M.Sc THESIS

MONITORING AND MODELLING OF GROUNDWATER RECHARGE THROUGH RECHARGING WELLS

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ABSTRACT

Sustainability of the globe is threatened by the growing water issues. Water use has grown more than the population increase which led to develop water scarce regions in the globe. Pakistan whose population has gone over 200 million is facing water stress because of enhanced population, increasing industrialization and urbanization. Similar is the case with Pakistan's 2^{nd} largest city, Lahore-capital of Punjab Province which is totally dependent on groundwater reserves for its domestic & industrial uses. High abstraction rates in Lahore has declined its water table and continuously declining with the increase of groundwater abstraction that also deteriorating the groundwater quality. The groundwater abstraction of 44.6 MGD in 1960 has increased to 804.4 MGD in 2018. Objectives of research were to monitor recharging wells by installing flowmeter and piezometers, simulate groundwater table of Lahore to determine the depletion rate and to determine the impact of recharging wells on depletion rate.

To fulfill the objectives of research work, flowmeter and piezometers were installed for monitoring of recharging well. Setting up of groundwater flow model was carried out using the software Visual MODFLOW to do the analysis of depletion. The model was calibrated and validated using observed data from 2015 to 2018 before the installation of recharging wells. The average depletion rate for groundwater was 0.86 m per year, -0.072 m per summer season and 1.02 m per winter season. Again, model was calibrated and validated using observed data of February and March, 2019 after installation of recharging wells. From model

results, it was found that the average depletion rate for groundwater was 0.7 m per winter season based on two months data.

The study shows that if the same urban development trends prolong, it will render groundwater system unsustainable as the groundwater recharging sources more or less remain at the same level while the abstraction rates continue to increase day by day. The gap between inflow and outflow is continuously increasing which is resulting in the depletion of groundwater storage. To overcome such rapid decline of water table, there should be rain water harvesting through recharging wells in Lahore city. The study underlines the importance of groundwater recharge through recharging wells to reduce the depletion rate of Lahore's aquifer.

ACKNOWLEDGEMENTS

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Last but not least sincere thanks are due to my parents, family members for their unreserved love, benevolent prayers and sacrifices in sustaining my efforts during the studies.

Muhammad Masood Ashiq

DEDICATION

Dedicated to

"My Respected Supervisor" Prof. Dr. Habib-Ur-Rehman

For highly professional advice, dynamic supervision and consistent technical & moral support.

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LIST OF ABBREVIATIONS

BRBD	Banbawali Ravi Bedian Depalpur
DHA	Defence Housing Authority
EC	Electric Conductivity
EPA	Environment Protection Agency
FAO	Food Agriculture Organization
GIS	Geographic Information System
GW	Ground Water
GWC	Ground Water Cell
JICA	Japan International Cooperation Agency
LDA	Lahore Development Authority
LIT	Lahore Improvement Trust
MET	Punjab Metrological department
MGD	Million Gallons per Day
MODFLOW	Modular finite Flow model
M-R Link	Marrala Ravi Link Canal
NESPAK	National Engineering Services Pakistan
OW2	Observation Well for recharging well 2
OWc2	Observation Well at center for recharging well 2
PCRWR	Pakistan Council for Research in Water Resources
PPM	Part Per Million
RW	Recharging Well
SDWF	Safe Drinking Water Foundation
UET	University of Engineering and Technology

UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Education, Scientific and Cultural Organization
USA	United States of America
USAID	United States Agency for International Development
UTM	Universal Transverse Mercator
WAPDA	Water And Power Development Authority
WASA	Water And Sanitation Agency
WHO	World Health Organization
WWAP	World Water Assessment Programme
WWF	World Wide Fund for nature

Chapter I
INTRODUCTION

1.1 GENERAL

Lahore city population is growing rapidly. This expansion has been highly articulated during the most recent twenty years. The number of inhabitants in Lahore has come to 11.12 million (Pakistan Bureau of Statistics, 2017). This expansion in population brings about upgraded water pumping, which is causing groundwater exhaustion in Lahore. Water that is being supplied to the inhabitants of Lahore is absolutely reliant on groundwater. The water utilized by the city is comprised of domestic and commercial activities, which is expanding with the expansion in the number of inhabitants in Lahore. Due to excessive usage of groundwater, the situation is going to be alarming about quantity as well as quality of groundwater. Groundwater analysis is carried out by developing the groundwater model to get the idea about the depletion rate of groundwater and same is done after installation of four recharging wells in the study area to check their impact on groundwater depletion rate.

1.2 PROBLEM STATEMENT

Water is absolutely essential not only for human life, but for all lives. In fact, it is the blood of life. It is used for a range of purposes which includes drinking, bathing, washing, air conditioning, agriculture, industrial processes, power generation, fire protection and many others. Globally, second largest source of fresh water is groundwater that is retained in underground reservoirs.

Despite having the largest glaciers in the world, Pakistan faces the possibility of water shortages. Pakistan is one of the 36 countries most affected by water stress in the world, its agricultural, industrial and domestic areas that mark water stress index of the Global Resources Institute. The annual availability of water per capita has decreased, mainly because of rise in population which is currently 1017 m^3 but it was 5600 m^3 when Pakistan came into being. Demand of water consumption is growing and up to 2025, it is likely to reach 339209 Mm^3 (274 MAF), while the supply is probable to remain stagnant at 235596 Mm^3 (191 MAF). So, it will result in a gap between the supply and demand of water about 103613 Mm^3 (83 MAF) (IMF, June 2015). As a result of rapid urbanization and population growth, available water resources are running out at an alarming rate. This situation is getting worse day by day because the water demands increase continuously.

Lahore being the capital of Punjab province, is the second biggest city in Pakistan because of higher population which was 11.13 million according to 2017 census. After Indus Basin Treaty, River Ravi was allocated to India which resulted in substantially reduced water supplies to it. Therefore, almost Lahore's full water demand is met from groundwater resources. The study of past events of groundwater over abstraction with decreased aquifer recharge has prompted a critical decline of groundwater. Lahore groundwater depletion rate is about 1.03 m per year on average and can be increased. Groundwater table depth in Lahore city lies between 186 m to 215 m. Groundwater extraction rate is greater than the recharge rate.

Groundwater plays a very important role, but often very valuable in the social and economic well-being of urban areas. Today, industrialization and urbanization have led to overexploitation and excessive extraction of groundwater by pumping more and more water. In Lahore, the main problem of public interest is the recession of the water level, mainly due to excessive pumping, continuous increase in impermeable areas resulting reduced infiltration and recharge rates. Since, water requirements are completely fulfilled by the supply of groundwater, it is very important to study the depletion of aquifers in relation to their low recharge and the increase in water demand.

Then again, suburbanization, industrial development and the greater impenetrability of the land have significantly reduced the recharge of aquifers. Due to the lower consideration of protection of aquifer in Lahore, these effects were analyzed long after they occurred. Whenever human beings disturb groundwater hydrological balance while developing the new cities, it results in depletion of groundwater tables. As a consequence, the vulnerability of the Lahore aquifer to deprivation has become the cornerstone of policies relevant to its protection. With the present withdrawal rate, the increase in population growth and the rates of land growth; it is more expected in the future that this downward fashion will eventually deplete the aquifer. If this condition persists, groundwater quality and quantity situations may worsen. A critical analysis determines that the energy crisis not only means as of power load shedding, but will also be water shedding which is bashing at gates of Lahore.

There are many techniques which are used in developed world to recharge the groundwater i.e. infiltration galleries, delay action dams, bank infiltration, infiltration ponds and recharging wells. In recent years efforts have been made by the LDA to install various types of recharging wells in the city of Lahore. Lahore Development Authority (LDA) in collaboration with UET Lahore had installed four recharging wells of large diameter in Junaid Jamshed Cricket Stadium of UET Lahore.

There was a dire need to investigate the impact of these four recharging wells on local groundwater depletion rate.

1.3 STUDY AREA DESCRIPTION

Lahore is the biggest city of Punjab and is highly urbanized. Lahore city has an aggregate land zone of 2,100 Km^2 and is as yet developing which has almost flat terrain with a mean altitude of 217 m and population of 11.13 million according to 2017 census. As far as the climate is concerned it is considered hot semi-arid. May, June, July and August are hottest months with monsoon rains while December, January and February are the coldest months with few western disturbances causing rain. Geographically UET Lahore lies within 31.5799°N and 74.3563°E as displayed in the Figure 1.1.

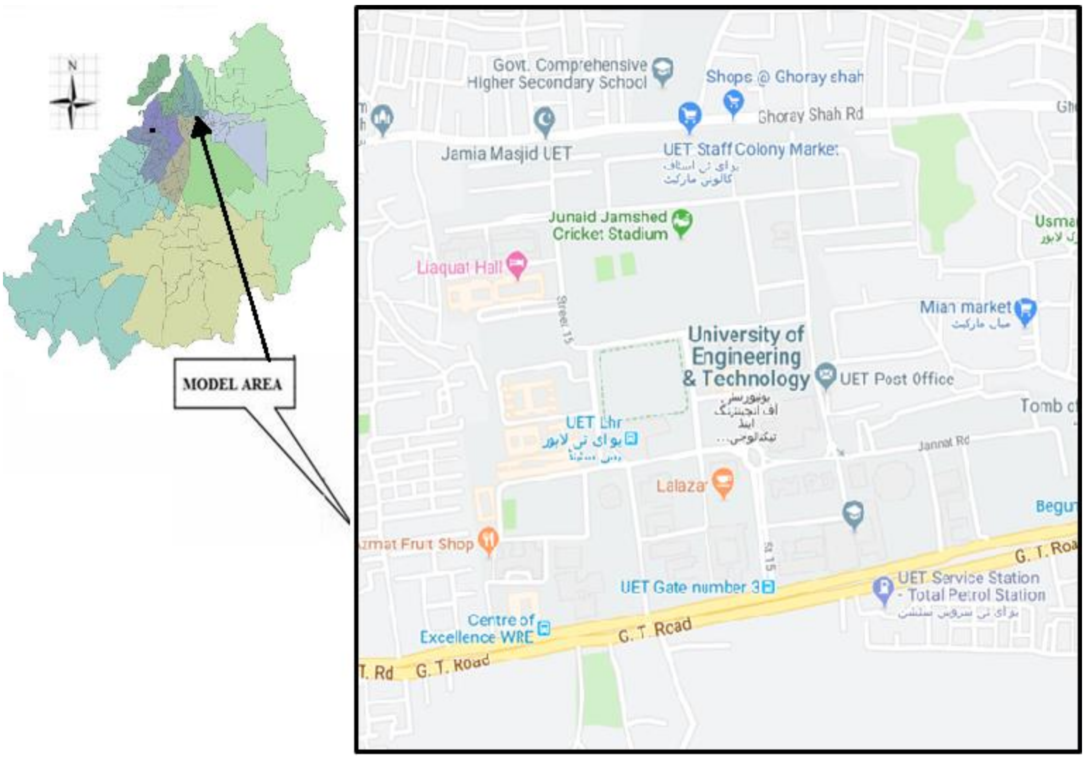

Figure 1.1 Study Area showing Map of UET Lahore

Lahore consist unconsolidated strata. It has the thickness of around 400 meters, (NESPAK, 1988). Aquifer of Lahore is made out of alluvial layers with irregular clay patterns. Lithology shows that it has small discontinuities of clay at some point but mainly it is unconfined aquifer. Subsequently, it is said that the aquifer of Lahore is homogeneous aquifer. Different arrangements, experienced in boring comprise of predominantly sand, sediment and mud; rock of mudstone or residue stone and calcareous solidification commonly called kanker available at most of the places.

From Figure 1.2, it can be seen that on east, there is Bambanwali Ravi Bedian Depalpur (BRBD) canal and on North and North West, there is Ravi River. Now, focusing on main study area, UET is a part of Lahore which lies adjacent to famous Grand Trunk Road. So, study area consists of UET and its adjoining area. At present, 12 tube wells are used to supply water to the inhabitants of study area and the pumping of the tube wells is around 10.87 thousand Gallon for each Day. In this way, the Model zone incorporates the zone under the purview of WASA and UET.

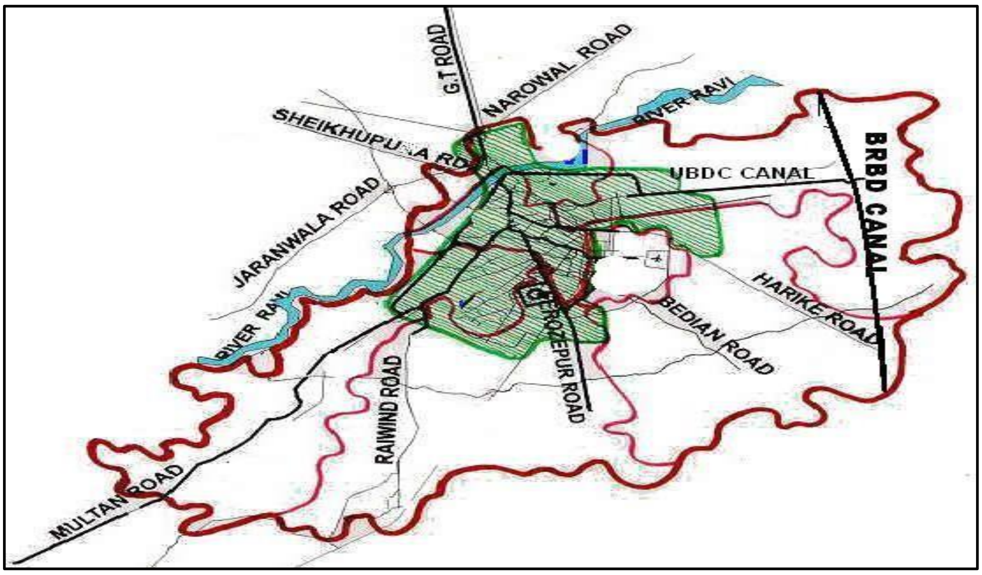

Figure 1.2 Areal Map of Lahore

1.4 OBJECTIVES OF RESEARCH

The main objectives of this research are:

1. To install flowmeter and observation wells to monitor groundwater recharge.
2. Assessment of groundwater depletion rate without recharging wells.
3. To assess the groundwater depletion rate considering recharging wells.
4. To carry out sensitivity analysis of Visual MODFLOW by changing mesh size.

1.5 SCOPE & LIMITATIONS OF THE STUDY

The scope of the study includes the installation of equipment to monitor recharging wells, setting up, calibration, and validation of a groundwater numerical model i.e. Visual MODFLOW. The study concentrated on quantity of groundwater recharge and abstraction, thus resulting in the simulation of groundwater levels fluctuations for checking the impact of recharging wells.

Due to time and data availability constraints, the study is limited to groundwater quantity analysis only. Also, data of only two months was used for checking recharging wells impacts on groundwater table because there was not sufficient time after installation of recharging well monitoring equipment. Long-term impact of recharging wells on groundwater table should be checked on basis of longer duration data.

1.6 OUTLINE OF THE THESIS

Chapter 1 presents the groundwater problems of Lahore but mainly of UET. Keeping in perspective on the city groundwater problems, objectives, scope and limitations of the present research are outlined in this chapter.

Chapter 2 follows the groundwater use far and wide, groundwater issues in Pakistan, in Lahore and UET. Also have the detail regarding groundwater models and past groundwater researches which are carried out in the area, are discussed in the part.

Chapter 3 describes the methodology that has been followed to attain the objectives of the current study. It also illustrates the installation of equipment to monitor the recharging wells and step by step procedure to formulate groundwater numerical model for the UET Lahore area.

Chapter 4 outlines the results and discussion regarding quantity of groundwater. Finally the chapter 5 has the conclusions & recommendations based on the study.

Chapter II
LITERATURE REVIEW

2.1 INTRODUCTION

This chapter discusses the groundwater use far and wide, groundwater issues in Pakistan, in Lahore and UET. Also details regarding groundwater models and past groundwater researches which are carried out in the area, are discussed in the part.
Water is a vital component for sustenance of life on earth. This limited component has a direct bearing on practically all segments of the economy. Freshwater in all its states account for only 2.5% of total planet's water. These are mostly ice covers and glaciated reserves (69%) and in form of underground water (30%) whereas all streams, lakes and swamplands represent only a small portion (0.3%) of total fresh water assets of the Earth. Overall in the world water resources are projected to be around 1.4 x 10^{18} m^3. Of all these resources 97.5% is present in oceans. 35 x 10^{15} m^3 is fresh water and only 0.3% of earth's water is in lakes, rivers and reservoirs. The rest of it is stored in permanent ice, glaciers and groundwater aquifers. The total atmospheric water of the world is estimated to be about 13 x10^{12} m^3 (Shiklomanov and Rodda, 2003).

Talking about the surface water resources of Pakistan then the Indus Basin brings 190 billion cubic meters (Bm^3) of water per annum on an average. Out of this 190 Bm^3, 179 Bm^3 is the contribution of three rivers namely Indus, Chenab and Jhelum whereas, only 11 Bm^3 is the share of eastern rivers. Furthermore, looking into the distribution of available water, for irrigation 129 Bm^3 is used, 50 Bm^3 goes into Indian Ocean and almost 11 Bm^3 is lost in system that includes infiltration, evapotranspiration and spills in case of floods. Out of total withdrawal, currently 93%

allocated for agriculture, 4% fixed for domestic and the remaining part goes to industrial use (Bakshi and Trivedi, 2011). With the passage of time this demand of water is going to increase that results a healthy competition of irrigation water with industrial and domestic use (USAID, 2009).

2.2 GLOBAL FRESHWATER RESOURCES

Postel *et al.* (2006) reported that freshwater on planet represents only 2.5% which is 1,386 million km^3 and humans can use almost $1/3^{rd}$ of this water. Humans use more than half of the useful freshwater supplies which includes surface and subsurface. Due to growing demand for agriculture, industry and residences, this quantity is growing. In their study, Clarke and King (2004) explained that the total amount of water abstracted for human use purposes is from 1,382 km^3 per year to 3,973 km^3 per year, which has nearly increased three times during last fifty years. Water for human use will increase by an additional 5,235 km^3 per year in 2025 as per forecasted by global forecasts. Figure 2.1 shows the freshwater availability throughout the world, in m^3/ capita/ year for 2007. Only Pakistan is ranked among countries where water is scarce, compared to China and Afghanistan has 1,700 to 5,000 m^3/ capita/ year whereas India and Iran have 1,000 to 1,700 m^3/ capita/ year.

Arnell (2009) and Falkenmark *et al.* (2007) stated that by 2025, five out of eight persons would experience water shortage. Hamdy *et al.* (2013) deliberated that over one fourth of the planet's people will be going to water shortage problem by 2050. Figure 2.2 presents an assessment of water stress in 1995 and 2025 in different countries. Figure 2.2 shows that about 7 billion population will suffer from water stress by 2050.

2.3 WHAT IS GROUNDWATER AND WHERE IS IT FOUND?

Water that accumulates under the ground is called groundwater. It exists between the spaces of particles of soil, or in the cracks of rocks. Different rocks soils have different capacities to contain the amounts of water. Zone of saturation is portion of soil and rock which is occupied completely with water but when it is partially filled then it is known as unsaturated zone. The water table is the top most line of saturated zone. The Figure 2.3 shows these terms (SDWF Report, 2014).

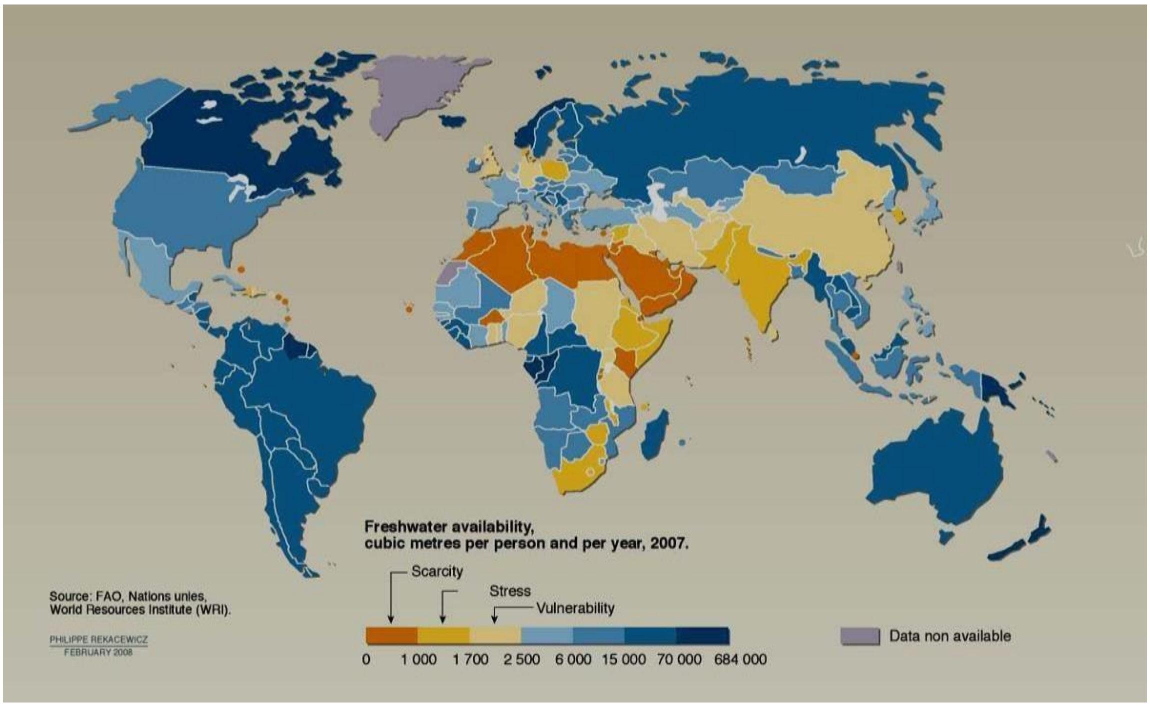

Figure 0.1 Freshwater Availability in 2000
(FAO, Nations Unies World Resource Institute)

2.4 WORLDWIDE GROUNDWATER RESOURCES

In their report, UN/WWAP (2013) showed that maximum of the Globe's freshwater is present in reservoirs laying underground, which makes more than 98% reserves of freshwater on earth. Figure 2.4 shows the worldwide groundwater reserves distribution.

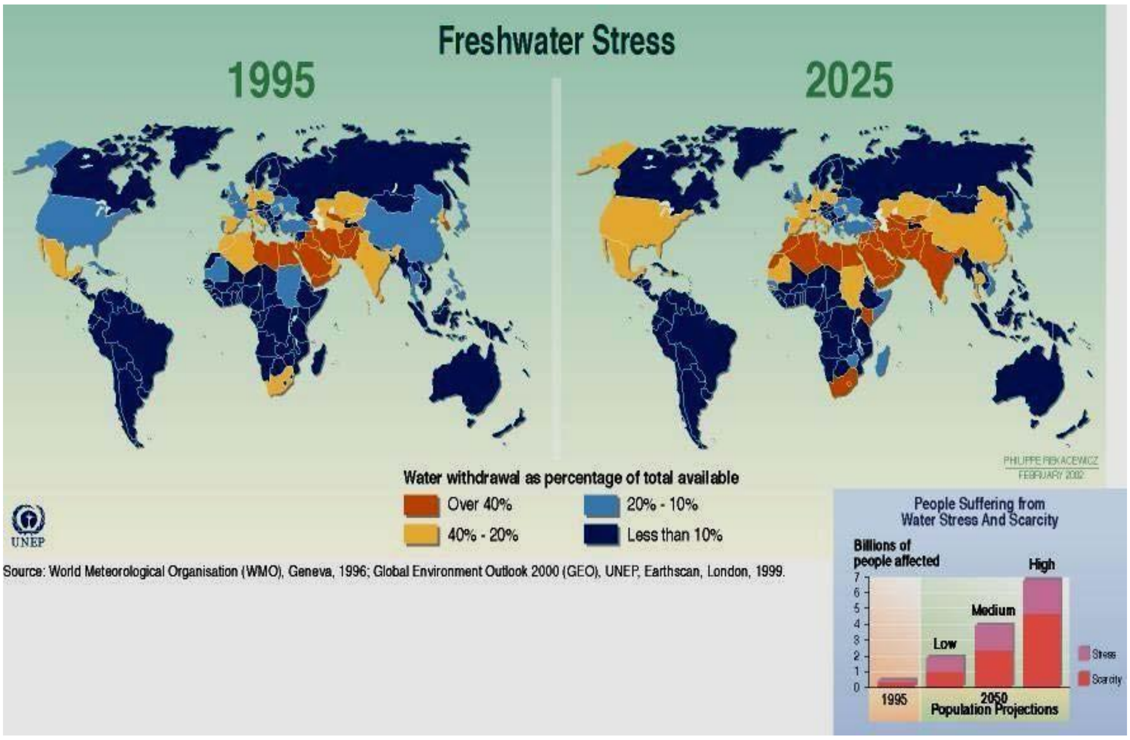

Figure 2.2 Freshwater Stress 1995 and 2025 (UNEP/GRID-Arendal, 2009a)

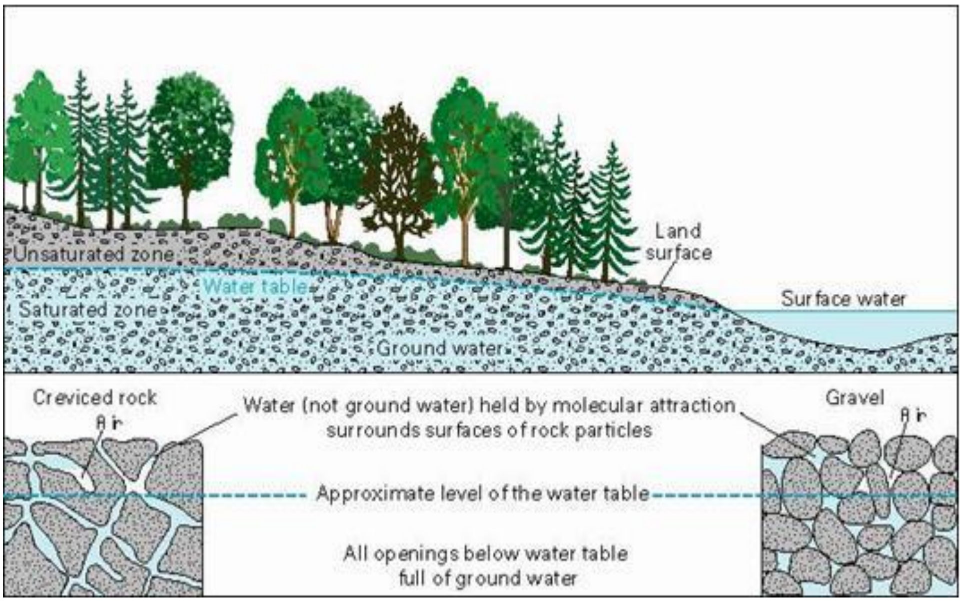

Figure 2.3 Schematic Diagram Showing the Water in the Ground (http://capp.water.usgs.gov/GIP/gw_gip/how_occurs.html)

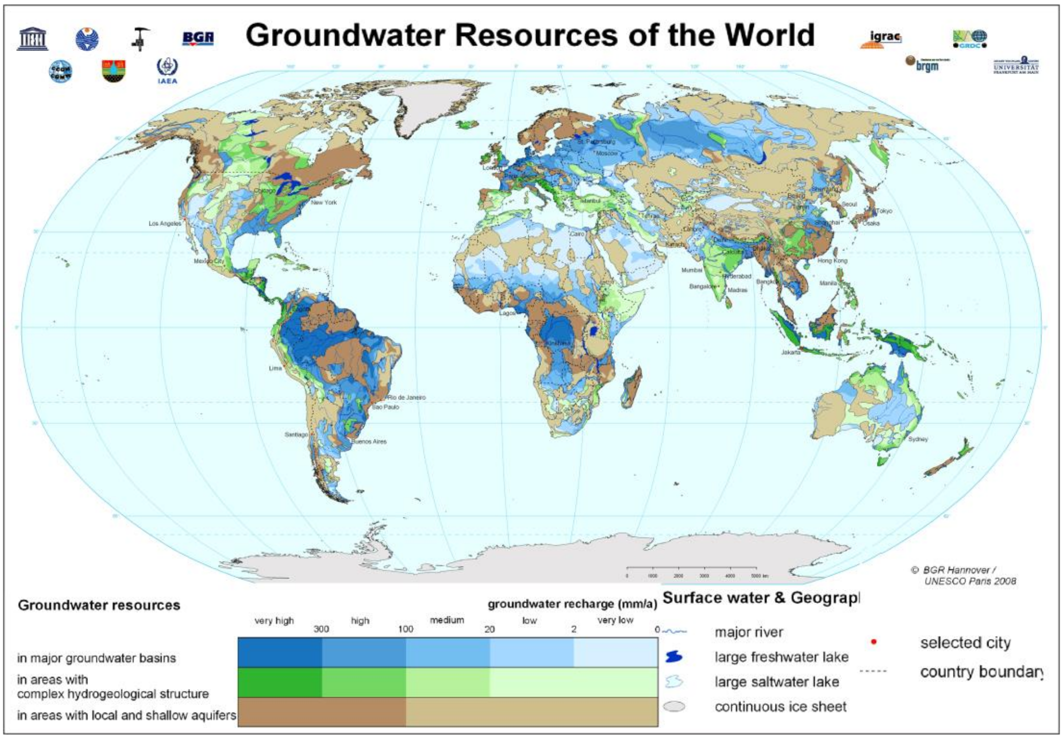

Figure 2.4 Worldwide groundwater resources (BGR and UNESCO, 2008)

2.5 WATER RESOURCES OF PAKISTAN

2.5.1 Surface Water Resources

Surface water resources of Pakistan are mainly centered on the flows of the Indus River and its tributaries. The Indus River consists of 2900 Km total length which covers drainage area of almost 966,000 Km^2. Jhelum, Chenab, Ravi, Beas and Sutlej are the five major tributaries which are on its east side. Besides, Soan, Harow, and Siran are three minor tributaries which drain in mountainous areas. Also, there are a number of small tributaries which are on its west and River Kabul is biggest of them. Generally, rivers in Pakistan show individual flow characteristics. But mostly, all of them start to rise during the spring and early summer season. Then, due to snow melting on the mountains and the monsoon rains, they exhibit a combined peak discharge in months of July as well as August. The flows are lowest in the rivers during winter season with mean monthly flows are only about one-tenth of those in summer i.e. during the period November to February. After the Indus Basin Treaty between India and Pakistan (1960), availability of three western rivers was limited to Pakistan which included Indus, Jhelum and Chenab, while India was permitted to take flows of three eastern rivers i.e. Ravi, Beas and Sutlej. This treaty also included construction of a number of link canals, barrages and dams on the River Indus and its two tributaries i.e. Jhelum and Chenab, to transfer water to irrigate the areas that were irrigated by rivers Ravi, Sutlej and Beas before the Indus Basin Treaty.

Indus Basin brings 190 billion cubic meters (Bm^3) of water per annum on an average. Out of this 190 Bm^3, 179 Bm^3 is the contribution of three rivers namely Indus, Chenab and Jhelum whereas, only 11 Bm^3 is the share of eastern rivers. Furthermore, looking into the distribution of available water, for irrigation 129 Bm^3 is used, 50 Bm^3 goes into Indian Ocean and almost 11 Bm^3 is lost in system that includes infiltration, evapotranspiration and spills in case of floods (Bakshi and Trivedi, 2011).

Another source of surface water is hill torrents in the mountainous areas of the country which has not been developed to its full potential. In Pakistan, with a total potential of about 19 MAF at about 1,200 sites, there are 14 distinct hill-torrent areas in all the four provinces. Out of this, nearly 60% can be established for production of the crop. About 6 Million acres of culturable wasteland can be irrigated in the hill torrent areas (Kahlown *et al*., 2003).

2.5.2 Groundwater Resources

Indus Plain has most of the groundwater resources of Pakistan which spread from Himalayan foothills to the Arabian Sea. These resources are stored in its alluvial deposits. The length of plain is almost 1600 Km and an area of 21 Mha is covered by it. It is consists of widespread unconfined aquifer which is the additional source of water for purpose of irrigation. Direct recharge from natural precipitation, river flow, and the constant seepage from the water conveyance system of canals, distributaries, watercourse and irrigation application during the previous 90 years resulted in this aquifer built up. This aquifer, with a potential of almost 50 MAF, is being misused to a greater level of almost 38 MAF because of above 562,000 private discharging wells and about 10,000 public owned discharging wells.

In Balochistan, main dependable sources of groundwater are dug wells, tube-wells, springs and karezes to irrigate the orchards and other cash crops because almost all the rivers have seasonal flows only. The total available potential is predicted as almost 0.9 MAF, out of this potential 0.5 MAF has already been used, thus leaving a balance of 0.4 MAF which may be consumed.

Groundwater has been overexploited in two the basins i.e. Pishin Lora and Nari beyond its development potential which produced mining situations and caused a huge overdraft of groundwater that may be resulted into drying up of the aquifers in the long-term (Kahlown *et al.*, 2003).

2.6 SOURCES OF WATER FOR THE STUDY AREA

2.6.1 Surface Water Resources

6.02 Mm^3 per day is the surface water that is diverted to the city of Lahore. Looking into back, it is found that water supply for city Lahore was provided through Ravi River. However with the passage of time the infrastructure through which water is supplied to city area becomes abandoned and no further improvements were made to sustain the system. Due to persistent decrease in flows of Ravi, it was not possible to divert water for city use (WWF, 2014). Flow in River Ravi mainly contributed by M-R link canal and five streams namely Ujh, Bein, Basantar, Degh and Hudiara. (Nazir and Akram, 2000). During 1922-1961, average River Ravi flows was 1300 Mm^3 per day that declined to 800 Mm^3 per day from 1985 to 1995 and further reduced to 175 Mm^3 per day during 2000-2009. However, maximum flows upto 260 Mm^3 per day were also seen for the period of 2009 (Basharat and Rizvi, 2011). After that when heavy monsoon rains were there in 2010 the maximum flow in River Ravi was recorded only 75-100 Mm^3 per day and it seems that in future the discharge in River Ravi will be only at that time when there is a discharge in Ravi tributaries or when the thein reservoir exceeds its capacity (Mahmood *et al.,* 2013).

2.6.2 Groundwater Resources

Confined and unconfined aquifers are the two major types of aquifer as shown in Figure 2.5. The aquifer of Lahore is viewed as a single contiguous, unconfined layer which is composed of unconsolidated alluvial soil having 400m thickness having hydraulic conductivity from 19 to 71 m per day (NESPAK, 1991 and CDM, 1975). Recently, the maximum observed water table depth in city area is 40 m and in area of Raiwind is about 12 m (Basharat and Rizvi, 2011).

While in UET area, it is 24 m (Irshad, 2018). The aquifer under the city and around the Lahore is deep having very high transmission of 2100 m^2/day considering 80 m thickness that contributes to groundwater flow (WAPDA, 1980). The groundwater flow movement follows the similar path as that of irrigation system, and also parallel to the system of rivers i.e. from northeast side towards southwest side, on the local scale. Below the ground, the groundwater exists in 10 to 30m depth but the drinkable water was taken out from 120-200 m depth (NESPAK, 1988). However, the depth of water table in the area fluctuates significantly because of different varying elevations of natural surface as well as due to the different patterns of discharging and recharging groundwater. Because of the rapid growth in population, migration of the outsiders in the city area and the establishment of the industries put the Lahore aquifer under stress which is going to increase day by day.

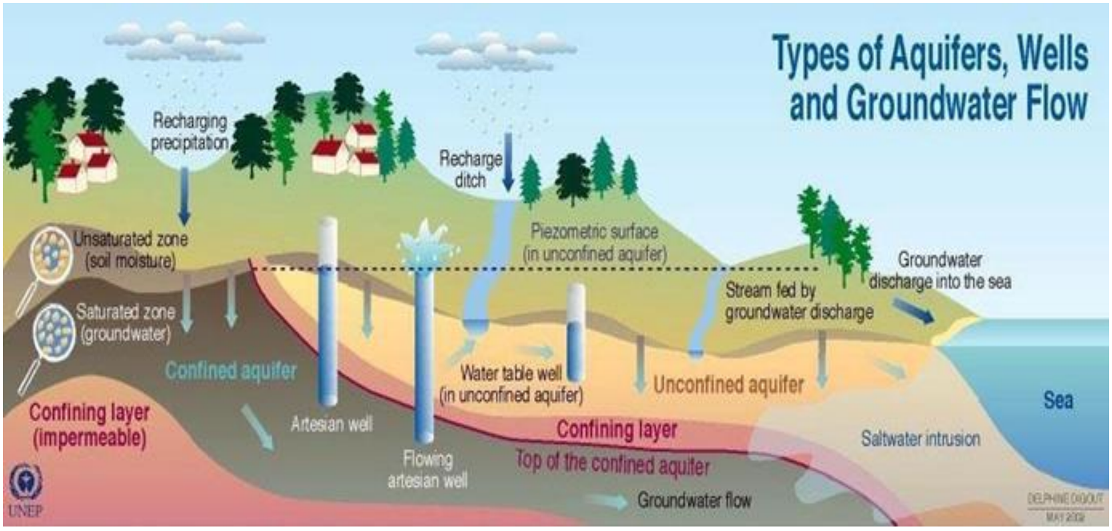

Figure 2.5 Types of Aquifer (http://www.ec.ca/water/index.htm)

In addition of above, reduction of groundwater recharge from agricultural area, less rainfall and more paved area of the city also affecting the groundwater quantity. This irregular and uncontrolled extraction of groundwater leads to an extreme dropping of groundwater depth in Lahore. During 1960, water table depth was 4.6m which goes to lower level due to extensive pumping and during last 30 years this depth is declining about half a meter per annum. In 1987 its range 8 m to 20 m that has dropped to 51 m in the year 2011 (Mahmood *et al.*, 2013).

2.7 GROUNDWATER USES

World's combined groundwater abstraction as per 2010 was assessed to be roughly 1000 km^3 per year, of which approximately 67% was utilized for irrigation, 22% for domestic uses and 11% for industrial uses. Two thirds of this amount was abstracted in Asia where major consumers were India, China, Pakistan, Iran and Bangladesh (IGRAC, 2010). They also suggested that the current global abstraction of groundwater represents approximately 26% of total freshwater withdrawal globally (Table 2.1), and that its rate of abstraction corresponds to some 8% of the mean globally aggregated rate of groundwater recharge.

IGRAC (2010) showed global groundwater abstraction as a percentage of mean annual recharge as shown in Figure 2.6. Pakistan was among those countries which had more groundwater abstraction than mean annual recharge.

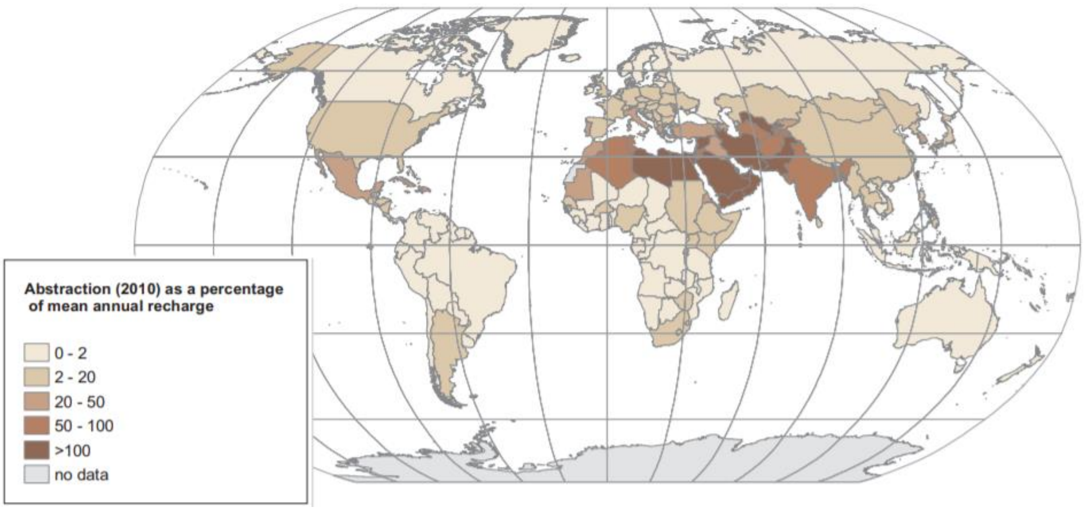

Figure 2.6 Groundwater development stress indicator at country-level (based on groundwater abstraction estimates for 2010) (Source IGRAC, 2010)

Table 2.1 Key Estimates of Global Groundwater Abstraction (Source IGRAC, 2010))

Continent	**Groundwater Abstraction**					**Compared to total Water Abstraction**	
	Irrigation km^3/yr	**Domestic km^3/yr**	**Industrial km^3/yr**	**Total**		**Total water abstraction km^3/yr**	**Share of Groundwater %**
				km^3/yr	**%**		
Asia	497	116	63	676	68	2257	30
North America	99	26	18	143	15	524	27
South America	12	8	6	26	3	182	14
Central America and the Caribbean	5	7	2	14	1	149	9
Europe (including Russian Federation)	23	37	16	76	8	497	15
Oceania	4	2	1	7	1	26	25
Africa	27	15	2	44	4	196	23
World	**666**	**212**	**108**	**986**	**100**	**3831**	**26**

In its report, the World Water Assessment Program indicates that most groundwater was exploited from 1970 to 1990 in many countries. World groundwater reserves can deliver 50% of the present water for household supply, 40% to the industrial sector and 20% for irrigation.

However, due to major financial benefits of groundwater over surface water as well as its availability at local level and its better quality without any treatment, groundwater value should not be seen by its volumetric withdrawal. The main extents of groundwater use consist of agricultural sector, industries and domestic sectors, and their overall use in these areas is concisely described in the following divisions.

2.7.1 Groundwater for Domestic Use

Morris *et al.* (2003) explained that underground water is a vital supply that over two billion people depend on for their domestic purposes. In 2000, it was found that more than half of the 23 megacities (with more than 10 million inhabitants) in the world depended or heavily relied on their native groundwater and it is assessed that hundreds of towns around the world depend on these waters. . Table 2.2 shows the groundwater population server by region.

Table 2.2 Estimated percentage of water use from groundwater (Morris et al., 2003)

Region	Population served (millions)	%age
Asia-Pacific	1000 - 2000	32
Central and South America	150	29
Europe	200 - 500	75
Australia	3	15
USA	135	51
Africa	NA	NA
World	1500 - 2750	-

The statistics of Pakistan reflect that water supply system is largely dependent on groundwater usage. The most of water supply schemes are designed on the basis of groundwater as compared to surface water source. Public Health Engineering Department has the mandate to provide water supply in almost all over the country, except those large cities, where, WASAs have been established.

WASA Lahore is responsible to supply water in urban sectors of metropolitan. Also, the other housing authorities like Defense Housing Authority, Model Town Society, Lahore Cantonment Board, Pakistan Railways and Walton Cantonment Board are responsible to provide water in their jurisdiction. UET had also installed five pumping wells to provide water to its inhabitants which is of less capacity relative to other societies. Groundwater extraction for non WASA areas is given in Table 2.3.

Table 2.3 Groundwater extraction of non WASA area (Modified and Upgraded by WWF-2014 from JICA Report, 2010 &Punjab Agricultural Census)

Non WASA Area	**Number of Tube Wells**	**Total Pumping Capacity (m^3/day)**
Walton Cantonment Board	53	259,200
Lahore Cantonment Board	53	244,512
Model Town Society	15	77,760
Pakistan Railway	52	200,448
Defense Housing Authority	20	97,632
Total	**198**	**889,702**

WASA, Lahore have installed more than 500 Tube wells to cater the domestic water needs of 6.0 million population of Lahore. The depth of these tube wells vary with respect to the area and variation lies between 150 to 300m. The water usage has increased with the increased population and improved living standard with variation from 180 lpcd (1967) to 274 lpcd (2013). The groundwater usage comes out to be 2.2

Mm^3 per day, by pumping for 14 to 18 hours per day. WASA Lahore has supplied water from source to household with a pipe system of about 7700 km length and 600,000 connections. Piped network almost covers 78% of area of WASA and 50% non-WASA area for providing drinking water. The unserved population gets water either through hand pumps, stand posts or small suction pumps. Due to absence of any act for groundwater usage, most of the housing societies and industries utilize excessive groundwater, which is a major cause of groundwater depletion. Housing societies are extracting groundwater at a rate of 0.37 Mm^3 per day, whereas, if there is no water supply in the area extraction comes out to be 0.35 Mm^3 per day, so the total extraction comes out to be 0.71 Mm^3 per day. The rural area comes in jurisdiction of Public Health Engineering Department. In conclusion, groundwater usage in Lahore comes out to be 3.79 Mm^3 per day (WWF-2014). Table 2.4 shows the breakdown of domestic water consumption.

Table 2.4 Breakdown of domestic water consumption (Modified and Updated by WWF from JICA Report of 2010)

Activity	**WASA Areas**		**Non-WASA Areas**		**Slum Areas**	
	Volume (Liters)	**% age**	**Volume (Liters)**	**% age**	**Volume (Liters)**	**% age**
Cooking	12.3	4.57	4.3	2.45	4.3	1.35
Clothes Washing	64	23.8	37	21.3	114.5	36
Drinking	20.2	7.5	14.8	8.5	15.8	4.96
Car Washing	23	8.55	7.25	4.2	2.1	0.67
Gardening	4.8	1.78	2.2	1.25	1.1	0.35
House Cleaning	42.25	15.7	30.25	17.4	68.5	21.54
Bathing	87.25	32.45	73.6	42.3	110.5	34.75
Other Uses	15.2	5.65	4.6	2.6	1.2	0.38
Total	**269**	**100**	**174**	**100**	**318**	**100**

2.7.2 Groundwater for Industrial Use

Morris *et al*. (2003) indicated that fraction of water abstraction for industry usage is greater in the developed and fast-emerging economical countries. With continuing development in the industrial sector, its requirement is further. Pakistan is rapidly becoming industrialized country, so the groundwater usage by these industries causing a serious threat to depletion of groundwater.

In Lahore, currently, there are almost 2700 industrial units that has been registered. Out of these, 2025 units are listed as large industrial units (JICA, 2010) which are the leading consumers of groundwater in Lahore. Out of all industrial units, textile industry, uses the largest amount of groundwater, which is 69% of total industrial usage (Basharat & Rizvi, 2011). Detail of different industrial usage of groundwater is given in Table 2.5.

Table 2.5 Industrial use of groundwater (Basharat & Rizvi, 2011)

Industry	**Groundwater Usage**
Textile	69%
Chemical	10%
Food	5%
Paper	5%
Others*	11%

*Other includes marble, leather, electronics and steel.

Consumption of groundwater by these industries is not well registered. It was roughly estimated by WASA that in Lahore almost 4000 private tubewells having capacity of 480,000 m^3/day are pumping water for supplying water to these industrial and other private purposes (JICA, 2010). Each industrial unit has constructed 1-4 tubewells with various capacities that ranges from 1200 to 2500 m^3/day that further depends on working type being done in each industry (Basharat and Rizvi, 2011). Roughly, the average groundwater usage by these units comes out to be 1800 m^3 /day, by considering 25% utilization, groundwater pumping comes to be 0.92 Mm^3 per day.

2.7.3 Groundwater for Agricultural Use

The increase in food making in recent ages has caused the rapid increase in the abstraction of groundwater to use it for the purposes of irrigation. Shah e*t al.*, (2005) in his research reported that groundwater usage is over 300 km^3 each year in India, Bangladesh, Nepal, Pakistan and China, which represents around 50% of yearly worldwide usage. Morris *et al.* (2003) indicate that the United States uses 43% of groundwater to meet their needs for irrigation. Table 2.6 shows the agricultural use of groundwater in some countries of the world.

Table 2.6 Agricultural Usage of groundwater in some particular countries (Lashari et al. 2007)

Country Name	**Groundwater Use (%)**
Pakistan	45
Bangladesh	69
Nepal	50
India	53
China	25
Australia	34

Pakistan is an agricultural country, which is heavily dependent on the surface water, but it is insufficient to cater the needs of agriculture usage, so groundwater usage has increased rapidly to fulfill this demand. According to the report of Bureau of

Statistics, total installed pumping wells in the Bari Doab are 200 thousands of which 6 thousands are installed in district Lahore having capacity 1200 m^3 per day with operating at rate of 0.14, which reflects the usage of these pumping wells comes out to be 1 Mm^3 per day. Currently, comparing the usage of groundwater in agriculture sector compared to surface water usage, it depicts the higher usage of groundwater. Generally, when cropping area decreases and intensification increases and the people do not think to leave fallow land and try to use the land maximum which they can use by growing different crops at the same time that leads to more use of water. Looking back 20 years, quantity of pumping wells for irrigation has a 10% increase (Qureshi *et al.*, 2010). Considering this increase and calculating the current number of tube wells it comes out 10,000 with pumping rate of 1.7 Mm^3 per day. These numbers of tube wells may vary depending on patterns of rainfall in the area and flow in rivers from year to year.

Table 2.7 Urbanization and Cultivable Land in Lahore (Khaliq-uz-Zaman, 2012)

Duration	**Total Area (Ha)**	**Cultivable area (Ha)**	**Cultivable area (%)**
1972	177204	166862	94.2
1973-80	177204	163413	92.2
1981-90	177204	114298	64.5
1991-2000	177204	81040	45.7
2001-2010	177204	52232	29.5

2.7.4 Commercial and Institutional Use

Currently, more than 5% (32,500) connections comes in educational institutions, hospitals, mosques, shops, offices, restaurants, public parks, offices, bus stands, railway stations and other places for public and barely no data is available for these connections. Roughly, commercial and institutional uses are about 20% of domestic usage. If domestic usage is considered, as 3.80 Mm^3 per day, then, commercial usage comes out to be 0.76 Mm^3 per day (277 Mm^3 per year) (WWF-2014).

Table 2.8 Summery of water usage by different sectors in Lahore city (Qureshi, S. A., 2014)

Sector	Name	Water use (Mm^3/day)	Water use (Mm^3/year)
Use for domestic purposes	WASA	2.2	803
	Non-WASA	0.88	321
	Private use	0.71	260
	Subtotal-1	**3.79**	**1384**
Use for non-domestic purposes	Industrial	0.92	335
	Commercial and institutional	0.76	277
	Subtotal- 2	**1.68**	**612**
Use for agricultural purposes	Groundwater	1.71	623
	Surface water	3	1095
	Subtotal- 3	**4.71**	**1719**
Groundwater use		7.18	2619
Surface water + Groundwater		**10.18**	**3716**

2.8 GROUNDWATER QUALITY

The groundwater is extracted from the Lahore aquifer since the first day of development. The groundwater level of the city has decreased due to population growth, while recharge to aquifer became very low after reduced flows in Ravi River on the Indian side. Lahore city's wastewater is also disposed in the Ravi River.

Sami (2001) and Afzal *et al.,* (2000) reported that pollution of the Ravi River is also contributed by Hudiara drain. It has a part in India of 44.2 km and another in

Pakistan of 54.4 km which makes total length as 98.6 km. The average contaminants from the Hudiara drain are greater from Indian side (Sami, 2001).

2.9 GROUNDWATER RECHARGE

Key source of water for drinking is groundwater which is recharged through the seepage of river, rainfall and agricultural fields. Recharge estimation from water bodies is a difficult method and no considerable research has ever been carried out in Pakistan. In main city areas, because of development of large scale infrastructures and no provision of recharge to groundwater, groundwater recharge is insignificant. Various methods have been established for groundwater recharge. Seepage is estimated up to a percentage of the available water volume either in canals or distributaries.

In order to prepare a master plan for drainage, WAPDA conducted a study in year 2005 to determine groundwater recharge for various sources. This study depicted seepage losses from canals and distributaries 15% and 8% of these total flows respectively. It was further determined that the aquifer recharge is made through the contribution of 75% seepage losses. No research has been conducted to determine the groundwater recharge for the river Ravi so as an approximation, River Ravi recharge can be taken as equal to the main canals. This method of recharge assessment for river Ravi appears appropriate as the mostly canals are not lined and flow rate capacity is up to 30 Mm^3 per day.

Rainfall is another source of groundwater recharge and studies show variation between 10 to 25% recharge depending on location and intensity. In populated areas the land is occupied by the infrastructure such as roads and buildings, so recharge is about 10% of the total rainfall. However in agriculture areas recharge comes out to be 25%.The remaining water is utilized as a run off or either it evaporates. In Lahore rainfall is sufficient for the groundwater recharge to the aquifer but due to paved areas groundwater recharge is not possible and water is lost through run off. Out of these total rainfall only 10 to 24% is recharged in irrigated agricultural areas (Basharat and Tariq, 2011). Providing favorable situations for groundwater recharge, 1/4th of the rainfall can be utilized for recharge. Groundwater table depth can be maintained from declining by making the providing places for recharge in parks, around roads and public infrastructure. (Sheikh, 1971).Total groundwater recharge for all sources comes out to be 6.50 Mm^3/day. Rainfall and irrigation canals only contribute for 11% groundwater recharge whereas river Ravi contribute 82% of the recharge to groundwater.

It clearly indicates the improvements of river Ravi in maintaining the groundwater depth for Lahore aquifer. The increased recharge values from this river are valuable for Lahore aquifer but the flow would reduce the downstream side due to more utilization of groundwater. River Ravi water is becoming contaminated due to mixing of wastewater without any treatment which is causing serious problem for the downstream water users. The enormous contribution of this river in groundwater recharge of Lahore aquifer presents that untreated waste water should not discharged into river Ravi which can cause serious concern for millions of the people those utilize groundwater as the major source of drinking water. Recharge to groundwater from various sources in given in Table 2.9.

Table 2.9 Recharge to groundwater from various Sources (Qureshi, A. S., 2014)

Water Source	Water Volume		Recharge to Groundwater		
	Available	Infiltration	From Water Source		
	mm^3/day	mm^3/day	mm^3/day	mm^3/year	%
Ravi River	47	7.07	5.31	1938	82.01
Distributaries	5.18	0.414	0.311	114	4.82
Canals	0.84	0.126	0.095	35	1.48
Rainfall (urban area)	2.44	0.24	0.12	44	1.86
Rainfall (non-urban area)	1.02	0.51	0.225	82	3.47
Return from Agriculture Groundwater use	-	-	0.41	150	6.35
Total Recharge to Groundwater			**6.5**	**2363**	**100**

2.10 GROUNDWATER FLOW AND GROUNDWATER MODELS

Groundwater moves very slowly in the pores of the subterranean layers relative to flow on the surface. If water is dispersed over the entire aquifer thickness, it is called the groundwater. It is known as perched water when it exists in the layers of subsurface hard strata. Different ways of enhancing groundwater are recharging through precipitation and increased irrigation applications, leaks from rivers, lakes, channel beds, water pipes. The pumpage takes out water from wells that withdraw water from the underground reservoir in some places. The collective influence of recharge, leakage, groundwater influx and withdrawals in the model provides the time variant groundwater elevations. Lateral groundwater flows (inflows and outflows) come from the system which depend on the model boundary conditions (Kumar, 2000).

Kumar (2006a) stated that mathematical equations are used in groundwater modelling. Groundwater models are used to visualize groundwater based on partial differential equations that may involve uncertainties related to data availability. Such kind of models create a simplified picture of actuality instead of being imitation of the aquifer system.

Models related to groundwater are classified into the categories which includes conceptual, mathematical, analog, and physical models. Statistical model solves the underground flow problems with the use of differential equations representing the physical phenomenon which happens in aquifer system. They can be represented by either numerical or analytical model. The numerical model is complex and provides a discrete solution. On the other hand, analytical model is relatively simple and gives a continuous solution for the entire model area. Due to assumption of a simplification of homogeneity, isotropy, geometry, initial conditions, etc., flexibility of analytical modeling is limited. In-depth information about analytical modelling can be seen in Bear (1979), van Genuchten and Alves (1982) and Walton (1989).

The flow problems relevant to groundwater can be solved by first assigning the initial and boundary conditions which will help ultimately to get solution of governing partial differential equations. For solving the problems of groundwater flow, four main approaches are the following:

1. Analytical method
2. Graphical method
3. Analogical method
4. Numerical method

Each method gives the solution in form of variables. These variables depend on partial differential equation, and are commonly in the form of a potentiometric levels i.e. h at any point, with at any time in flow domain boundary. The kind of numerical model be influenced by the numerical technique used to get solution of these models. Finite difference models i.e. MODFLOW, and finite element models i.e. SUTRA are used mostly these days (Tariq, 2008).

Model to study groundwater flow are based on two main equations which are Darcy equation i.e. Eq. 2.1, and groundwater balance equation i.e. Eq.2.2. With combining these two equations, a partial differential equation is made. In order to solve these equations, finite difference or finite element method is adopted which requires the division of the area into finite intervals called as cells. Algebraic equations can be added unlike of partial differential equations. As a consequence, the model area is discretized into properly sized cells depending on model domain size as well as data type availability to formulate model (Tariq, 2008).

$$\mathrm{Q} = \mathrm{K\,i\,A} \tag{0.1}$$

Where K denotes hydraulic conductivity of soil strata, i denotes hydraulic gradient, A represents area of soil mass from which flow occurs.

Water balance equation of groundwater model considering a distinct time step can be shown as,

$$\mathrm{Rr} + \mathrm{Rc} + \mathrm{Ri} + \mathrm{Si} + \mathrm{Ig} = \mathrm{Et} + \mathrm{Tp} + \mathrm{Se} + \mathrm{Og} + \Delta\mathrm{S} \tag{0.2}$$

Variables in equation 2.2 can be represented as;

Rr is rainfall recharge, Rc is recharge from canal bed, Ri is recharge due to irrigation applications, Si & Se denotes influent & effluent seepage occurring due to natural streams, Ig & Og are sub surface flows coming in and out to adjacent basins, Et is evapotranspiration losses, Tp is abstraction from groundwater, ΔS is change in storage in groundwater.

All above parameters are in volumetric units.

2.11 UNCERTAINTY IN GROUNDWATER MODELING

Rojas *et al.,* (2008) showed that accurate and reliable prediction of groundwater flow has become critical to sustainable groundwater management practices due to declining groundwater resources. Singh *et al.* (2010) showed that uncertainty in modeling could result from lack of familiarity about complex natural system variations within the subsurface.

Modeling uncertainty can be of following categories:

Conceptual

Parametric

Stochastic uncertainty.

Modelling uncertainty in groundwater modeling is presented in the Figure 2.7.

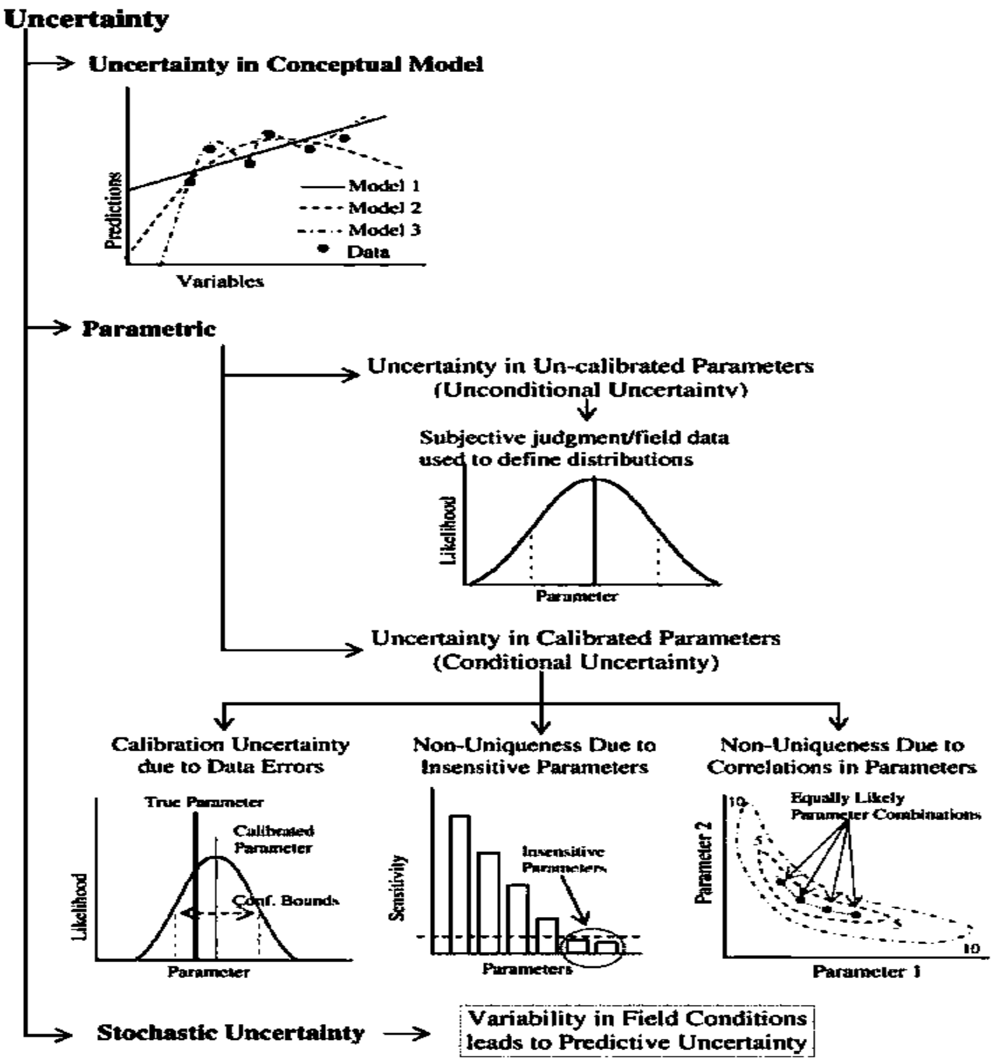

Figure 2.7 Types of uncertainty in groundwater modelling (Singh et al., 2010)

2.12 GROUNDWATER STUDIES CARRIED OUT IN PAST

Groundwater Cell (GWC) of Lahore Development Authority (LDA) formerly known as Lahore Improvement Trust (LIT) had issued 8 reports regarding operating the tube wells and their performance in the Lahore during 1973. Reports No. 4 and 6 had the estimate for withdrawals from groundwater and recharge to groundwater respectively for the 1973's historical flood.

NESPAK (1986) critically studied the Lahore water supply system which includes design of well and water distribution system as well as preliminary evaluation of the aquifer and the groundwater response due to growing abstraction rates.

In 1988, a groundwater resource assessment study of Lahore Aquifer was done by Binnie and Partners and NESPAK. They established a computer numerical model i.e. MODFLOW of the Lahore region. Ravi River was taken as western boundary for the model. Model was calibrated and then it was used to check the influence of future water managing policies on the Lahore aquifer which comprised of setting up of new wells to encounter upcoming water demands, the consequence of the planned sewage lagoon ponds in southern side of Lahore, and mainly the Thein Dam i.e. Ranjit Sagar Dam construction on upstream side of Lahore which would result in reduction of the flow in the Ravi River. In order to make the model more accurate and to include the area laying west of the Ravi River, it was suggested to increase the model domain area i.e. 30 km x 37 km = 1110 km^2 (NESPAK, 1991).

Arshad *et al.*, (2009) revealed that groundwater has long been used in the development of irrigated agriculture which resulted in rapid increase of pumping wells in the Indus Basin oh Pakistan. He did model simulation by MODFLOW for an irrigation canal in Punjab, Pakistan for infiltration into the groundwater under different scenarios like crop, land and water application for time dependent data. Due to average flow of 106 m^3/s, the average monthly rate of seepage for the canal was estimated as 12.10 m^3/s/million-m^2.

Amir (2012) demonstrated the relation of groundwater between Ravi River aquifer and aquifer of Lahore. The site was located nearby the new Shahdara Bridge and downstream of Shad-Bagh waste disposal. At two transacts, the flow interaction was assessed. Peizometric data of groundwater, river water level data and water quality data were collected from 14th November, 2007 to 8th June, 2008 to see the phreatic surface profile from river to the aquifer, river stage data and hydraulic-heads. MODFLOW numerical model development resulted that Ravi River was acting as an infiltrating water source all over the year as profile of the water table of the Ravi River was in the direction of the Lahore city. Water transfer amount from the Ravi River to the neighboring aquifer came out to be 0.041 m^3 per second per kilometer of Ravi River length which meant 1.845 m^3 per second for a 45 kilometers length of Ravi River adjacent to Lahore.

Afzal (2013) did analysis on Lahore groundwater system by using MODFLOW numerical model. For period of 10 years from 2000 to 2009, model was calibrated and validated, and then simulation was carried out for the next 20 years on basis of these calibrated and validated duration. It was assumed that groundwater abstractions are continuously increasing for the simulations period. While recharge of the aquifer more or less is constant. The increasing gap between recharge and abstraction provides threat to the groundwater aquifer system. Based on these groundwater withdrawals, the groundwater is decreasing at a critical rate of 1.27 m/year. This extreme groundwater abstractions making Lahore aquifer unsustainable.
Aher *et al.* (2015) studied concept of recharge trench cum recharge at Aurangabad as shown in adjoining figure. In the considered area where source water was having silt, the shaft was filled with boulders, gravels and sand to make an inverted filter. After

water budgeting, it was observed that the shortage of water reaches about 31680 lit/day. The drinking water requirement of the village was 43680 lit/day and now drinking water availability is 43682 lit/day.

Missimer *et al.* (2015) critically studied the groundwater on MODFLOW model to assess the potential usage of existing as well as abandoned larger diameter wells which were operating the alluvial wadi aquifer system. The model was made to estimate the possible injection rate of water into the wells and to assess the potential for storage in the aquifer. Modeling results showed that existing wells, under gravity feed conditions could store up to 1000 m^3 per day and with well filling to produce a pressurized system could store up to 3,900 m^3 per day.

Chen *et al.* (2016) conducted a study on groundwater simulation for effective water resources management in northwestern China. For efficient management of water resources, Visual MODFLOW has been used. Based on the results, it was concluded that groundwater levels were decreasing at the rate of 1 m per year in irrigated areas and 0.2 m per year in non-irrigated areas. It was also concluded that the annual groundwater budget for the Zhangye Oasis was -7.64 x 108 m^3.

Patel *et al.* (2018), in the city of Surat, India, did a comparative analysis for the cost estimation of the storm water drainage system with as well as without recharging wells, considering the benefits of a new urban area. Two types of stormwater drainage system i.e. conventional stormwater drainage system (without groundwater recharging wells) and stormwater drainage system with groundwater recharging wells were used. He summarized the conclusion in terms of benefits of

25.43% comparing to a conventional stormwater drainage system and this had also enhanced the quality & quantity of groundwater with an elevated groundwater table. Lastly, the economic analysis was carried out for both types of drainage systems, with the conclusion of groundwater recharging wells having diameter as 20 cm.

Page *et al.* (2018) studied the use of managed aquifer recharge (MAR) as a method for sustainable urban water management. MAR offers an approach for recycling of underused urban storm water as well as treated wastewater to increase their water resource potential, and to reduce the adverse effects related to their disposal. Figure below illustrates different MAR techniques. One of these typically includes shallow wells with very deep groundwater in unconfined aquifer which allows good quality water to infiltrate. Different MAR techniques are shown in Figure 2.8.

Glass *et al.* (2018) established and calibrated a transient groundwater flow model i.e. MODFLOW for Hanoi, Vietnam for understanding the local groundwater flow system and to suggest way out for the sustainable water resources management. The results proposed to relocate the wells from the main depression cones and to extend the bank filtration to halt the local overexploitation.

Irshad (2018) made the MODFLOW groundwater model for assessing the groundwater depletion rate of Lahore which was 0.96 m per year for 2005-2015 and it is and will be 1.03 m per year (0.82 m per year for UET Area) for 2016-2020. The model was used to calculate water table which was found to be 186m to 215m for 2015 and will be 160m to 210m for 2035.

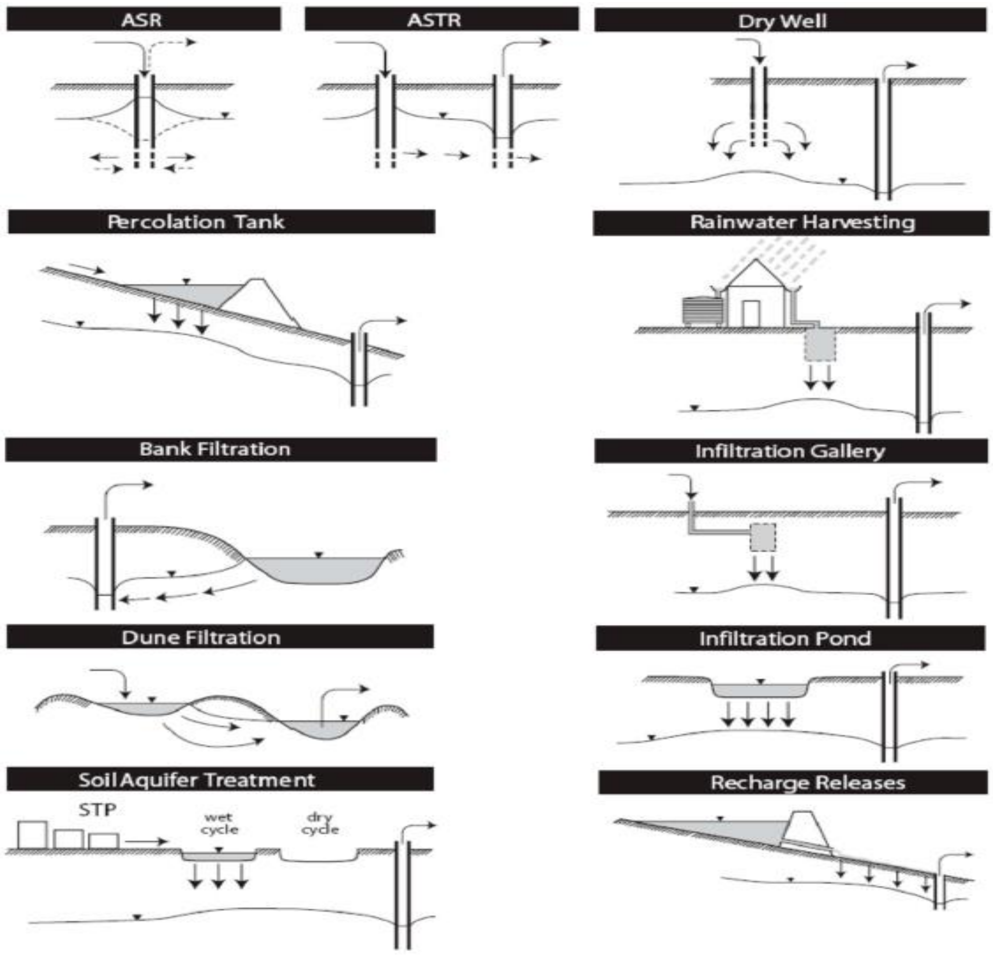

Figure 2.8 Different Managed Aquifer Recharge (MAR) Techniques (Page et al. 2018)

Four recharging wells (each of 15 ft dia. & 30 ft depth) have been constructed in Junaid Jamshed Cricket Stadium, UET Lahore for groundwater recharge on July, 2018 (Asian Consulting Engineers Pvt. Ltd., 2018). Each recharging well is constructed at each corner of the stadium. Drainage layout Plan is shown in the Figure 2.9 which includes runoff collection in mini catchments represented by yellow color, runoff diversion from mini catchments to four sumps shown by light green color and ultimate disposal to four recharging wells shown with orange color. Construction of recharging well, mini catchments for runoff collection and sump for desiltation of runoff before entering into recharging wells can be seen in the Figures 2.10, 2.11 and 2.12 respectively.

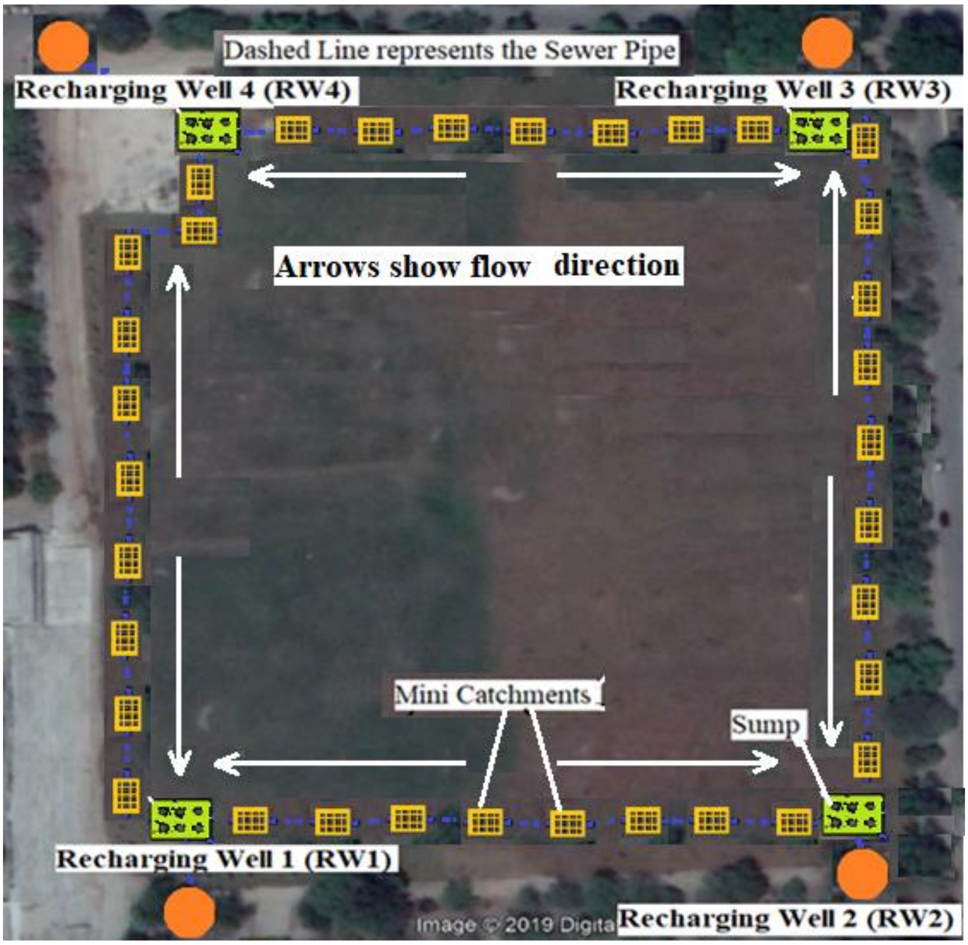

Figure 2.9 Junaid Jamshed Cricket Stadium Drainage Layout Plan

Figure 2.10 Recharging Well Wall during Construction

Figure 2.11 Mini Catchment Pit for Runoff Collection

Figure 2.12 Sump for Desiltation

2.13 SUMMARY

The chapter deliberated the significance of groundwater and its usage throughout the globe. It discussed the situation of sub-continent's groundwater, its consumption in every walk of life and the shortages of fresh groundwater due to its over-abstraction. It gives a clear idea of the freshwater situation in Pakistan and its provinces. It also focused on managing the storm water by different techniques mainly by recharging wells for its effective use and groundwater resources preservation. The chapter can be concluded:

Globally, freshwater represents only 2.5% which is 1386 million km^3 (1,123,641,962 MAF) and humans can use almost $1/3^{rd}$ of this water. Humans use more than half of the useful freshwater supplies which includes surface and subsurface. Maximum of the Globe's freshwater is present in reservoirs laying underground, which makes more than 98% reserves of freshwater on earth.

In Pakistan, Indus Basin brings 190 Bm^3 (154 MAF) of water per annum on an average. Another source of surface water is hill torrents in the mountainous areas of the country with a total potential of about 19 MAF. Unconfined aquifer of Indus basin from its mountainous north to plain south has a potential of almost 50 MAF while in Baluchistan it is almost 1 MAF.

In Lahore, 6.02 Mm^3 (48.8 x 10^{-4} MAF) per day is the surface water that is diverted to the city. Groundwater of city is depleting excessively due to the reason that Lahore gets almost all water for its use through groundwater abstraction.

World's combined groundwater abstraction as per 2010 estimate was assessed to be roughly 1000 km^3 (810.71 MAF) per year, of which approximately 67% was utilized for irrigation, 22% for domestic uses and 11% for industrial uses. While for Pakistan, groundwater potential is being misused to 38.5 MAF out of 51 MAF.

In Lahore, groundwater usage as per 2014 estimate came out to be 2619 Mm^3 (2.12 MAF) per year while recharge was 2363 Mm^3 (1.91 MAF) per year. Out of total groundwater usage, 53% is domestic, 24% is agricultural, 13% is industrial and 10% is commercial & institutional.

There are many suitable means to recharge groundwater by rainfall harvesting i.e. infiltration galleries, infiltration ponds and recharging wells or through river recharge techniques i.e. delay action dams, bank filtration and trench cum recharging wells. One of them is construction of larger diameter recharging wells. All such techniques are suitable for aquifer recharge in Pakistan as well as in Lahore.

So, UET Lahore in collaboration with LDA had installed four recharging wells in Junaid Jamshed Cricket stadium. Hence, there was a dire need to investigate impact of these four recharging wells on local groundwater recharge rate through monitoring and modelling.

Chapter III
METHODOLOGY

3.1 INTRODUCTION

This chapter describes the methodology that has been followed to attain the objectives of the current study which includes illustration for data collection, data analysis, installation of equipment to monitor the recharging wells and step by step procedure to formulate groundwater numerical model to calculate depletion rate before and after installing recharging wells in the study area.

3.2 INTEGRATION OF WORKING ACTIVITIES

The methodology of the research consists of the various inter connected activities. Several activities were running parallel to the each other while others are dependent to its predecessors.

The study consists of four main components which includes data collection from different sources, data analysis, installation of equipment to monitor the recharging well i.e. a flowmeter & two piezometers and assessment of groundwater table position using Visual MODFLOW to assess the depletion rates for both the cases i.e. without recharging wells and with recharging wells. Then groundwater model was calibrated and validated for each case to make it more relevant to actual conditions.

The methodology to achieve the objectives is presented in Flow diagram shown in Figure 3.1.

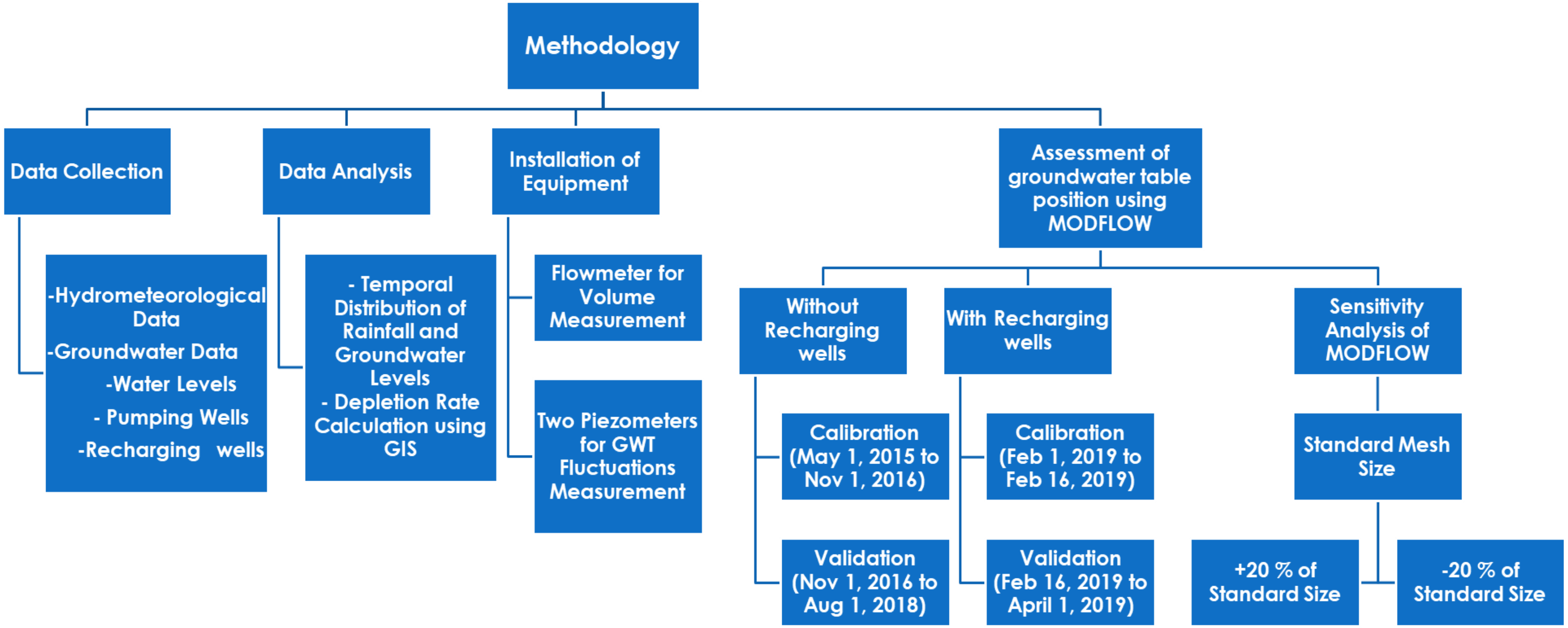

Figure 3.1 Flow diagram expressing the Methodology

The study consists of four main components; data collection, data analysis, installation of equipment and model setup.

3.3 DATA COLLECTION

For the study, data were collected from different sources for required durations is given in Table 3.1.

Table 3.1 Collected Data with Durations and Sources

Sr. No.	Data Type	Duration	Source
1	Topographical data	Accessed on May 1, 2018	Google Earth
2	Bore log data (i.e. Aquifer Thickness, Hydraulic Conductivity etc.)	1967, 1991	WAPDA, NESPAK
3	Daily Precipitation data	May, 2015 to March,2019	PMD Lahore
4	Piezometeric data	2015 to 2018 & Feb 1 to April 1, 2019	WASA & UET Lahore
5	Pumping Well data	2015 to 2018 & Feb 1 to April 1, 2019	WASA & UET Lahore

3.4 DATA ANALYSIS

After data collection, temporal distributions of data were plotted as shown in Figures 3.2 and 3.3. In Figure 3.2, there was continuous drop in seasonal water levels with the passage of time from May 1, 2015 to August 1, 2018 due to excessive groundwater pumpage and less groundwater recharge because of increase in impermeable areas. It was also evident that excessive rainfalls decreased the groundwater depletion rate till November 1, 2017 but after this time there was increased depletion rate as there were very small rainfalls. Similarly, groundwater level fluctuated due to each rainfall event as shown in Figure 3.3. It was increased after each rainfall event due to groundwater recharge through recharging wells.

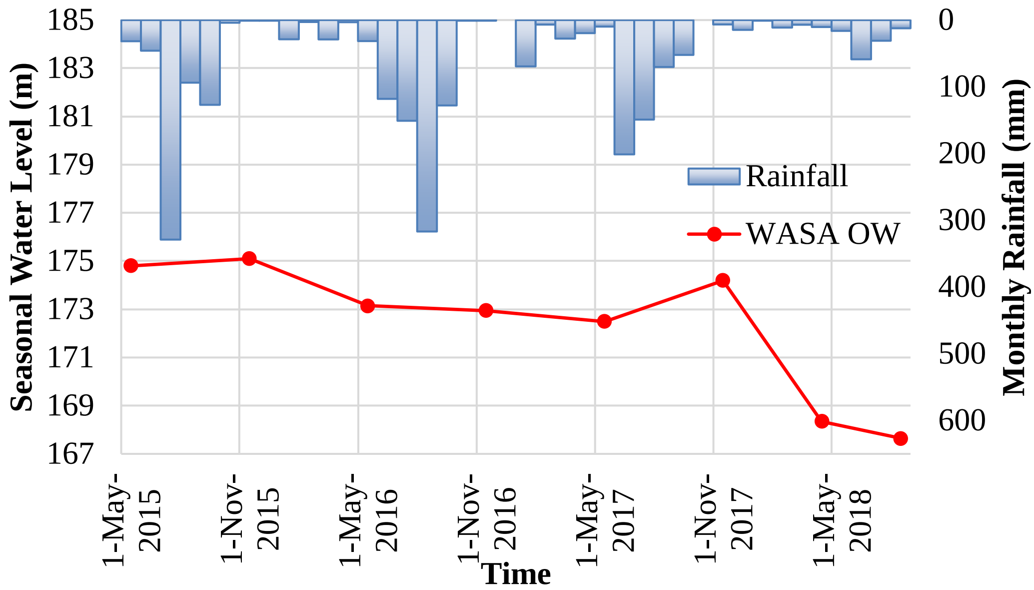

Figure 3.2 Temporal Distribution of Rainfall and Groundwater Levels data (observed *by WASA)*

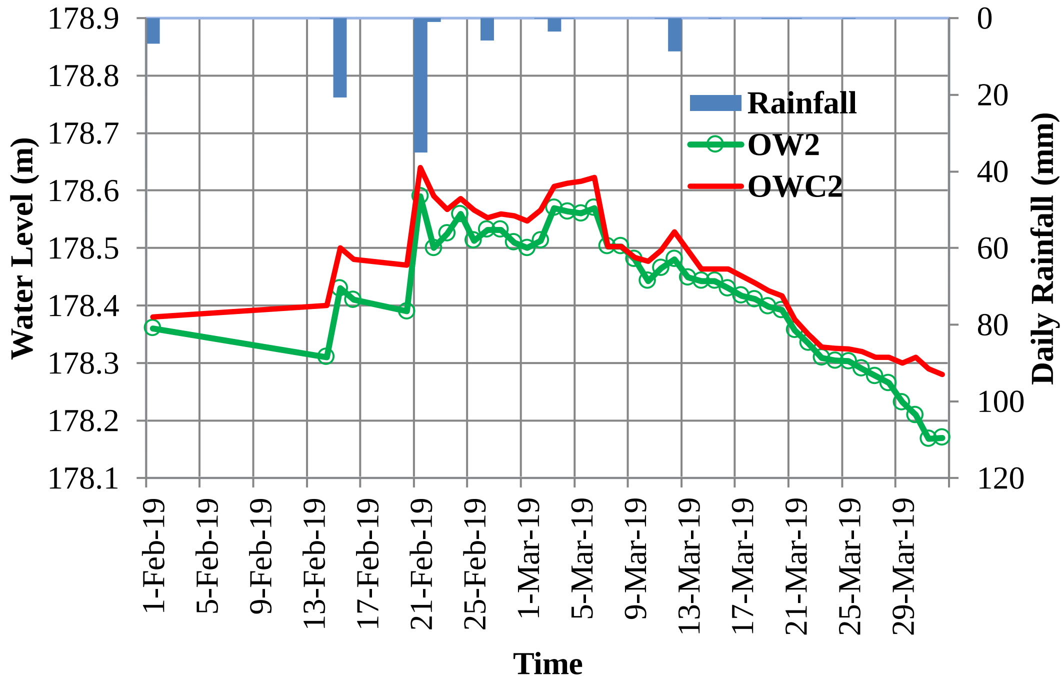

Figure 3.3 Temporal Distribution of Rainfall and Groundwater Levels data (observed in present study).

GIS was used to obtain water table elevation contour maps of each season for above mentioned duration by using piezometric data observed by WASA and me in UET. Some of them are shown in Figures 3.4 through Figure 3.7.

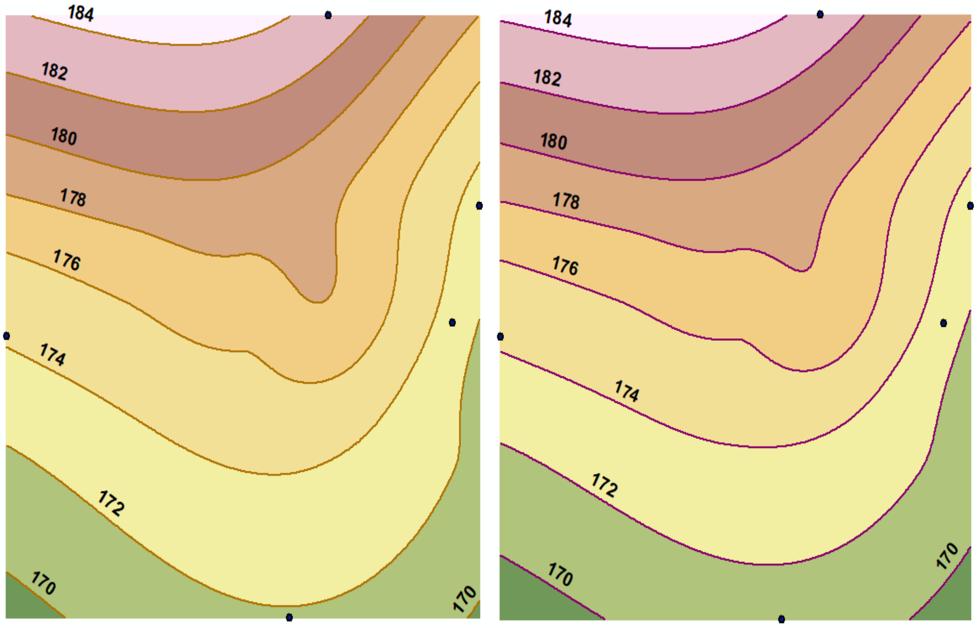

Figure 3.4 Water Table Elevation Contours for Summer (1st May, 2016 and 1st Nov, 2016)

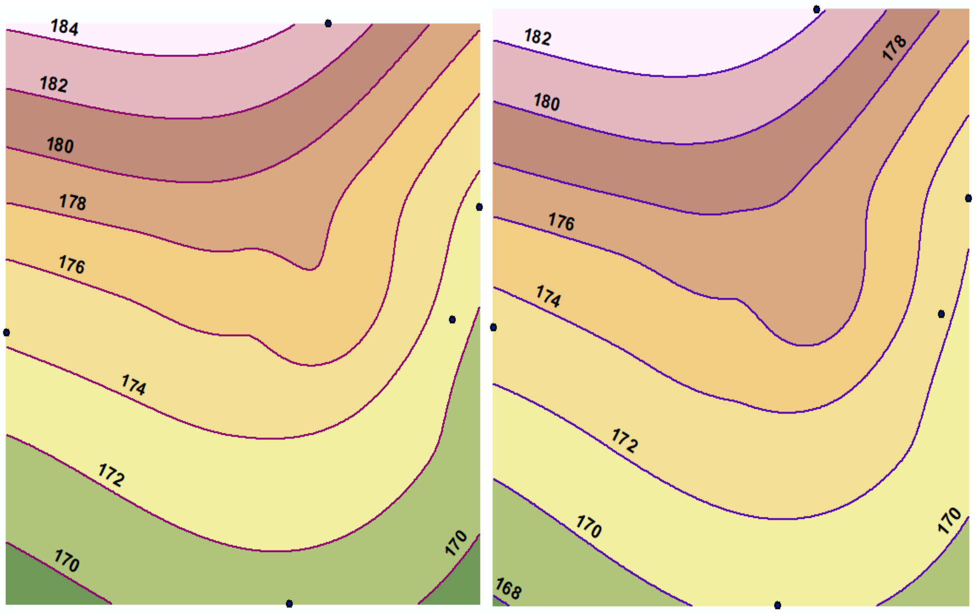

Figure 3.5 Water Table Elevation Contours for Winter (1st Nov, 2016 and 1st May, 2017)

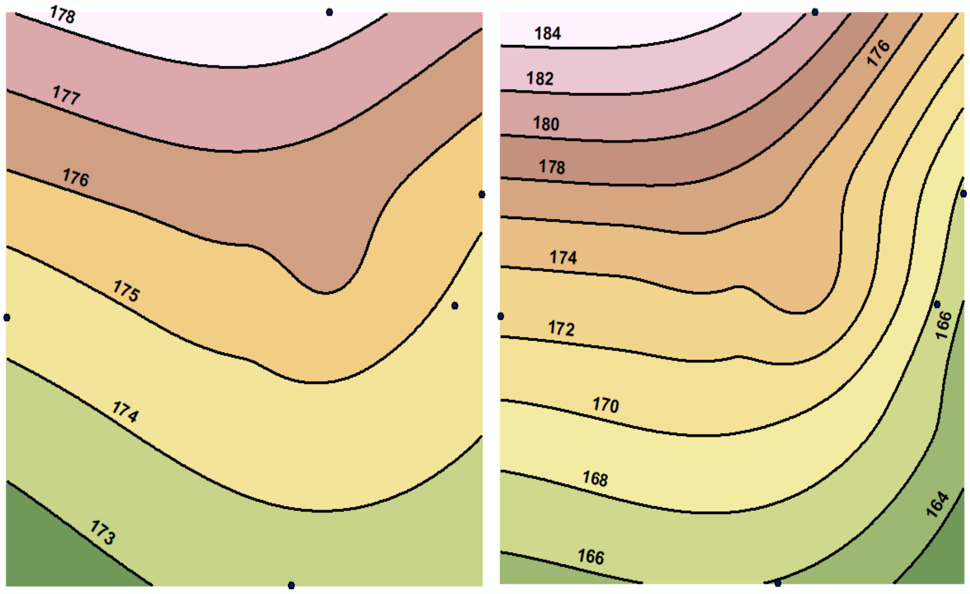

Figure 3.6 Water Table Elevation Contours for Annual
(1st May, 2015 and 1st Aug, 2018)

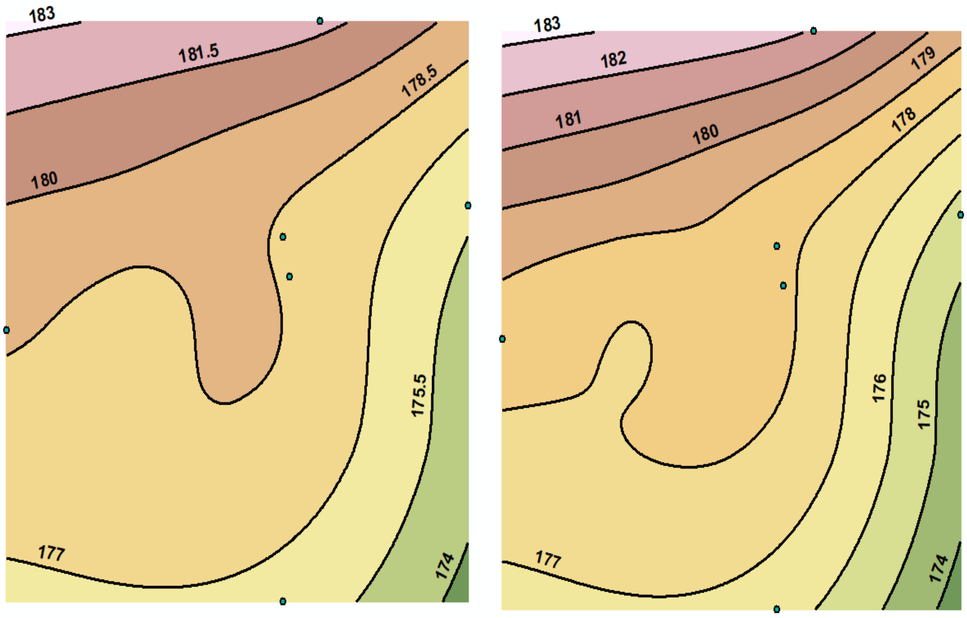

Figure 3.7 Water Table Elevation Contours for Winter
(1st Feb, 2019 and 1st April, 2019)

From Figures 3.4 through 3.7, it was clear that water table elevation was increased after each summer season due to monsoon rainfalls which helped in reducing depletion rate. Water table elevation was decreased after each winter due to very less rainfalls in winters.

Average depth for each contour map was calculated by isohyetal method which was used to calculate depletion rate. So, for the case of without recharging wells, corresponding average depletion rates for winter, summer and annual were obtained as 0.84 m per winter season, -0.08 m per summer season and 0.68 m per year respectively for duration of 1^{st} May, 2015 to 1^{st} August, 2018. For the case of with recharging wells, average depletion rate for winter was 0.45 m per winter season on the basis of two months data.

3.5 INSTALLATION OF EQUIPMENT

Layout of Junaid Jamshed Cricket Stadium is shown in Figure 3.8 where four recharging wells labelled as RW1, RW2, RW3 and RW4 are shown. Two piezometers labelled as OW2 and OWc2 in Figure 3.9, each of 150 feet depth and 2 inch diameter, were also installed on February, 2019 to monitor groundwater behavior due to recharge. One of them (OW2) was installed adjacent to RW2 and the other one (OWc2) was at center of RW2 and RW3. After their installation, their reduce levels were found out by shifting of reduce level from bench mark at Annexe block UET as shown in Figure 3.10.

To monitor the working of recharging wells, one of them (i.e. RW2) was equipped with a flowmeter on May 30, 2019 to note the amount of volume gone in the recharging well after each rainfall event. Flowmeter can measure maximum volume of 1 Mm^3. Installation of flowmeter is shown in Figure 3.11 (b) where 8 inches diameter flowmeter was fixed in 9 inches diameter pipe which connects sump with the recharging well.

Figure 3.8 Layout of Junaid Jamshed Cricket Stadium showing installed two Piezometers

Figure 3.9 Piezometer installation in Junaid Jamshed Cricket Stadium, UET

Figure 3.10 Shifting of Reduce Level from Annexe Block to Piezometers in Junaid Jamshed Cricket Stadium, UET

(a) Flowmeter Dial

(b)

Figure 3.11 (a) Flowmeter Dial and (b) Flowmeter and its installation in Sump in Junaid Jamshed Cricket Stadium, UET

3.6 SETTING UP OF VISUAL MODFLOW

In this section groundwater flow model formulation for UET Lahore area aquifer will be carried out for both, before and after construction of recharging wells using Visual MODFLOW 2011.

3.6.1 Model Domain

The model consists of an area of aquifer as 1.5 km x 1.5 km (2.25 km^2). The domain to be modelled comprises of the area of UET Lahore. Study area being modelled is shown in the Figure 3.12. The boundaries of model are assigned in the Universal Transverse Mercator (UTM) co-ordinate system. The model domain consists of one layer having thickness of 400 m. The area is being simulated with grid spacing of 30 x 30 m resolution. Model grid layout consists of 70 rows and 70 columns (Figure 3.12), after this surface elevations were imported as shown in Figure 3.13.

Geographic Boundaries for the model

X1 (minimum coordinate) (m)	438109	X2 (minimum coordinate) (m)	439495
Y1 (maximum coordinate) (m)	3493410	Y2 (maximum coordinate) (m)	3494800

3.6.2 Boundaries of the Model Area

Numerous assumptions cited by the investigators to calculate the groundwater recharge from the rainfall showed that it can be taken as 20% of total annual precipitation. Considering this assumption, 20% of the annual rainfall directly recharges the model area, which came to 157 mm per year for my study area. As shown in Figure 3.14, boundaries with variable height for each stress period were assigned for all sides in the model.

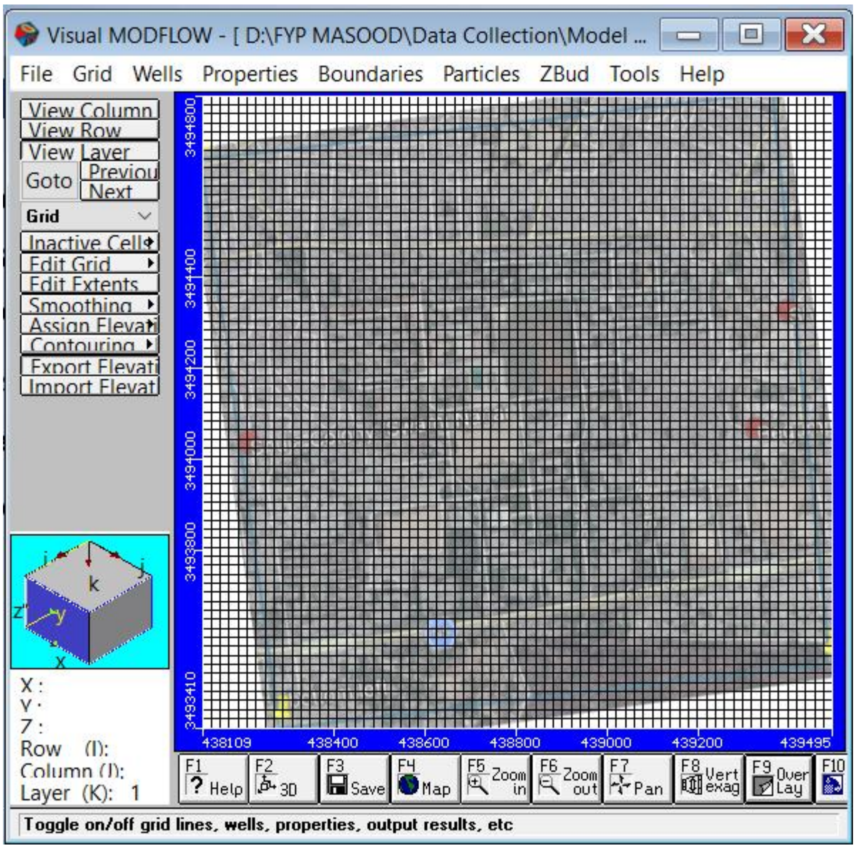

Figure 3.12 Model Grid Layout

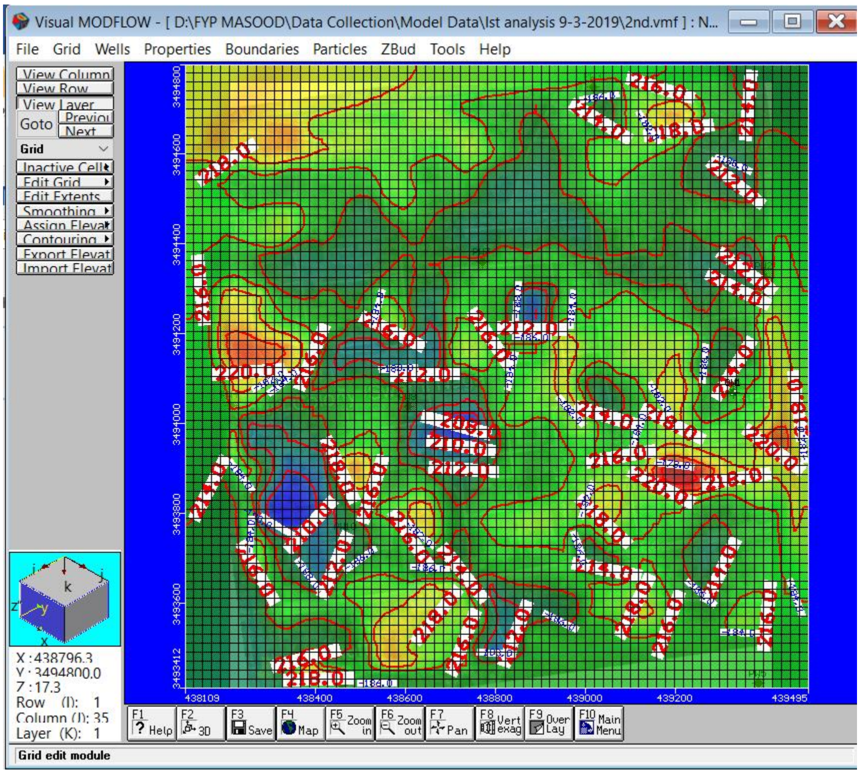

Figure 3.13 Model Layout Showing Surface Elevations

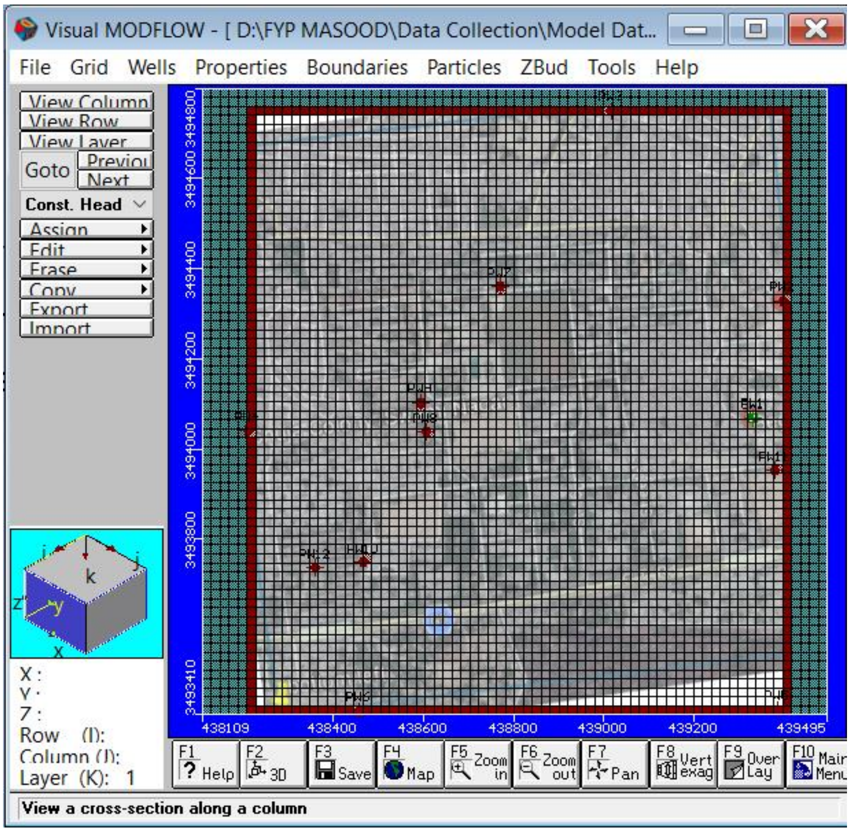

Figure 3.14 Model layout showing Boundaries around Model Domain

3.6.3 Aquifer Parameters

The average hydraulic conductivity, storage, porosity of aquifer is necessary to define for each cell. A list of conductivity values defined for Lahore area by several agencies or researchers is given in Table 3.2. Hydraulic conductivity under current study after calibration came out to be 38 m/day.

Table 3.2 Conductivity values for Lahore area

Author	**Hydraulic Conductivity (m/day)**
Greenman *et al.* (1963)	26.3
Bhatti (1969)	22
CDM (1975)	71
Revised CDM	42
NESPAK (1991)	19 – 33
This Study (used value)	38

3.6.4 Abstraction from Study Area

To develop the well package in the model (Figure 3.15), groundwater abstraction data of the following agencies/ societies was used:

i. Water & Sanitation Agency (WASA) Lahore

ii. University of Engineering and Technology (UET), Lahore

Twelve pumping wells were added in the model, seven of them were installed by WASA and five of them were installed by UET. Discharge was calculated on basis of pumping capacity and daily pumping hours. Daily pumping hours were taken as 8 to 12 during winters and 14 to 18 during summers after obtaining data from WASA, UET and local surveys.

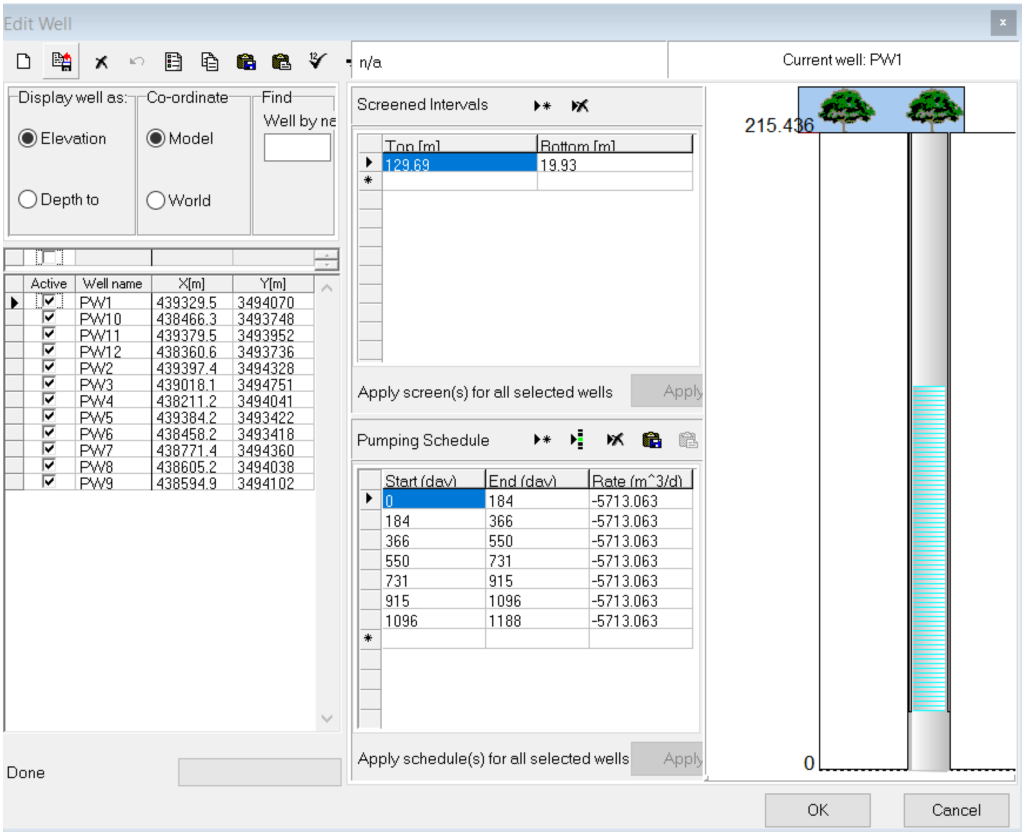

Figure 3.15 Model Input for Pumping wells

3.6.5 Volume Calculation for Recharging Wells

Runoff depth to calculate volume for each recharging well was calculated using SCS Curve Number method. Hydrologic Soil group was taken as C (slow infiltration rates) *(SCS County Soil Survey Reports)*. Based on Group C and Land Use; Fair condition, grass cover over 50% to 75%, SCS Curve No. was selected as 78 *(US Soil Conservation Service, 1975)*.

Following formulae were used to calculate runoff.

$$S_{max}\ (cm) = \frac{2540}{CN} - 25.4 \qquad (3.1)$$

$$R_S = \frac{[P - 0.2S_{max}]^2}{[P + 0.8S_{max}]} \text{ for all } P > I_a.\ \text{ELSE } R = 0 \qquad (3.2)$$

Where S_{max} is maximum surface retention, CN is Curve number, P is rainfall, I_a is initial abstraction and R is runoff.

Runoff volumes produced from two major rainfall events which occurred on Febrauary 15 and 21, 2019 were calculated as 4.73 and 42.43 m^3. All other rainfall events from February 1 to April 1, 2019 did not contribute to runoff.

Table 3.3 Runoff volume calculation for recharging wells

Parameter	**Value**		**Unit**
Curve No.	78		
S_{max}	7.16		cm
$I_a = 0.2\ S_{max}$	1.43		cm
Date of Rainfall	Feb 15, 2019	Feb 21, 2019	
Rainfall (P)	2.07	3.51	cm
Runoff (R_S)	0.05	0.46	cm

Area of Stadium	36350	36350	m^2
Volume of Runoff	18.91	169.71	m^3
1/4th Volume of Runoff = Volume for one Recharging well	4.73	42.43	m^3
Volume of Recharging well	150.23	150.23	m^3
Percentage filled of Recharging well	3.14	28.24	%

So, recharge to four wells were 4.73 and 42.43 m^3 per day for both events respectively.

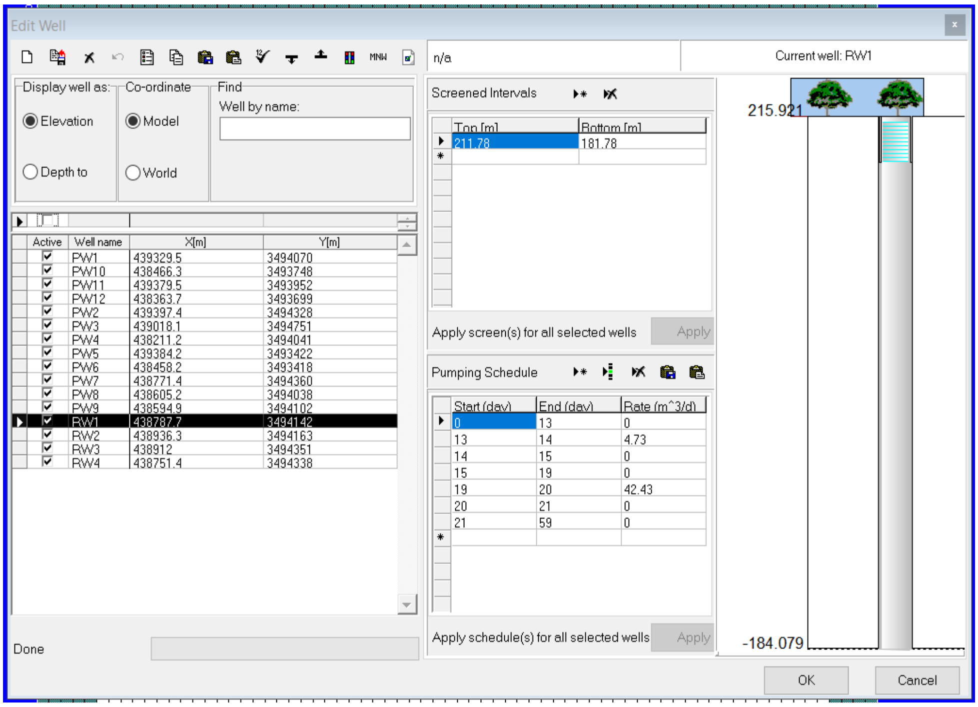

Figure 3.16 Model Input for Recharging wells

3.6.6 Calibration and Validation Period, Time Step and Units for Model without Recharging wells

The choice of calibration duration depends on the extent of data availability and historical groundwater conditions in the study area. As for as the availability of data is concerned, the data of observation well that is being used, is of WASA tube wells static water levels. Only one observation well comes in the jurisdiction of study area and the data of almost 3.5 years has been used which was divided into seven stress periods. Each stress period consists of each season i.e. summer, winter. Therefore the selected calibration period covers the 1.5 years period (three stress periods) i.e. from May 1, 2015 to Nov 1, 2016. Stress period also depends on the availability of the data.

Actually, stress period is the period in which recharging and discharging constituents remains constant within the model. The model has the facility for sub-dividing each stress period into several time steps to give a minimal increase in computational accuracy. Trial simulations of model area were made at 1 day time step & 1 hour time steps. It was found that no appreciable difference in results was observed, therefore the each stress periods was divided into ten time steps for further simulations as convergence of results is achieved & computational time is less. Any set of units can be used in the Visual MODFLOW. For the current study, metric system was adopted.

3.6.6.1 Model Calibration

For the model configuration, calibration is a significant step as this exercise makes the model equivalent to the real aquifer. The WASA observation well was used to calibrate the model. The acceptable error range between the simulated and observed groundwater tables depends on the required accuracy. Trial and error method was used until the calculated results matched those measured for the calibration of the groundwater model.

Model was calibrated by changing several parameters during the calibration process. Hydraulic conductivity and storage values were altered in different ranges for model calibration. During calibration, it was seen that the model was not sensitive to the thickness of the layer; the value of 400 m was thus taken for the model. The graph between the calculated head and the observed head has been plotted to show the applicability of the aquifer system. The heads observed in an observation well were calibrated by modifying the input parameters. The calibration graphs are shown in Figures 3.17, 3.18 and 3.19. From each of them, it is clear that model was well calibrated for each stress period as root mean squared values came as 0.08 m, 0.046 m and 0.257 m respectively which were very near to zero, this gave the clear indication about very good relationship between calculated and observed head values.

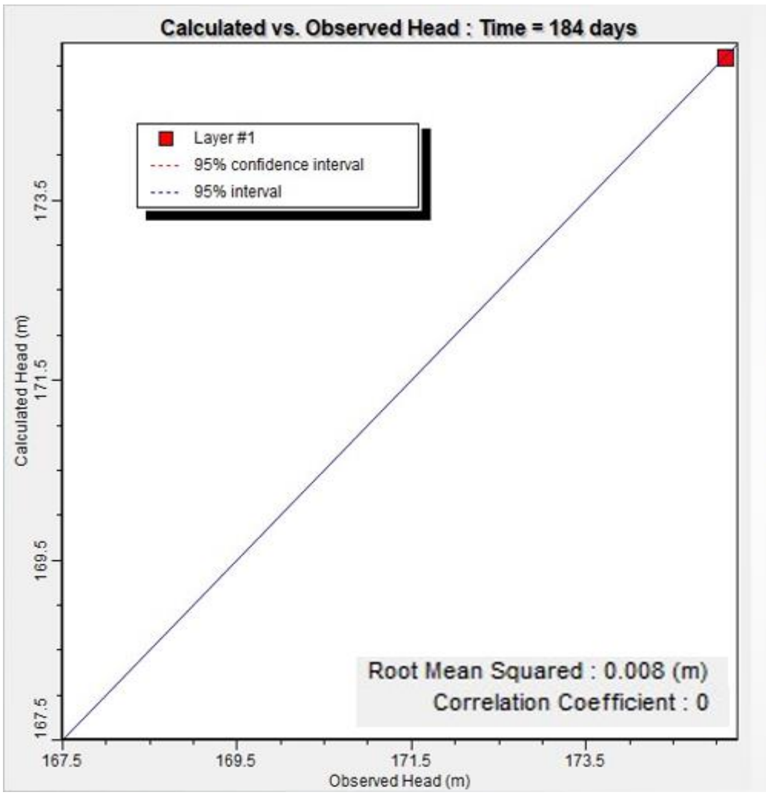

Figure 3.17 Calibration of the model for the stress period 1st Nov, 2015

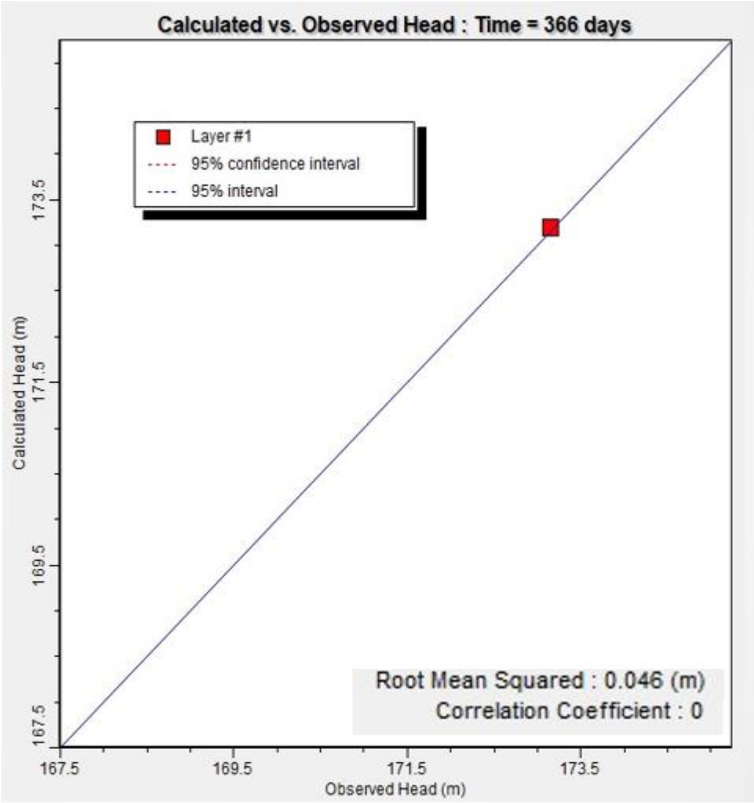

Figure 3.18 Calibration of the model for the stress period 1st May, 2016

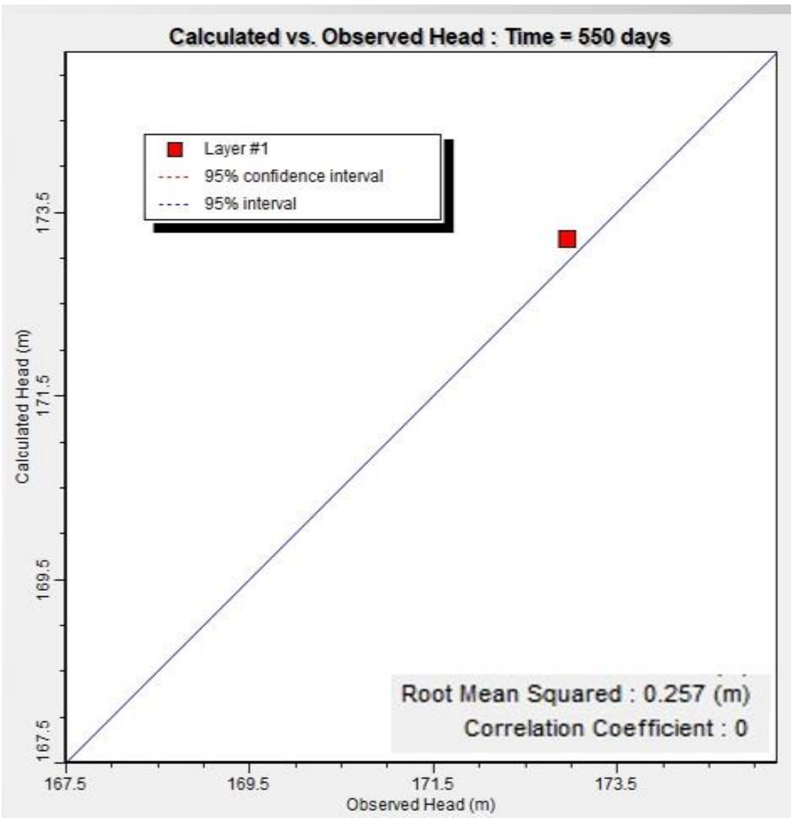

Figure 3.19 Calibration of the model for the stress period 1st Nov, 2016

Following parameter settings were utilized as the final values for the Calibration.

Table 3.4 Calibration parameters

Parameter	Value
Hydraulic conductivity (K)	38 m/day
Specific yield (S_y)	0.22
Specific storage (S_s)	5.3E-04 m^{-1}
Effective porosity	0.32
Total porosity	0.38

3.6.6.2 Model Validation

Model was validated from 1st May, 2016 to 1st Aug, 2018 as shown in Figures 3.20 to 3.22. From each of them, it is evident that model was well validated for each stress period as root mean squared values came as 0.145 m, 0.042 m and 0.212 m respectively which were very close to zero, this gave the clear indication about very good relationship between calculated and observed head values.

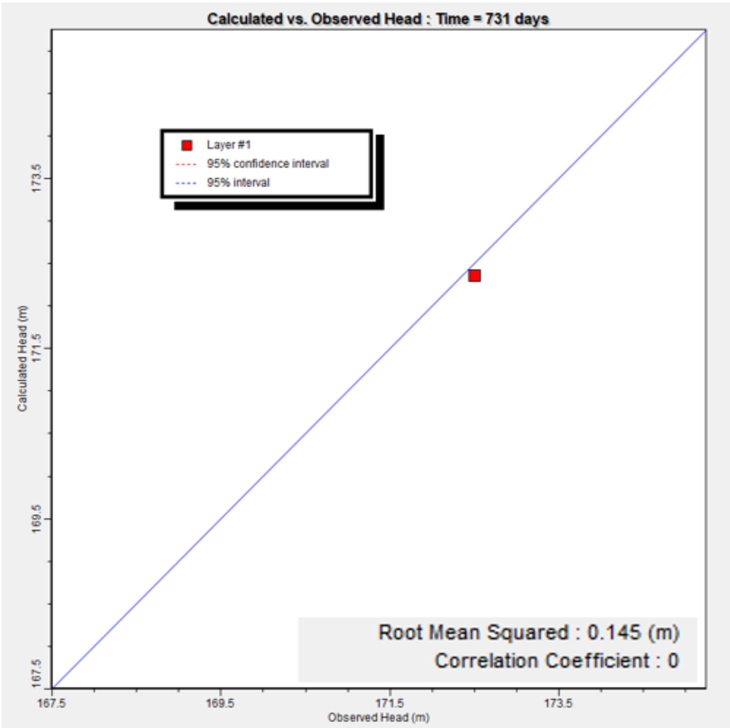

Figure 3.20 Validation of the model for the stress period 1st May, 2017

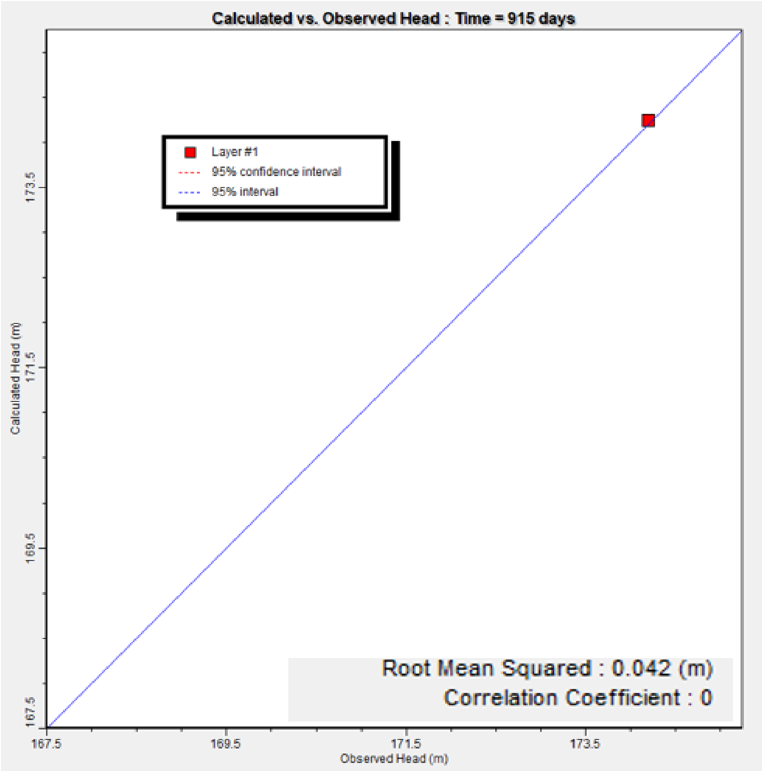

Figure 3.21 Validation of the model for the stress period 1st Nov, 2017

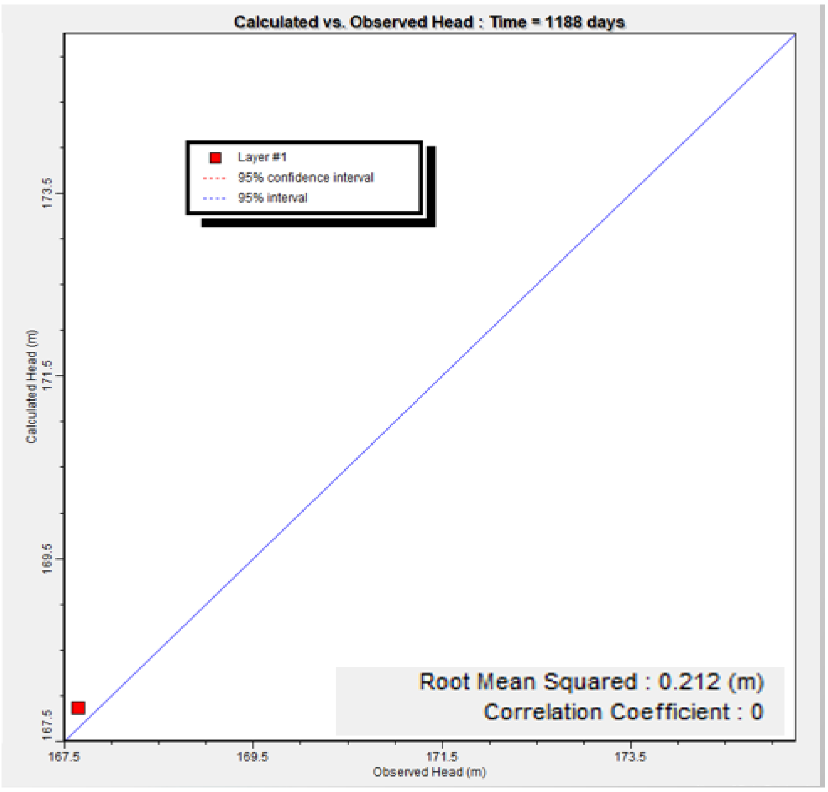

Figure 3.22 Validation of the model for the stress period 1st Aug, 2018

3.6.7 Calibration and Validation Period, Time Step and Units for Model with Recharging wells

As already discussed, the choice of calibration period is dependent to some extent by data availability and historic groundwater conditions in the study area. As far as the availability of data is concerned, the data of observation wells that was being used, were water levels of UET's observation wells. Two observation wells came in the jurisdiction of study area and the data of almost 2 months had been used which was divided into seven stress periods. Each stress period consists of each rainfall event. Therefore the selected calibration period covers the 16 days period (three stress periods) i.e. from Feb 1, 2019 to Feb 16, 2019. Stress period also depend on the availability of the data.

It was found that no appreciable difference in results was observed, therefore the each stress periods was divided into ten time steps for further simulations as convergence of results is achieved & computational time is less. Any set of units can be developed in the Visual MODFLOW. For the current study, metric system was used.

3.6.7.1 Model Calibration

Calibration of the model is confirmed by taking a 45 degree line where X equals to Y is in the 95% confidence interval lines. A 95% confidence interval permits the user to visualize a range of calculated values for each observed value, with a 95% certainty that the modeled results will be satisfactory for a given observed value. The 95% interval is the interval where 95% of the total number of data points is expected. The model was run several times to reach the realistic solution. The heads observed in an observation well were calibrated by modifying the input parameters. The calibration graphs are shown in Figures 3.23, 3.24 and 3.25. From each of them, it is clear that model was well calibrated for each stress period as all the values in each graph lie within 95 % confidence interval with correlation coefficients as 1. Also, root mean squared values came as 0.053 m, 0.084 m and 0.049 m respectively which were very near to zero, this showed better relationship between calculated and observed head values.

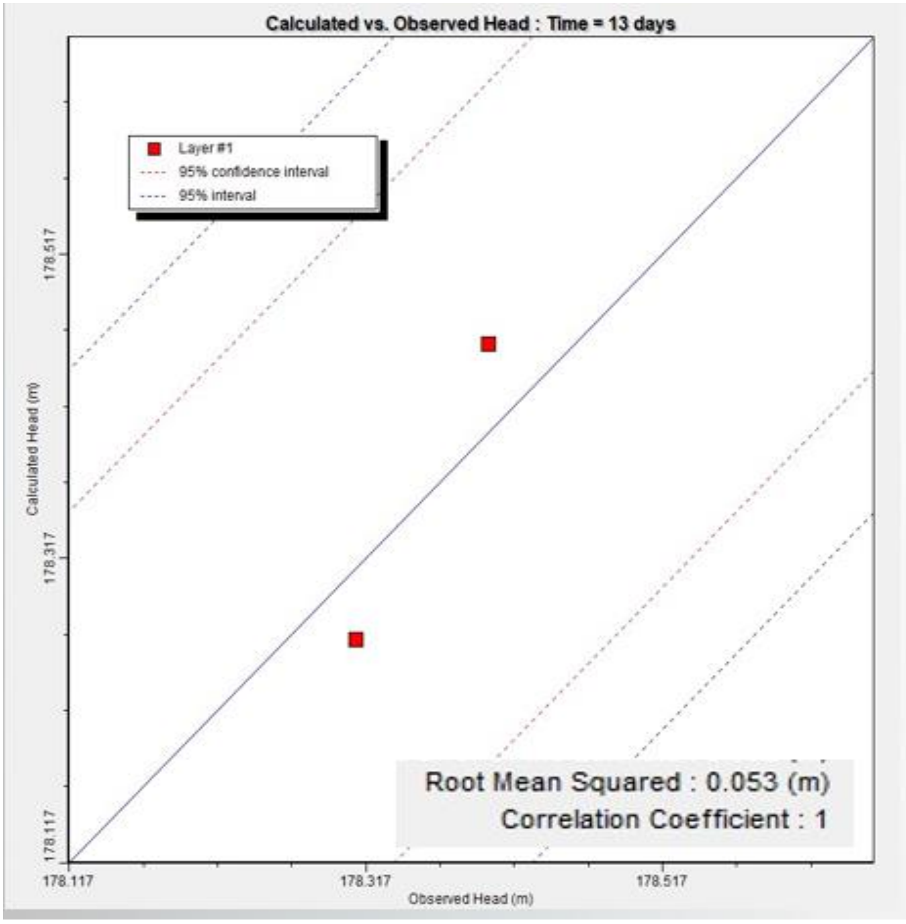

Figure 3.23 Calibration of the model for the stress period 14th Feb, 2019

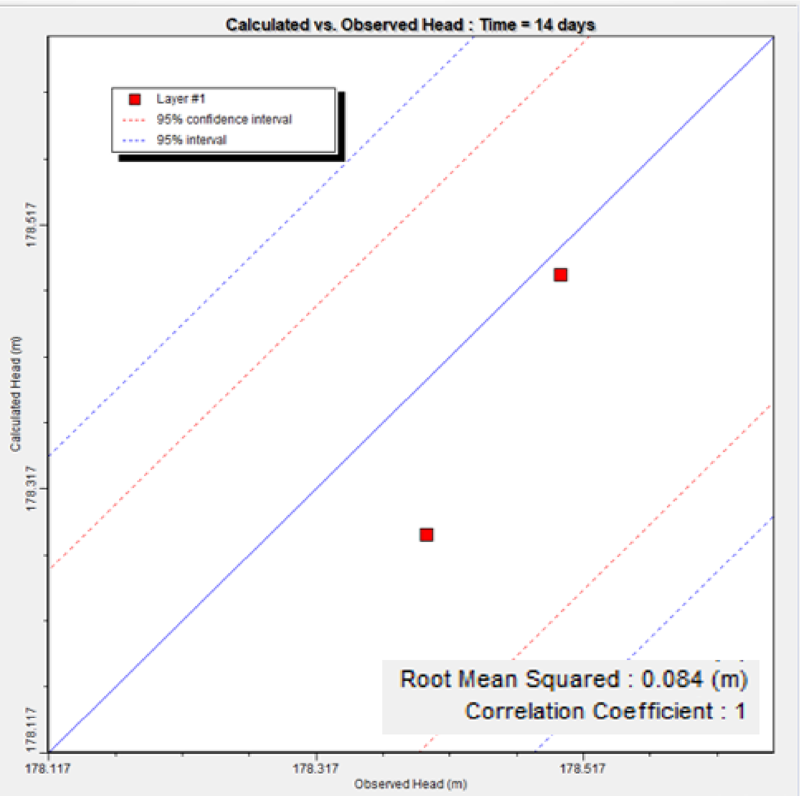

Figure 3.24 Calibration of the model for the stress period 15th Feb, 2019

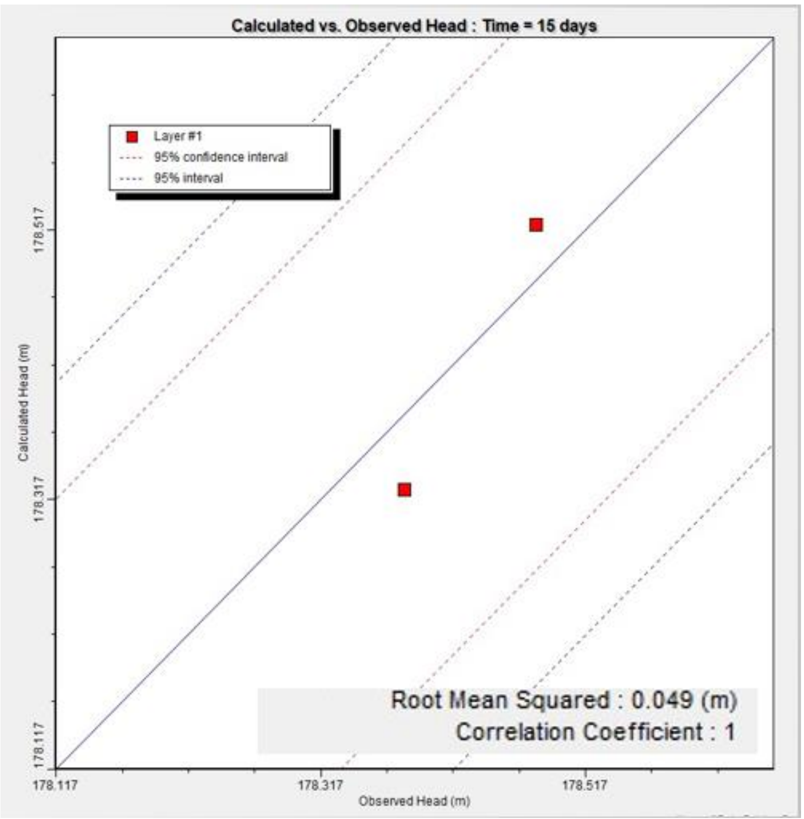

Figure 3.25 Calibration of the model for the stress period 16th Feb, 2019

3.7.1.2 Model Validation

Model was validated from 16th Feb, 2019 to 1st April, 2019. The validation graphs are shown in Figures 3.26, 3.27 and 3.28. From each of them, it is evident that model was well validated for each stress period as all the values in each graph lie within 95 % confidence interval with correlation coefficients as 1. Also, root mean squared values came as 0.052 m, 0.058 m and 0.041 m respectively which were very near to zero, this confirmed better relationship between calculated and observed head values.

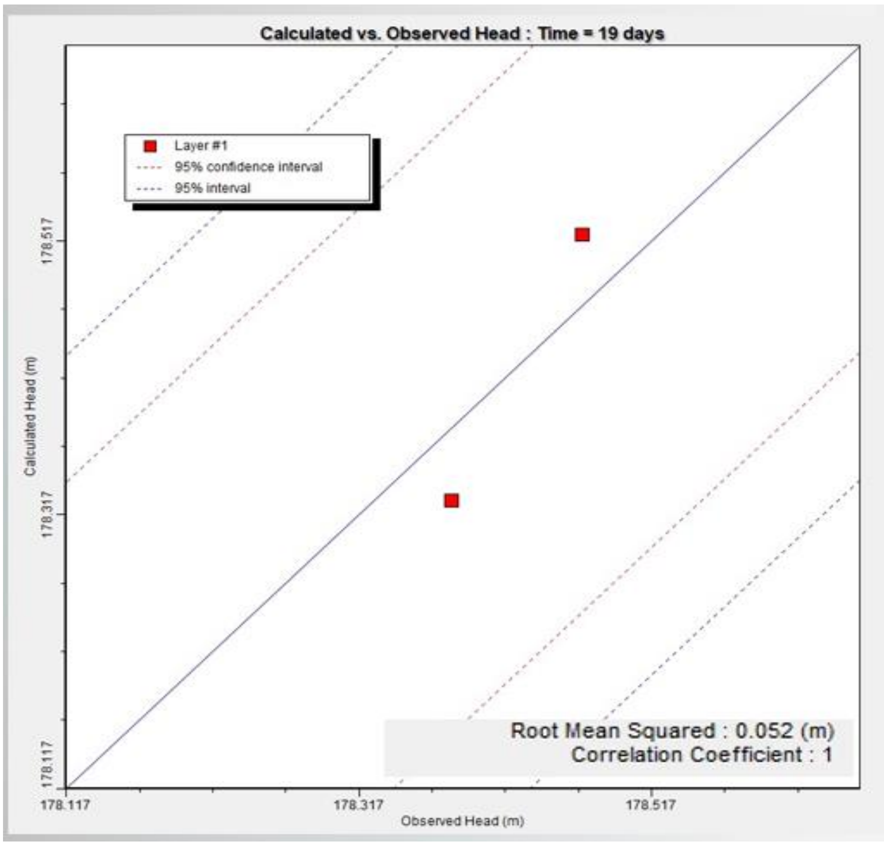

Figure 3.26 Validation of the model for the stress period 20th Feb, 2019

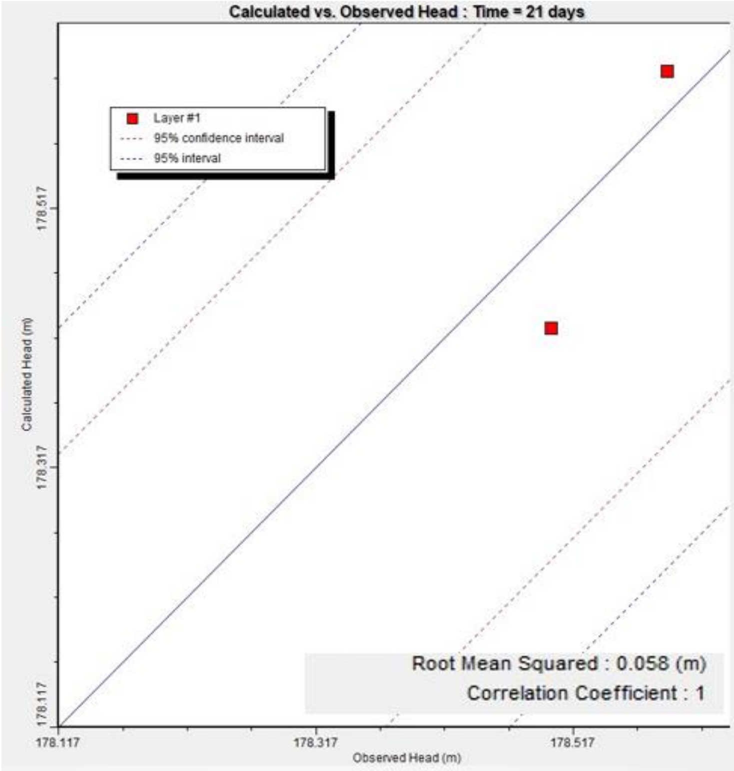

Figure 3.27 Validation of the model for the stress period 22nd Feb, 2019

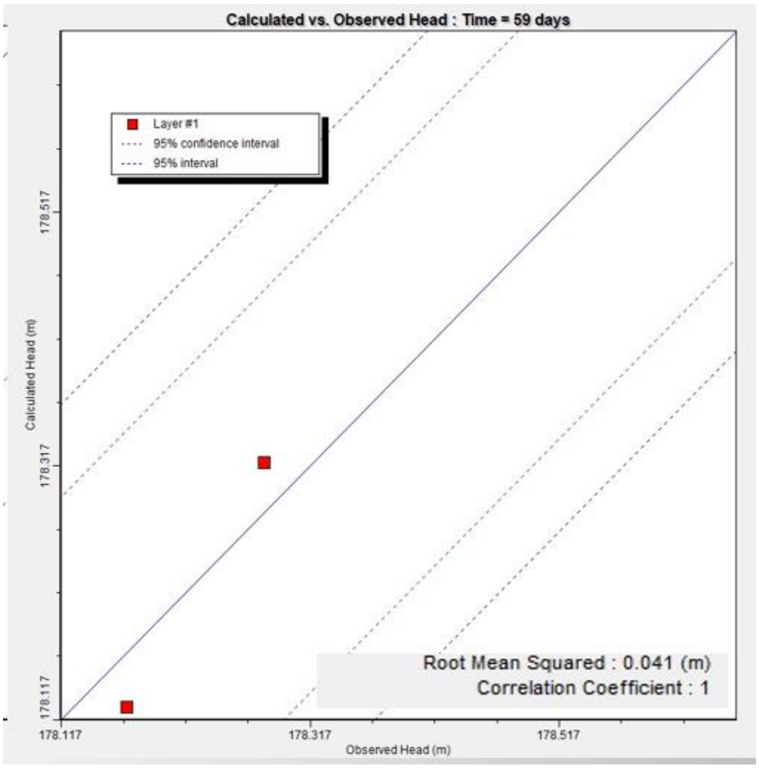

Figure 3.28 Validation of the model for the stress period 1st April, 2019

3.7 LIMITATIONS

Following are the limitations of the study regarding recharging well performance and groundwater modelling:

1. Recharging well filter was not choked and performing well.
2. Rainfall intensity was taken constant throughout the event.
3. Modelled area has isotropic and homogenous porous material.
4. Runoff volume to fill recharging well was calculated for only Junaid Jamshed Cricket Stadium but there was also some runoff volume contribution from the adjoining area.
5. Groundwater abstractions remained same for the simulation periods

Chapter IV
RESULTS AND DISCUSSION

4.1 INTRODUCTION

In this chapter, results regarding the depletion rate before and after installation of recharging wells are discussed to check either recharging wells had positive impact on groundwater table position or not. Also, relationship between rainfall and rise in groundwater table because of this rainfall under the action of recharging wells is also shown.

4.2 GROUNDWATER DEPLETION RATE FOR THE STUDY AREA

The model was calibrated and validated for both cases of without and with recharging wells. 12 tube wells were used as input for the abstraction from the system. Based on this groundwater abstraction, discussions were made regarding groundwater mining due to over exploitation of the groundwater resources in Lahore.

4.2.1 Without Recharging Wells

After setting the model parameters, the model was run and found that at end of the 1st stress period (1st Nov, 2015) as shown in Figure 4.1, the groundwater elevations range from 174 m to 178 m in the study area and at end of the 7th stress period (1st Aug, 2018) as shown in Figure 4.2, results have the range of water table elevation from 166 m to 180 m. Model results for each stress period were exported to excel sheet to calculate average groundwater elevation for each stress period. Difference between these average groundwater elevation values of every two adjacent stress periods gave the depletion rate between them. This was carried out for all the stress periods. Then weighted average was taken of all the depletion rate values to calculate average annual depletion rate. Similarly, weighted average of depletion rate values was taken for summer and winter stress periods to calculated seasonal variations. From model results it has been assessed that the average depletion rate for groundwater during almost 3.5 years, is 0.86 m per year, -0.072 m per summer season and 1.02 m per winter season.

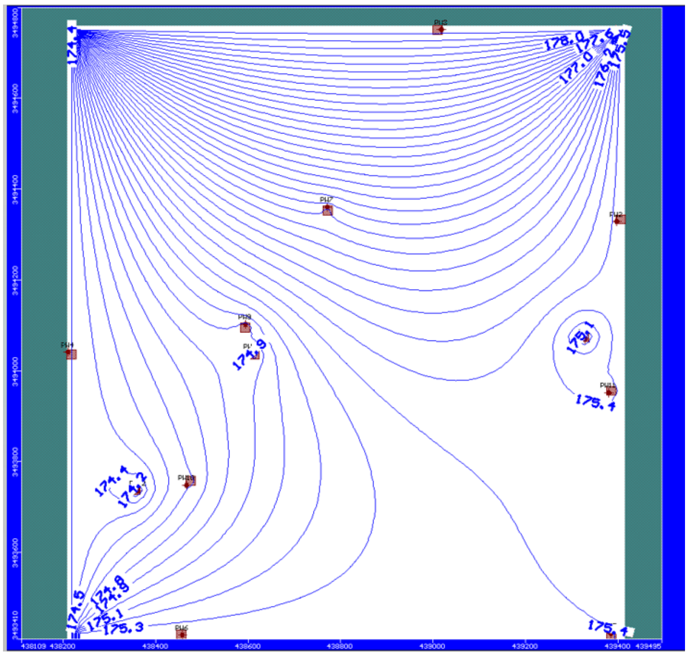

Figure 4.1 Groundwater elevations as computed by the model for the 1st stress period (1st Nov, 2015)

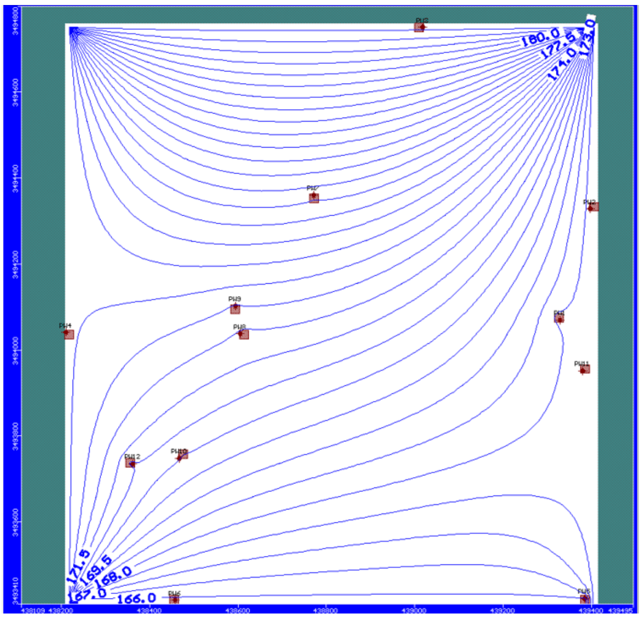

Figure 4.2 Groundwater elevations as computed by the model for the 7th stress period (1st Aug, 2018)

4.1.2 With Recharging Wells

After setting the model parameters, the model was run and found that at end of 1st stress period (14th Feb, 2019) as shown in Figure 4.3, the groundwater elevations ranges from 183 m to 173 m in the study area and at the end of 7th stress period (1st April, 2019) as shown in Figure 4.4, results has the range of water table elevation from 182 m to 173 m. Model results for each stress period were exported to excel sheet to calculate average groundwater elevation for each stress period. Difference between these average groundwater elevation values of every two adjacent stress periods gave the depletion rate between them. This was carried out for all the stress periods. Then weighted average was taken of all the depletion rate values to calculate average depletion rate for two months. From model results it has been infer that the average depletion rate for groundwater is 0.7 m per winter season based on two months data.

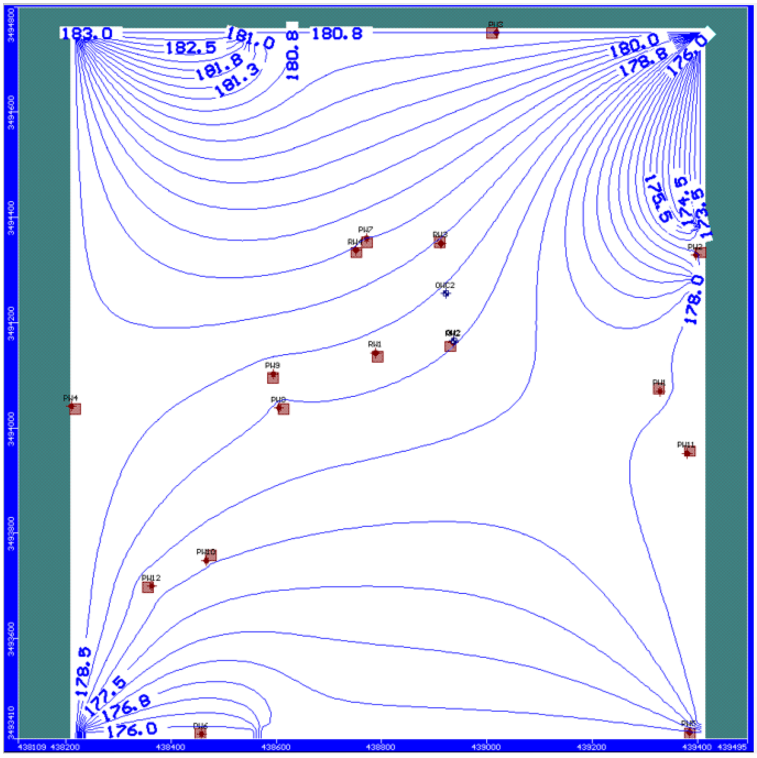

Figure 4.3 Groundwater elevations as computed by the model for the 1st stress period (14th Feb, 2019)

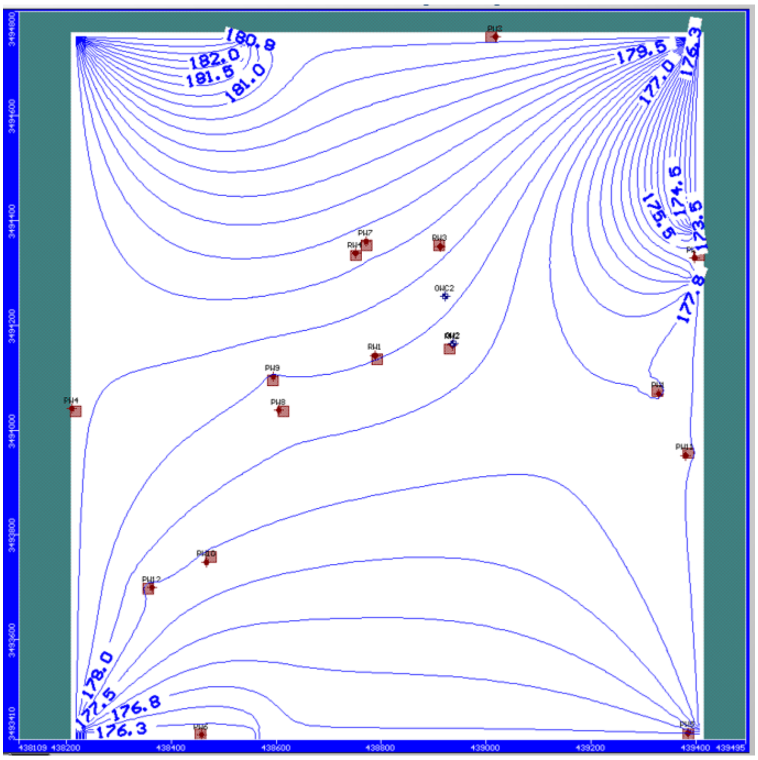

Figure 4.4 Groundwater elevations as computed by the model for the 7th stress period (1st April, 2019)

The results of calculated depletion rates for different cases are summarized in Table 4.1.

Table 4.1 Water Table depletion rate as simulated by the model.

Model Type	**Stress Period**		**Average Groundwater Depletion Rate (m)**		
	Date	**Days**	**per summer season**	**per winter season**	**per year**
Without Recharging Wells	May 1, 2015 to Aug 1, 2018	0-1188	-0.072	1.02	0.86
With Recharging Wells	Feb 1, 2019 to April 1, 2019	0-59	-	0.70 (based on 2 months data)	-

4.3 SENSITIVITY ANALYSIS OF MODEL

Sensitivity analysis of Visual MODFLOW model was carried out by changing the mesh size to investigate its impacts on groundwater level values. Standard mesh size used for modelling was 30 m. Mesh size was decreased by 20% to 16 m and then increased by 20% to 24 m and model was made to run for each case. After simulation, it was found that there was no difference between water table elevations for standard mesh size and varied mesh size as shown in Figure 4.5. So, model was not sensitive to mesh size as aquifer is isotropic and homogenous. Also, there was no effect of cell size variation on groundwater elevations for the case of groundwater table slope, as slope was not steeper because study area is a plain area. But if study area was a mountainous area where groundwater table would be very steeper then there might be significant change in groundwater elevation.

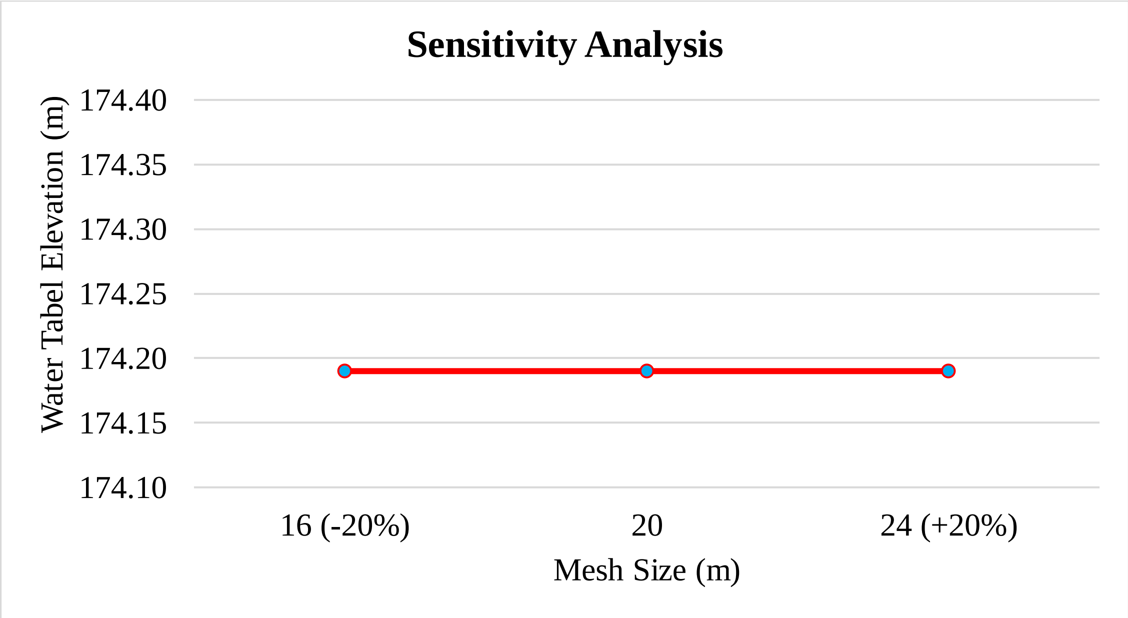

Figure 4.5 Results of Sensitivity Analysis by Changing Mesh Size

4.4 RAINFALL – GROUNDWATER RELATIONSHIP IN TERMS OF DEPTH

From Figures 4.3 and 4.4, it is evident that flow direction is from North to South (i.e. top to bottom) of model domain. This is because of the gradient difference from top to bottom in the aquifer. So, considering Figure 4.3 and 4.4, groundwater is moving towards the recharging well (RW2). So, flow is from observation well 'OWC2' to observation well 'OW2' with steeper slope. As soon as rainfall event occurs, runoff volume is collected in to the recharging well and due to recharge, groundwater slope becomes mild for the case of 20 cm rainfall event as shown in Figure 4.6 and then milder for the case of 35 cm rainfall event as displayed in Figure 4.7. The water table rise due to each event is shown in Table 4.2.

Table 4.2 Rainfall – Groundwater Relationship

Sr. No.	Date	Rainfall (mm)	Rise in Groundwater Table (cm)	
			OW2	OWC2
1	Feb 15, 2019	20.7	12	10
2	Feb 21, 2019	35.1	20	17

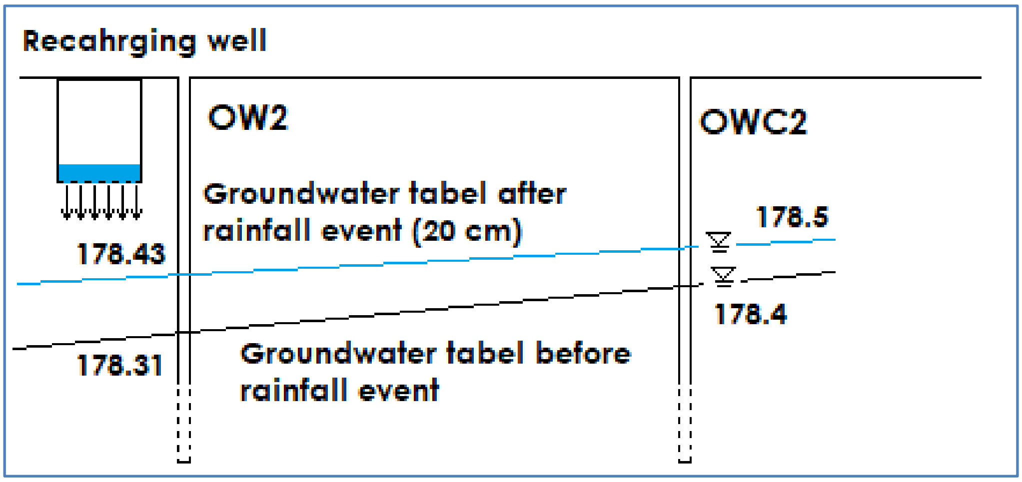

Figure 4.6 Groundwater Table Fluctuation after 20 cm Rainfall on Feb 15, 2019

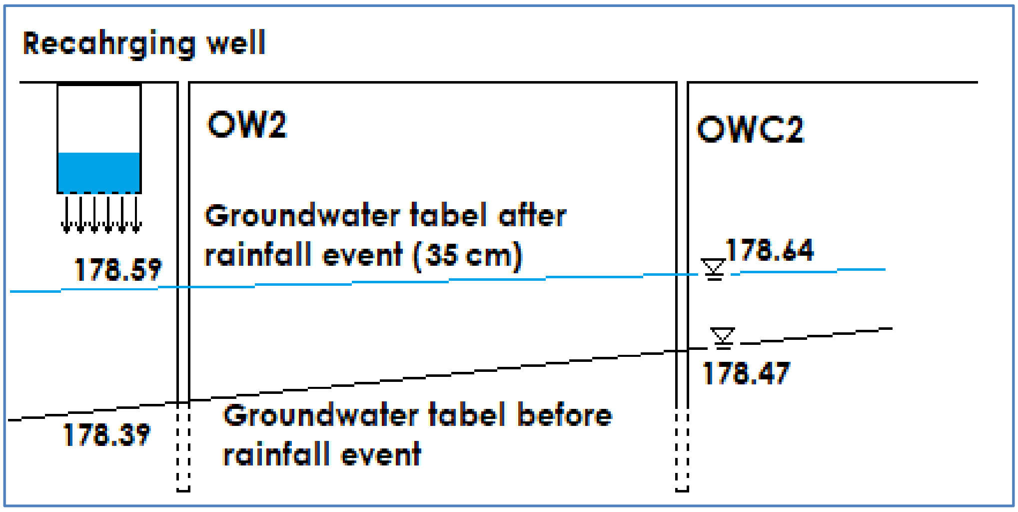

Figure 4.7 Groundwater Table Fluctuation after 35 cm Rainfall on Feb 21, 2019

4.5 CHOCKING OF RECHARGING WELLS

Recharging wells were monitored after two main rainfall events which occurred on July 16, 2019 (Figure 4.8 through 4.10) and July 25, 2019 (Figure 4.11 & 4.12). There was ponding on sumps adjacent to recharging wells (i.e. RW2 and RW3) after rainfall event as mini catchment pits were flooded. After two days of first rainfall event and one day of second rainfall event, runoff water was dried and flowmeter readings were noted for both events which were 98 m^3 and 2.8m^3 respectively. Then, after some other rainfall events, flowmeter reading was noted on August, 23 2019 which was 17.43 m^3.

Figure 4.8	Ponding on Sump connected to RW2 after Rainfall on July 16, 2019

Figure 4.9	Ponding situation on July 17, 2019 due to Rainfall occurred on July 16, 2019

Figure 4.10 Ponding situation on July 18, 2019 due to Rainfall occurred on July 16, 2019

Figure 4.11 Ponding of Water on Sump connected to RW2 after Rainfall on July 25, 2019

Figure 4.12 Ponding situation on July 26, 2019 due to Rainfall occurred on July 25, 2019

The small values of runoff flow volume into the recharging well (RW2) after rainfall events indicated that recharging wells were not performing well and found chocked. Chocking of recharging wells may be due to chocking of filter material which resulted because of silt carrying runoff water. So, there is dire need for changing of filter material after every monsoon season.

Chapter V
CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

Data was collected from departments for required duration and then data was analyzed by plotting its temporal and spatial distributions. After this, groundwater model i.e. Visual MODFLOW was set up to assess the depletion rate of the study area before installation of recharging wells. Same was done after installation of recharging wells to check its effect on local groundwater table position. Also, for monitoring groundwater recharge, equipment i.e. a flowmeter and two piezometers were installed. The results are concluded as in follows:

5.2 CONCLUSIONS

Based on the research work, following are the conclusions;

- Installed flowmeter and two piezometers were checked and they were working properly at the time of installation. Cumulative runoff volume of 149.53 m^3 was passed through the flowmeter till August 23, 2019.
- Visual MODFLOW was well calibrated and validated for the study area as results were in 95% confidence interval.
- Groundwater depletion rates in the study area without recharging wells were assessed as 1.02 m per winter season, -0.07 m per summer season and 0.86 m per year based on 3.5 years data from May, 1 2015 to August 1, 2018.
- Groundwater depletion rate in the study area with recharging wells was assessed as 0.70 m per winter season on the basis of two months data from February 1, 2019 to April 1, 2019.

- Study shows that groundwater depletion rate has reduced due to the installation of recharging wells in the study area.
- Groundwater depletion rate with recharging wells was observed as -0.31 m on the basis of recent monsoon rainfalls from mid-June to end of July, 2019.
- Visual MODFLOW was not sensitive to mesh size up to the 20% variation because of negligible slope of hydraulic grade line and aquifer was assumed to be homogenous.
- Flowmeter readings were surprisingly insignificant on July 16, 2019 which gave signs that filter of recharging well was likely to be choked and became less efficient in recharging the groundwater.

5.3 RECOMMENDATIONS

Two types of recommendations are given, firstly based on the findings of the present research work and secondly on the basis of possible future directions.

5.3.1 Based on Findings

1) Larger diameter recharging wells are recommended with certain modifications to recharge groundwater efficiently. In the existing design it is expensive to replace the chocked filter so filter pit should be provided at inlet only which can be seasonally cleaned.
2) Piezometer adjacent to recharging well was choked so it should be reinstalled.
3) One of the piezometers was tempered i.e. lock was broken, stones were inserted, due to which it became ineffective in measuring groundwater level. Hence, there is a dire need to install security cameras on nearby electric poles for monitoring the equipment against theft and tempering.

5.3.2 Based on Future Directions

1) Flowmeters and piezometers should be installed to each recharging well in stadium to monitor them efficiently.
2) This research should be extended for Monsoon period for the better assessment of Recharging wells performance.
3) Long-term impact of recharging wells on the groundwater depletion rate and quality must be checked.

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