop the model. Our main objective of this study is to perform numeric modeling with the help of software to get the future groundwater depletion rate in the corporation with the previous data. Different steps involved in groundwater modelling are shown in (Fig. 1).

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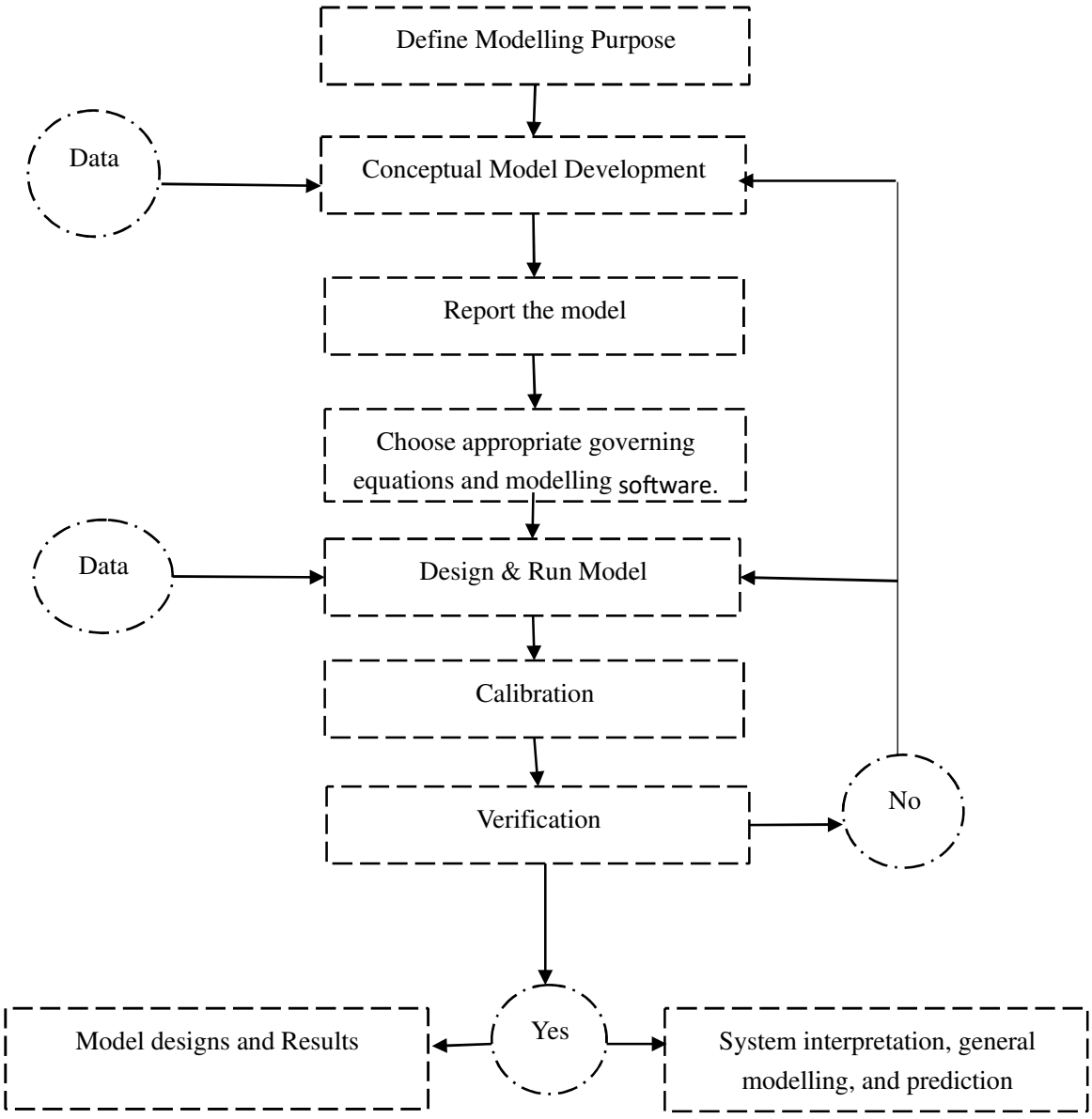


Figure 1: Groundwater modelling process

1 Methodology

1.1 Study area visit and data collection

Before forming the underground water depletion model, a site visit of the study areas was done. Under the guidance of the director of WASA, staff members gave a briefing about static water levels, bore log data, and pumping stations, etc. We made a site visit to pumping stations around Johar Town (Fig. 2) to get familiar with its working principle. We collected all the coordinates of every single well with help of a GPS device allotted from the university lab. The research approach involves multiple inter-connected activities. Several tasks were carried out in conjunction, while others were carried out dependent on their predecessors. The study consists of three main steps, which include data collection, data analysis, and setting up a model to assess the impact of the recharging well on groundwater levels. The groundwater model was calibrated and validated to get results accurately comparable to real conditions.

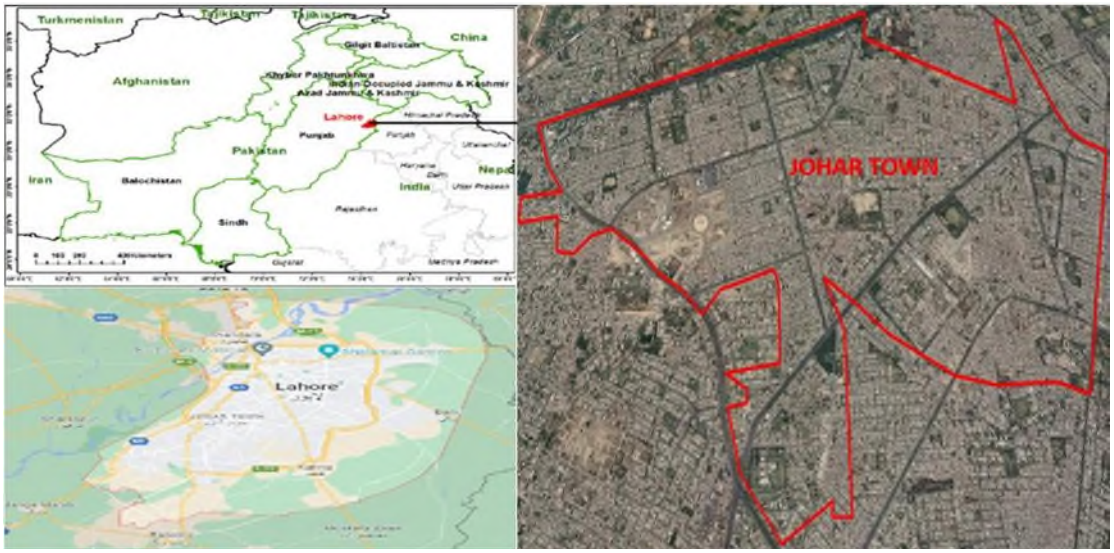


Figure 2: Study area map (Johar Town Lahore, Pakistan)

Data collection includes static water levels, discharge capacity of wells, Bore log data and Rainfall data. Data from numerous sources were gathered for the research purpose. Static water levels, discharge capacity of wells and Bore log data was provided by Water and sanitation authority (WASA) for 5 years (2016-2021) while Rainfall data of study area was obtained from Pakistan meteorological department (PMD) for 11 years (2011-2021).

All of the above data was analyzed and the model set includes

- Model properties (hydraulic conductivity, storage, and initial heads, etc.)

- Boundary conditions
- Calibration and validation
- Data analysis

1.2 Model Preparation

The domain to be modeled comprises the area of Johar Town Lahore. Aquifer being modeled consists a layer having a thickness of 400 m. This grid consists of 50 columns and 50 rows. The study area along with geographical points and model corners are shown in the (Fig. 3a).

1.2.1 Model refining

Columns and rows were refined for the cells where pumps were installed. This was done for accuracy in the results. The model is refined to get more accurate simulated results in the cells; it was refined to the default value of 2 (Fig.3b).

1.2.2 Grid Elevation

Grid elevations were imported from an Excel sheet consisting of more than 11 thousand elevation points at different locations in the study area. This was done using Google Earth Pro, from which a KMZ file was then imported into the Global Mapper software. This software gave us results in an Excel sheet, which was then imported into VISUAL MODFLOW. After matching the fields to their respective columns data was imported (Fig.3c).

1.2.3 Abstraction data and aquifer parameters

For developing the well package in the model, groundwater abstraction data, the number of pumps installed, their capacity, and their working hours were acquired from WASA, Lahore. Seventeen pumping stations operate under WASA in Johar Town, Lahore. The pumping time of these pumps varies between winter and summer, at 11 hours in summer and 9 hours in winter respectively. The pumping schedule, consisting of discharge, start and end times, along with well coordinates and screen intervals, is shown in Fig. 3d. Before running the simulations, the observation wells were also assigned to the model to monitor the model's behavior and the flow. Observation values such as static heads and time were entered. For the development of the numerical model, the physical parameters of the aquifer, such as transmissivity, specific storage, storage coefficient, and hydraulic conductivity, had to be defined, because each cell of the grid represents the flow domain. Transmissivity describes the ability of the aquifer to

transmit groundwater throughout its entire saturated thickness. The rate of groundwater flow across an aquifer segment of unit width at a unit hydraulic gradient is the transmissivity. Hydraulic conductivity is a measure of the ease with which fluid can move through the porous and fractured rock that makes up the aquifer material. The conductivity depends on the type of soils that are found in the region. Its value ranges from 25m/day to 70m/day with a mean value of 50m/day (Ashiq and Khan, 2020). Hydraulic conductivity in this study is 38m/day. The amount of water that an aquifer stores or releases per unit change in head, per unit surface area of the aquifer, is known as the storage coefficient.

1.2.4 Boundaries of model area

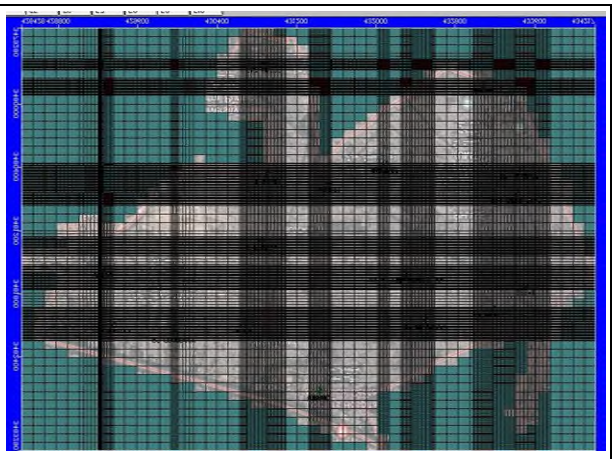
The aquifer has known boundaries only at its ends which are also changing due to pumping from an aquifer and comparatively low recharge to the aquifer (Fig.3e). Boundary conditions to all four sides were given as per site and study area specifications.

1.2.5 Time step and contouring

The stress period is the length of time over which the recharge and abstraction values are held constant in the model. The model will split each stress cycle further into several phases to enhance the precision of composition. In our project, we split the period into two stress periods i.e. pre-monsoon and post-monsoon. VISUAL MODFLOW gives us the contouring for the elevations we have created such as layer top, layer thickness and layer bottom. We can give different coloring schemes to the elevations for our better understanding. The top layer's elevation is shown in (Fig. 3f).



(a)



(b)

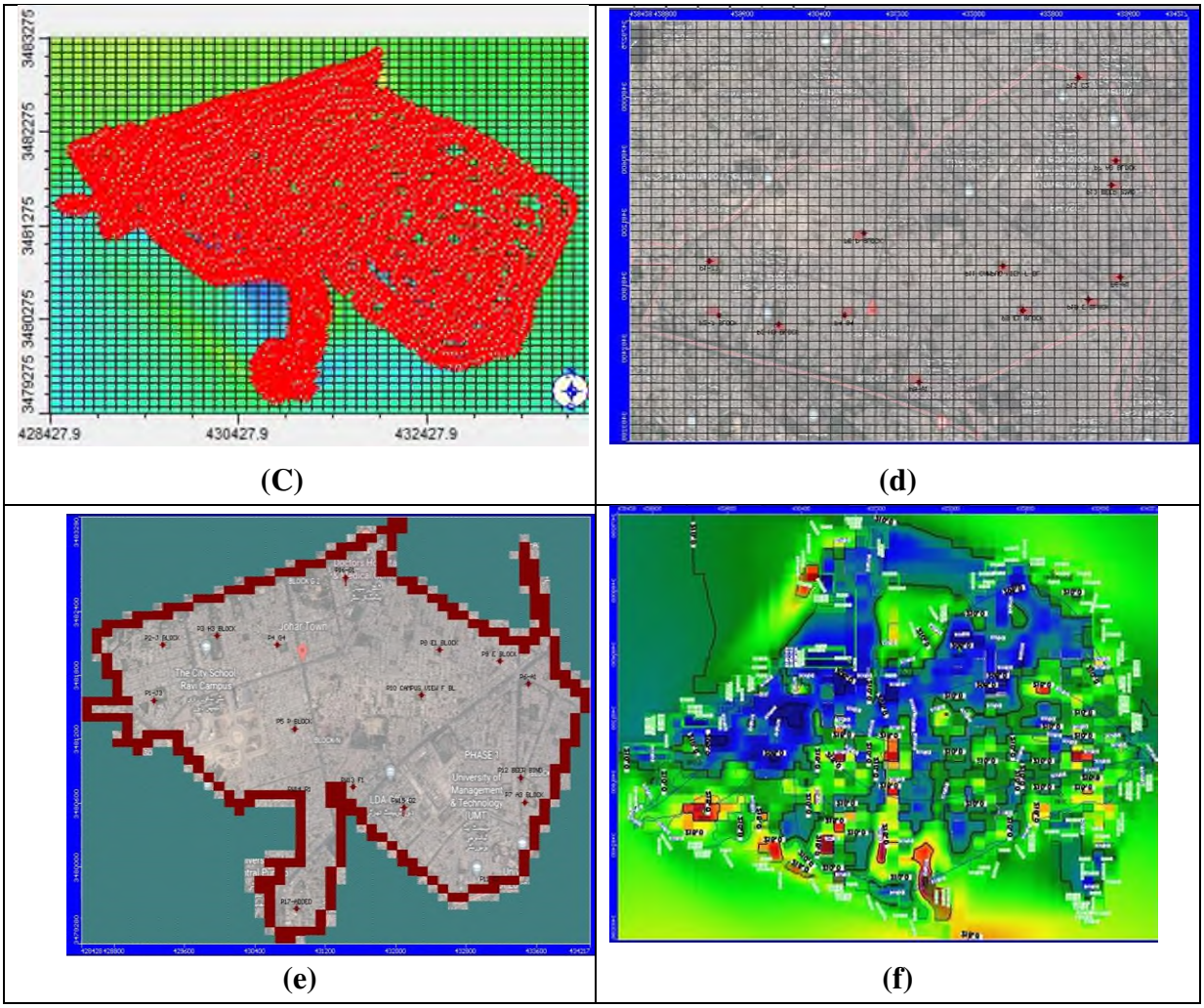


Figure 3: (a)Model corners and geographic points (b)Refining rows and columns(c)Grid elevation(d)Operating pumping station(e)Model layout showing boundaries around model domain(f)Top layer elevation

1.2.6 Model Calibration

The calibration period selection depends on the length of data and history. Groundwater conditions in the field of analysis and observation well data used in the current study are located inside the WASA office and it consists of static water levels. This data is incorporated into the model. Calibration of the model is a substantial step before it is used for simulations. Observation well data have been used for calibration. The trial-and-error approach is used until observed and calculated values get a match within the permissible limits by varying different parameters and executing multiple simulations (Table. 1).

Table 1 Calibration of different parameters

Parameter	Calibrated Value	Status
Conductivity	0.00043	OK
Storage	0.00055	OK
Effective Porosity	0.36	OK
Specific yield	0.24	OK
Total Porosity	0.41	OK
Evapotranspiration	53.1	OK
Recharge	123.4	OK

Note: Different parameters were selected on base of trial and error

In this study, hydraulic conductivity was varied along with other parameters, such as storage and initial head, and boundary parameters (constant head, recharge, and evapotranspiration), but only hydraulic conductivity was found to be influential. There are different approaches for testing model accuracy; the model calibration is checked by comparing observed and calculated values along a 45-degree line within the 95% confidence interval, and by the root mean square error (RMS). For the current study several simulations are executed to achieve satisfactory results. As the hydraulic conductivity dominated varying the results it was checked to its min value of 25m/day, a mean value of 48m/day, and a maximum value of 70m/day. The results before and after changing properties are given in the form of graphs for the stress period of 167 days (Fig. 4). As it is clearly shown we got better results in our required range after calibration of the model. RMS value of each well is in the range of -1 to +1 and the correlation coefficient also lies in the range so our results are quite satisfactory.

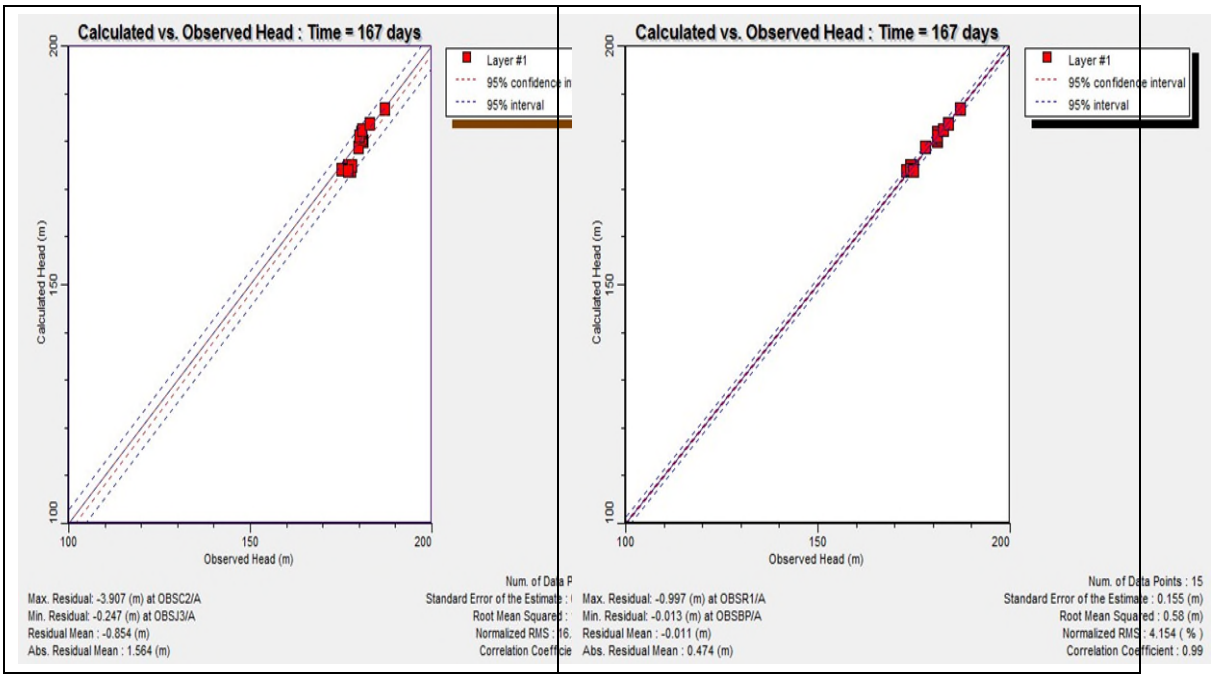


Figure 4: Calculated vs. Observed Head for stress period of 167 days (Before and after calibration)

1.3 Results and Discussion

Rainfall data collected from Parliamentary Committee on Water Resources for the previous ten years is shown in the form of the chart where there is annual precipitation on the y-axis and years on the x-axis. A maximum rainfall event was observed in 2013 (Figure 9). Fluctuations of water table depth for 2015-2021 are shown in the form of a graph where there are years on the x-axis and water table depth on the y-axis (Fig. 5). The total water depletion for the six years is

2.11 meters (Fig. 6).

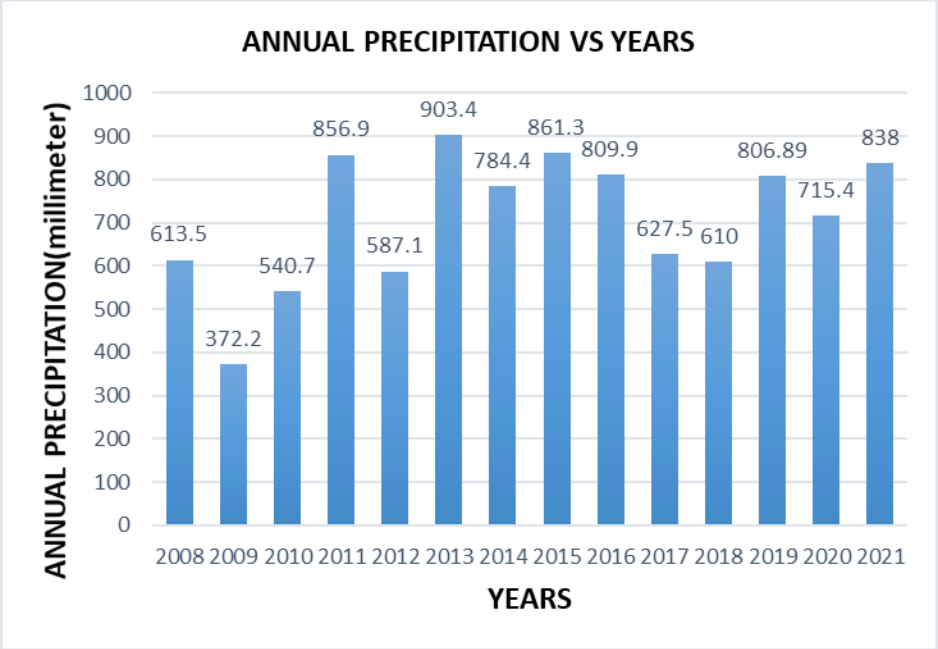


Figure 5: Annual precipitation vs. Years

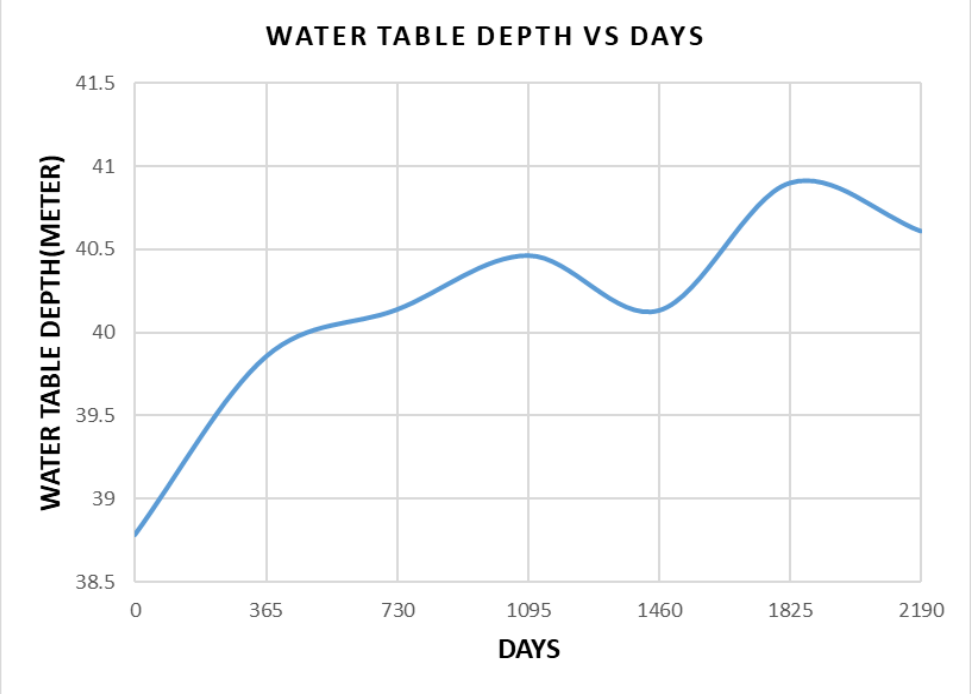


Figure 6: Graph showing depletion of groundwater (2016-2021)

The sensitivity study was carried out in VISUAL MODFLOW to check the effect of hydraulic conductivity on groundwater level values, which played a key role; we checked its effect by varying the conductivity value, increasing it by 20% and also reducing it by 20%, in which the water level rose to 198m and was reduced to 184m for

the second value (Fig. 7). The standard conductivity value we used in our study was 38m/day and we calibrated and validated our model against this value.

1.3.1 Urbanization impact on Groundwater Recharge and Depletions Significances

Johar Town's groundwater is being depleted at a rate of 0.8757 meters per year. This is not as severe as in some other places in Lahore, but it is still a significant problem. The nearby groundwater level is going down, and this is causing a number of issues. For example, it is becoming more expensive to draw water out of the ground, and the water is also becoming less clean. If we keep extracting large amounts of water, the ground may even start to subside. The Ravi River is also being affected, because groundwater is no longer flowing into it as it used to.

The primary reason for the reduction in groundwater is that Johar Town is becoming more urbanized. When farms are replaced with buildings and roads, the groundwater cannot recharge easily, because rainwater can no longer infiltrate into the ground. As a result, the groundwater level keeps declining. We are also pumping out a considerable amount of water in densely populated areas, which makes the problem worse. The Ravi River is already struggling because of pollution, and the loss of groundwater inflow is making its quality even worse. The same thing is happening in similar cities, such as in Switzerland: as cities develop, groundwater recharge declines. This is a particular problem in Lahore because the city relies entirely on groundwater for its water needs.

1.3.2 A Comparative View of Regional Research

The rate of groundwater depletion in Johar Town is comparable to that in areas of the Indo-Gangetic Plain. Most of the water there is used for irrigation, which is the main reason for the depletion. Even though Johar Town is a city, the areas bordering it are farmland facing similar problems. The groundwater decline in Johar Town is a warning sign, since Pakistan does not have abundant water resources. Demand is expected to be considerably higher than supply in the future. We need to start taking better care of groundwater so that we have sufficient water going forward.

1.3.3 Managed Aquifer Recharge (MAR) Strategies Viability

Even if we can find ways to put water back into the ground, the existing rate of pumping is not sustainable. We need to start conserving water and finding ways to recharge the groundwater. One way to do this is to collect rainwater and use it to recharge the groundwater. We can also build basins to help water infiltrate into the ground. Another option is to create recharge ponds and design cities with green spaces that can support groundwater recharge.

1.3.4 Management Suggestions and Policy Implications

The current study's findings have implications for the management of groundwater in Lahore. We need to monitor the groundwater frequently to see what is current and make changes accordingly. We also need to determine how much water is being extracted and ensure that new developments are built with recharge systems. We need to think about the water system as a whole, including the rivers and the groundwater, and develop a plan to manage them together. We also need to educate people about the importance of conserving water and get them involved in the process. We should design cities with open spaces and permeable surfaces so that the groundwater can recharge naturally.

1.3.5 Restrictions and Prospects for Further Study

This study has provided a lot of information about the groundwater in Johar Town. There are, however, still some limitations. We did not account for the effects of climate change, which could become a factor in the future. We recommend that future research also study the effects of climate change and test different methods for recharging the groundwater. We also need to develop a system for monitoring the groundwater over time and to study the economic effects of the depletion.

This study has shown that we can use computer models to understand what is happening to the groundwater in Johar Town. The main findings are that the groundwater is being depleted at a rate of 0.8757 meters per year and that the water table has dropped by 2.11 meters since 2015. We also found that the hydraulic conductivity of the rock is the most significant factor in determining how the groundwater behaves. The model we used was able to forecast groundwater levels with a good degree of precision. However, we also found that precipitation is not sufficient to recharge the groundwater and that we need to find ways to do so.

All of these results show that we need to start managing the groundwater in a sustainable manner so that we can protect the water supply for the future.

"This research presents the inaugural localized MODFLOW application for Johar Town, determining a quantified annual depletion rate of 0.8757 m/year with statistical reliability—a notable improvement over wider regional estimates." The hybrid data collection framework and sensitivity assessment, which pinpoints hydraulic conductivity as the key factor, provide a replicable approach for urban aquifers with limited data throughout South Asia.

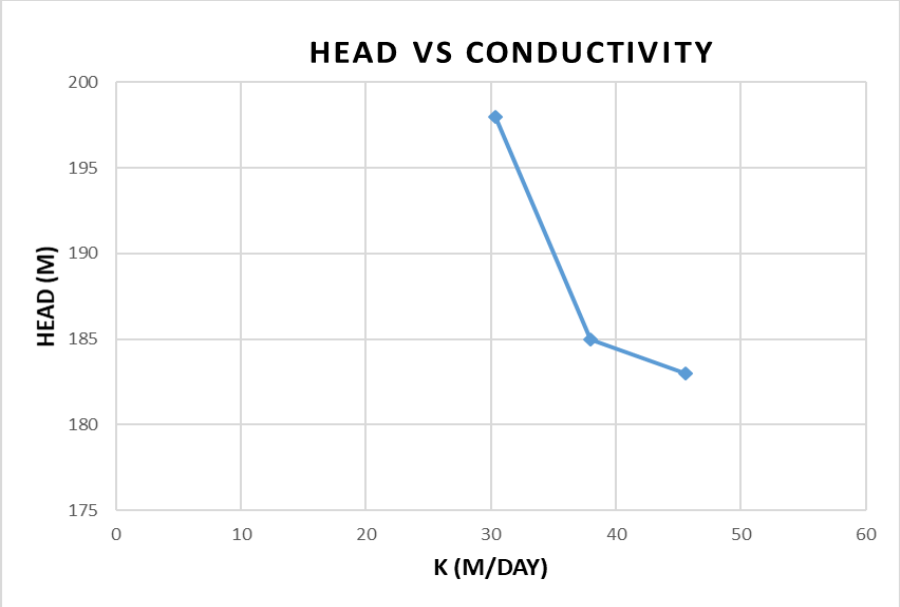


Figure 7: Sensitivity analysis results by varying conductivity

1.4 Conclusion

Groundwater depletion average from (2015-2021) was found to be 0.8747m/year and sensitivity analysis depicts that model is sensitive toward increment in hydraulic conductivity value. Hydraulic conductivity for this model was used as 38m/day and Visual MODFLOW, well calibrated and validated for the study area as the results were within a 95% confidence interval. Rainfall plays an important role in recharging the aquifer and precipitation was maximum in 2013 which is 903.4mm which can play a vital role in recharging the groundwater.

Recharge applications (Inverted wells, ponds, plantation of trees and construction of engineering structures, etc.) are recommended to reduce the groundwater depletion rates in the study area. As even after providing Inverted wells, groundwater abstraction rates are not sustainable, hence some other Managed Aquifer Recharge (MAR) technique may be provided. Monitoring groundwater levels is required for the sustainable management of water. Currently, annual readings are taken for the groundwater levels, which should be taken monthly. A large set of data would be more reliable for future planning. New housing societies in the city must extract groundwater according to per capita requirements. They must develop a sustainable groundwater system that balances the amount of abstraction and recharging. Plantation of trees is an effective way of recharging. Public seminars on saving water should be conducted on national and international levels and people are encouraged to use less water and reuse the water for other daily purposes.

Acknowledgements

The authors are extremely grateful to WASA and PMD Pakistan for providing the necessary data for this study.

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