Groundwater Assessment of the Peshawar District and its Potential for Future Demand

By

Nasir Ali

A thesis submitted to the College of Science and Engineering, Flinders University, in partial fulfillment of the requirement for the degree of master's in

Water Resources Management

FLINDERS UNIVERSITY ADELAIDE

AUSTRALIA

SESSION: 2018

Declaration

I declare that in writing this thesis, I have not incorporated any material without acknowledgement that is submitted previously in any university for the fulfillment of any degree or diploma; and that to the best of my knowledge, belief and understanding it contains no such materials published previously or written by another person except where due reference is provided.

Signed: Nasir Ali

Student Number: 2176636

Date: 13 October 2018

Acknowledgement

I bow my head to the omniscient almighty GOD for allowing me the strength and courage to successfully complete this document. I would like to acknowledge Flinders University for providing me the opportunity to conduct my major thesis and their help and support throughout the years.

I am indebted to thank many people who directly or indirectly played their part in the accomplishment of this task. I greatly acknowledge the support, consistent encouragement and advice of my supervisors Ilka Wallis and the Okke Batelaan. I am proud and exulted to have worked with them, without their consistent support literally I would have never achieved this.

I am also highly thankful to my dear friend engr. Amir Gul, who always helped me and consistently provided the necessary data required for the modelling work. Special thanks to my friends Asif Ahmed from Denin, engr. Ali Ahmed from Singoor, and engr. Ghayas Ahmed from Drosh for their support and encouragement throughout the course of this study.

I would like to express my deep and sincere thanks and respect to all my teachers for providing me the encouragement, knowledge and skills. I am also thankful to all the nice staff of the library and OASIS, who always welcomed and gave a positive gesture with their beautiful smile all the time.

Finally, I would like to pay my gratitude to my parents and family member, and last but never the least to my wife and my two sons for their love, encouragement and patience during my absence and stay in Australia.

Abstract

A three-dimensional numerical model of the Peshawar District groundwater flow system has been developed with the aim to assess groundwater flow patterns in response to abstraction. The reliance of the population, agriculture, industrial and commercial activities on groundwater has put this resource under stress. Despite being such an important source of fresh, potable water for the entire district, the Peshawar groundwater system is poorly understood and under studied. Unregulated abstraction has led to a decline in the water table in densely populated areas, especially Hayatabad. This is an indication that the current rates of groundwater abstraction are unsustainable.

The hydrological and geological data of the Peshawar District was integrated to make the conceptual hydrogeological model of the area, which became the basis for the numerical modelling. Using the computer code MODFLOW-2005 (Harbough,2005) and the model user interface ModelMuse (Winston, 2006) the numerical modelling of the area was carried out by considering the steady state condition with the geological unit of two layers. The top layer is the shallow unconfined aquifer while the deep bottom layer is the semi-confined aquifer.

The model extends around 45km in E-W and 50km in the N-S direction with a total model area of 1745 km^2. The grid cell area is 2500 m^2 with grid size of 50m both in x and y direction. The topographical map and the raster image of the project area was imported to the MODFLOW-2005 model using ArcGIS (Arc Map 10.4.1). Based on available pumping tests and previous studies on the lithology of the Peshawar District, the hydraulic conductivities of the shallow and deep aquifer were assigned. These initial values were altered during the model calibration process. Groundwater recharge in the area constituted recharge from rainfall and infiltration from irrigation.

The model was run under steady state conditions with rainfall and irrigation losses as recharge inputs. The flowing river is in hydraulic connection with the model area and a considerable amount of water flows into the model domain, while the abstraction by pumping accounted for a loss in groundwater from the system. The drainage channels in the model also contributed to discharge by draining the water towards the river, while the water flowing as base flow towards the river also contributes as a discharge from the system. Based on the model results the average linear velocities, hydraulic gradients and flow directions in both layer 1 and 2 were determined. Based on the analysis of the water budget, hydraulic heads and through the assessment of flow patterns an improved understanding of the hydrogeology of the project area was obtained. The calibration of the model also allowed model sensitivities to specific input data to be determined. The model findings about the flow direction indicates that the groundwater flows from the south to north -east and from west to the east towards the Kabul River. The water budget analysis indicates that the reliance is more on the Kabul River, which contributes almost half of the water to compensate the pumping from the model area. Thus, for a sustainable groundwater development, the Kabul River flow and its usage

in the upper catchment areas from where it originates would play an important role regarding the future groundwater development of the model area.

This modelling exercise has been made to represent the real-world situation of the project area, therefore uncertainties are associated due to the simplifications. The boundary conditions, scarce data, and the lack of the detailed hydrogeological understanding may have an associated uncertainty. Therefore, it is important to consider the limitations when extrapolating or interpreting these groundwater modelling results.

I am dedicating this thesis to my parents,

My beloved wife

And my two sons Zayan Nasir and Zoraiz Nasir

Table of Contents

List of Figures

List of Table

Acronyms

AutoCAD- Automated Computer Aided Design

DXF- Drawing Exchange Format

DEM-Digital elevation model

FATA - Federal and Tribal Agencies

FEMWATER - Finite element flow and transport model

GIS- Geographical Information System

KP- Khyber Pakhtunkhwa

MES- Military Engineering Service

Msl- Mean Sea Level

PEST- Parameter estimation

PFI- Pakistan Forest Institute

PDA- Peshawar Development Authority

PHED- Public Health Engineering Department

RMSE- Root means square error

RSWL- Reduced Standing Water Level

SRTM-Shuttle Radar Topography Mission

SCARP- Salinity Control & Reclamation project

TXT- Text File

UPU- Urban Policy Unit

UN- United Nations

VES- Vertical Electrical Sounding

WAPDA- Water and Power Development Authority

WASID- Water and Soil Investigation Department

WSSP-Water and Sanitation Services Peshawar

List of Symbols

A: Area

Km^2: Square Kilometer

ha: Hectare

m: Metre

ft – feet

h – Hydraulic head

K – hydraulic conductivity

m – Metre

mm – millimeter

qx, qy, qz – Velocity component in x, y and z directions

s – second

S – Storage coefficient

T – Transmissivity

Chapter 1

Introduction

1.1 Background

Most of earth's freshest water is not found in lakes or rivers but is stored under the ground in aquifers, which are the most valuable source of water supply when there is no rain fall (Morris et al, 2003). Groundwater occurs beneath the surface within the saturated zone in soils and geological formations. Its contribution is vital because more than 30 % of the world population is directly dependent on these groundwater aquifers for drinking purposes (Connor, 2015). Surface water has been affected by human activities and its inadequate availability has made many cities and towns of the world rely on groundwater resources. The quality of the groundwater is stable and its reserve quantity of fresh water is greater compared to surface water, therefore aquifer development will continue for economic development to provide a reliable water supply for industrial, agricultural and domestic purposes.

Most of the groundwater studies are made with an objective to assess and quantify the groundwater resource. The quantification in terms of the volume involves how much water is stored inside the specific geological formation and for how long it will remain stored in response to the varying recharge and the discharge volumes. If precipitation exceeds evaporation rate then the water that does not runoff but infiltrates down can potentially reach the water table and contribute to groundwater.

The past half century has witnessed an explosion in groundwater development for the industrial, agricultural and the domestic purpose reaching a withdrawal rate of 750-800 km^3/year (Shah et al. 2000). When the abstraction rate exceeds the average recharge, depletion of the groundwater storage and the lowering of the water table takes place. Hence for the sustainable management of the groundwater resources it is crucial to keep balance between recharge and abstraction without effecting the integrity of the ecosystem.

The development of computer based numerical models has resulted in the frequent use of mathematical models for groundwater management (Ślesicki, M., 2009). The models are a set of developed equations, which describe the complex groundwater flow and the water balance in the geological water stratum. For solving the equations, the most commonly employed method is the finite difference method where groundwater movement for each node and its neighbor is calculated. When appropriately designed, groundwater models can assist in forecasting the future outcome of groundwater behavior, which would be highly helpful in the decision-making process on the policy level (Barnett et al., 2012).

Peshawar District is the urbanised and populated city of the Khyber Pakhtunkhwa province (KP) in Pakistan. The reliance on groundwater resources has resulted in the unavailability of water in the scorching summer and the dry seasons. The annual rainfall is low and unpredictable while the rapid urbanisation and increased growth in the population has resulted in greater water demand (Shahida, 2006). The increased number of abstraction wells without assessing the groundwater aquifer system may lead to the overexploitation of the precious resource.

1.2 Problem Statement

The major source of water supplied to the Peshawar District is obtained from the ground water which has resulted in shortage of water in the congested settlement of the district. The project area encompasses a major hub and metropolitan city of the Khyber Pakhtunkhwa province, where the migration of people from rural areas has put additional strain on the water resources. Rapid increase in population and unplanned industrial development has resulted in the over exploitation of the scarce groundwater resources. The seasonal shortage and lowering of the water table is responsible for the increased pumping cost and electricity. Untreated wastes from the streams become mixed with the Kabul River and the over pumping may induce more water from the River Kabul effecting the water quality of the shallow upper layer of the aquifer.

According to the United Nations Report (UN, 2014), half of the world's population lives in cities and this may increase to 60% by the end of 2030. Internal migration to cities from rural areas is a common phenomenon in Pakistan and the city of Peshawar has experienced huge expansion because of this trend. Migration to the cities not only improves the socio-economic conditions of the household's family but also provides good employment opportunities to the migrants (UN, 2014). However, the existing infrastructure of the water supply systems is under tremendous pressure to meet the increasing demand of the city. According to the latest 2017 census report, the population of Peshawar city has increased by more than other districts in the Khyber Pakhtunkhwa province and has a growth rate of 3.99% over the last 18 years (UPU, 2018).

According to the Water Supply Master Plan main draft report (UPU, 2014), 30% of the aquifer is under high stress and the poor infrastructure including old pumps and bores has increased the pumping and maintenance cost. In the summer when the temperature reaches an average of 48 degrees centigrade, the demand of water increases further and in the areas where the depth to the water table is already high encounters more severe problems.

Understanding the complex hydrological setting and flow pattern of the Peshawar basin has remained a challenging task and is probably not well understood. Therefore, it is very crucial for the sustainability of the groundwater resources that the aquifer and the water balance component of the basin be studied and understood. To better understand the impact of pumping and other anthropogenic abstraction it has been realised that groundwater modelling would be a powerful tool for groundwater management and development.

1.3 Research Questions

Based on the problems as discussed above the following research questions have been proposed.

- How much water is being pumped from the groundwater in the Peshawar District?
- What are the possible recharge sources to the system in response to the pumping?
- What is the groundwater flow pattern and flow direction?
- Would the water extraction from the ground be enough in the future for the rapidly increasing population?

1.4 Research Aim

Groundwater abstraction rate of the Peshawar District is directly linked with its increased population and rapid urbanisation (Adnan and Iqbal 2014). The annual rainfall recharge is very small and the groundwater infiltration from the distributary canals and irrigation is dependent on the influx from the Kabul and Bara Rivers which may fluctuate based on the consumption from the upper catchment areas. It is worrisome that 95% of the population depend on the tube wells for drinking and other domestic purposes. Unregulated and increased pumping rates, along with construction of more impervious layers (concrete structures) in the urbanised areas may put the groundwater under even higher stress.

The water dependent private and public industries are also responsible for water crises. These include marble factories, paper mills, oil industries and automobile stations. As these industries grow with the passage of time more water is abstracted from the ground, with further depletion to groundwater a concern in the vicinity of these areas (Manzoor Ali, 2007). Past research studies on groundwater of Peshawar District have been carried out giving more focus on the water quality, however, the aquifer assessment in response to pumping has not been investigated for the entire district. Therefore, it seems necessary to carry out research as to how the pumping could impact the ground water resources.

The necessary monitoring data required to assess the groundwater behavior is poor and discontinuous. The detailed urban water supply and urban planning documents also reveal the same data scarcity. Therefore, it is necessary that a rational groundwater model of the district be made, which could provide a way forward to predict the impacts of the water abstraction in a holistic manner.

Based on the above-mentioned discussion the main purpose of this study is to use groundwater modelling to assess the Peshawar groundwater resource with an aim to update and improve the understanding of the flow pattern in response to the abstraction and recharge.

The specific objectives include

a) To develop a GIS map of the area
b) To estimate the recharge of the area.

c) To develop a conceptual model of the Peshawar District based on the available groundwater data and analysis.
d) To model the area and simulate Peshawar groundwater.
e) To calibrate the model in the steady state condition so that a transient run could be made possible to test the fluctuated temporal input data at a later stage.

1.5. Organising and Structuring of the Thesis

The thesis has been divided in to five chapters with the outlines explained below.

Chapter 1. Introduction:

The introduction part of the thesis describes the problem statements, research questions, research aim, and the scope of the work based on which the problems discussed would be solved by collecting the required data. It also includes the literature review of studies done on a national and regional level. The methodology part explains the methods used in data collection and the process involved in modelling the groundwater. The chapter includes a detailed flow chart of the methods involved in the groundwater modelling process.

Chapter 2. Study Area

The chapter describes the study area in relation to its location, land use pattern, demography, rainfall, climate, surface and groundwater, and associated infrastructures.

Chapter 3. Topography, Geology and Hydrogeology

In this chapter the topography, geology and the hydrogeology of the Peshawar basin is described. The surface and groundwater interaction are also discussed.

Chapter 4. Groundwater Flow Modelling

This chapter covers the primary and the secondary data and their screening, synthesising and processing to make them fit the model as input data. The development of a conceptual model of the area is also discussed in detail. The numerical modelling computer codes, software and transferal of the GIS-ArcMap 10.4.1 shape files in to ModelMuse Modflow-2005 is also explained in detail. Model design and calibration under steady state condition has been explained in detail. The discussion, analysis and interpretation of the model results is also included in this chapter.

Chapter 5. Conclusion & Recommendations:

Based on the model results and the discussion, conclusions are made and remaining questions or points of interest have been suggested for future research efforts. Based on the modelling discussion and the results, recommendation have also been proposed.

1.6 Scope of Work

The scope of this study includes the following tasks.

1. Collecting necessary data including the hydrogeological, meteorological and abstraction rates within Peshawar District.
2. Analyse the available data and calculate the recharge, establish aquifer properties and delineate boundaries of the groundwater basin.
3. Make the GIS map of the study area and show the pumping area and hydrological features.
4. Import all the data to the ModelMuse MODFLOW-2005 from the GIS-ArcMap 10.4.1 and build the model.
5. Run the model under steady state conditions.
6. Calibrate the model based on the known observation heads and do the sensitivity analysis.
7. Use the model as a tool for analysis and future predictions in response to the pumping, both temporally and spatially.

1.7 Literature Review at Regional Level

Groundwater research at the regional level started in early 1960 when the water logging problem was raised in Mardan, Charsadda and the areas of Peshawar District near Kabul River. The problem was intensely addressed when Water and Power Development Authority (WAPDA) introduced the Salinity Control & Reclamation Project (SCARP). WAPDA (1963) made a detailed report on the Sherkera tube well irrigation project, a place located approximately 30 km away from the Peshawar District. This detailed groundwater investigation report included five holes, out of which two were converted in to tube wells for pumping tests. The report contains useful information about groundwater levels, volume of the water stored, and annual recharge of that specific area.

Malik, (1967) carried out a detailed study about the records of the groundwater level of the whole Peshawar vale, where the areas of Peshawar, Mardan, Sawabi, Nowshera and Charsadda were included. In the report it describes the results of the development activities done by the Water and Soil Investigation Department (WASID) in the year 1963 to 1966. Water level obtained from the 88 wells and monitored from 1920 to 1963 have been discussed and analysed. The report covers the whole Peshawar vale but is not specific to the Peshawar District.

Kazmi, (1968) carried out the groundwater investigation survey in the areas, which were being regulated by Warsak Dam reregulating reservoir. The report describes the groundwater investigation results of the Water and Soil Investigation Department (WASID) from the year 1963 to 1968. The report gives detailed information about the known borehole logs and the chemical analysis.

Arif, and Khan (1970), made a detailed study on the groundwater on the right bank of River Kabul in the Peshawar. The issue raised and discussed was mainly on the problem of water logging. The report explains the results of the Water and Soil Investigation Department (WASID) investigation results. The report also discusses the Kazmi findings and makes its own analysis from the existing literature.

Siddiqi, (1972) investigated and presented the results of the work done by the Water and Power Development Authority (WAPDA) from 1968 to 1970. The report is about the Mardan area where WAPDA implemented its SCARP project. The investigation report is based on the field surveys, 38 drilling test holes and the twelve aquifer tests.

Naqavi, and Hamadan, (1978) described the groundwater resources under Mardan SCARP project in Mardan SCARP area. The report makes an analysis of Siddiqi's (1972) work but they never carried out further investigation. Useful illustrations and analysis have been made by the authors. The reason to focus on the Mardan area was due to the salinity problem near the Kabul River there, and the initiation of SCARP to counter the issue. The study was important in the context of the Peshawar District as well because the salinity problem in the riparian zones of the Peshawar District is also an ongoing problem.

Sajjad, (1983b) made a compilation report of the data, which focused more on the right bank of Kabul River. The author compiled the previous work of the WAPDA, Malik, and Kazmi reports as well as some of the unpublished data. The report contains useful information about the pumping tests results, borehole logs and the water quality.

Bloemendaal, and Sadiq (1985), have written a comprehensive report on the Maira Area, Mardan and the Peshawar District. The report technically explains the groundwater resources specifically focusing on the Maira area. The paper discusses the investigations carried out by WAPDA/TNO-DGV in 1983 to 1985. In the report 14 drilling boreholes, several aquifer tests, electrical resistivity surveys, and water budget calculations have been made. The report is generic, which helps in general understanding of the area and the associated geological formations.

Robberts, (1988), wrote a comprehensive report about the hydrogeology of the Peshawar District. The report is basically a desktop study compiling different technical reports of the previous investigations. The report has valuable information about the groundwater resources and development of the Peshawar District.

Kruseman, and Naqavi, (1988) wrote a comprehensive book that was a consolidation of the reports that were previously written in conjunction with the project of groundwater investigation in Khyber Pakhtunkhwa province. The book not only contains general information about the Khyber Pakhtunkhwa (KP) provincial areas but also about the regional groundwater investigations done by different departments and authors. Hydrogeology of the Intermountain basin of Peshawar and Mardan district have been discussed in detail. The total recharge and the discharge of the whole Peshawar vale has been calculated. The book has been written in a language suitable for the planners, managers and groundwater experts. The hydrogeology of Peshawar area has been discussed and illustrated with cross sectional diagrams and tables. Contour heads have been generated and the scenario to explore the future potential of the groundwater resources has also been made.

Bundschuh, (1992) carried out a comprehensive investigation of the groundwater resources of the Peshawar Valley. The investigation was completed in 3 months with the main aim of classifying the groundwater suitable for agricultural and drinking purposes. The report has classified the Peshawar vale to include a scattered area of approximately 8000km^2 which is comprised of Peshawar, Sawabi, Noshehra, Karlang and Mardan district. As per the findings of the author, the water table depth of the valley district is less than 5m except for the areas near the mountains and the southern parts where the water table depth is in the range of 10 to 30m. The groundwater flow direction has been shown to be towards the centre of the basin, while the electrical conductivity at the mountain side is less than 800 *µS/cm* but at the center a maximum of 8000 *µS/cm* has been reported. The author has also presented the water samples in the piper diagram and has made his analysis.

Asim, (2005) did a detailed study of the Peshawar basin, which covers an approximate area of 5500 Km^2. He undertook the study to characterize the hydrochemistry and the paths of groundwater flow in the basin. Based on his investigative studies three types of aquifers in the Peshawar basin have been identified, which are the Peshawar Piedmont Aquifer, Peshawar Lacustrine Aquifer and the Flood Plain Aquifer. He obtained borehole data from the WAPDA and constructed a fence diagram of the basin. The physio-chemical data of the shallow and the deep tube wells were presented which include pH, Temperature, total dissolved solids and the electrical conductivity. He did the numerical modelling of the basin by using FEMWATER (a finite element flow and transport model). Northern, western and the southern edges were taken as no-flow boundary while the eastern edge where the Indus River flows was considered as a constant head. In the model result he argued that topography itself is not the only parameter responsible for the pressure heads, but that the effect of tectonic compression also contributes. The deep and the shallow wells in the southern part of the basin are more open for active flow of water.

Nasreen, (2006) did a detailed research on the soil, surface and groundwater of the Peshawar basin. The main purpose of the study was to monitor the environmental degradation of the Peshawar basin by studying the physio-chemical parameters of water and soil. Physical parameters like, pH, electrical conductivity, temperature and total dissolved solids were tested. Anions, cations and the heavy metals in ground- and surface water was determined. Based on the results, she concluded that physical parameters are within the permissible limits while the anion and cation levels in the areas exceed the permissible limit, which could be hazardous. Those high concentrations as mentioned above were attributed to the water movement through the limestone, gypsum, dolomite and the sulfide seams and salts within the quaternary sediments of the basin.

Basharat et al. (2009) did groundwater modelling of the Nowshera District, which is adjacent to the Peshawar District. The aim of the study was to estimate the future groundwater potential for drinking and agricultural purposes. The field investigation was carried out by the Hydrogeological Directorate of WAPDA, which included 1134 electrical probes, 25 test holes and several aquifer tests. Modflow 2000 was used to simulate the model. An unconfined aquifer layer to a depth of 200m was selected. The areas where the outcrop was visible was considered as no flow boundary, while the other boundary selected was the general head boundary. The main recharge to the ground is irrigation and percolation from the canals while in the barren areas the rainfall is the sole source of recharge. Based on the model results there is a huge stock of water, around 69 cusecs are available for future exploration. The results were interesting in the context of the Peshawar District because the selected area was adjacent to the Peshawar and both districts share boundaries.

Farid et al. (2013) carried out a field investigation survey of the Maira area with an aim to estimate the aquifer parameters by using electrical resistivity and pumping test. Maira area is near the Peshawar District situated at the east of the Peshawar. The results of the investigation, carried out in the alluvial aquifer of varying layers of gravel, sand and clay, were quite useful. A total of 51 VES were installed at different location of the Maira area and the survey results were interesting in terms of finding fresh aquifer water zones in the area. Depth of the water table along the river areas is less than 5m while at the center of the Maira area the water table depth has been calculated at 30 m.

Masud et al. 2013) calculated the water balance of the Pabbi region near the Peshawar District. They calculated the recharge from the rainfall and percolation from the canals. In the discharge, tube wells and the handpumps were included by obtaining the record from the government line departments. Based on the analysis they came up with the conclusion that the depth to the water table of the Pabbi region is increasing with a rate of 37mm/year.

Khan and Waheedullah (2013) investigated some part of the groundwater of the Peshawar District by using the Terrameter SAS 4000. They selected three locations and a total of six points were selected, 2 from each location. The three selected locations include Pakistan Forest Institute (PFI), University area and the Hayatabad area. Based on the results from the resistivity survey the shallowest water table was observed at the PFI, which is 23m, while the deepest water table observed is from the Hayatabad sides where a depth of 92 and 82 have been calculated. The results of the survey also indicate that the dominant subsurface strata are sand, gravel and clay in the PFI and University areas, while coarser materials like gravel with sand stone were dominant in the Hayatabad area.

Adnan and Iqbal (2014) did a GIS based study and spatially analysed the groundwater quality of the Peshawar District. In the methodology they took the samples from 105 wells points located at different, scattered locations to determine the physiochemical parameters of the groundwater. The parameters were electrical conductivity, total dissolved solids, turbidity, PH, hardness, chloride and nitrate. Based on the analysed laboratory results and the spatial distribution map of the physiochemical parameters, the authors conclude that most of the parameters were found higher in the city area of the district. However, pH and the nitrate concentration were found to be higher away from the city area.

Khan, Guldaraz, and Akbar (2014) conducted research to quantify the groundwater recharge and the discharge of the Peshawar District. Their hypothesis was based on the question that if the recharge is less than the discharge then the groundwater level is decreasing at times. The authors carried out a detailed survey to find out the total pumping rate within the district. The report includes data from 670 government well tubes, 63 dug wells and 552 private wells. Beside this detail a separate comprehensive survey of the hand pumps has also been mentioned. 51 % of the population in the Peshawar District is rural so they do not have access to the government tube wells, but each locality has its own hand pumps from which the people extract water. They mentioned that a huge amount of water at a rate of 81.8 m^3/sec is being extracted from the administrative town 2, town 3 and town 4. Dug wells and private wells are scattered on an area of 1169km^2, while the hand pumps and the tube wells are distributed over the total area of the district, which is 1257km^2. The total depth of discharge calculated is 286 mm/year. In the report there is no mention of the recharge figure but the 57mm/year deficit shown by the authors indicates that the recharge taken from various sources was 229 mm/year. The authors have concluded in their study that the water level is decreasing at the rate of 57 mm/year, which is an indication that mining of the groundwater is taking place in the Peshawar District.

The United States Agency for International Development (USAID) in collaboration with Urban Policy Unit, Planning & Development Peshawar (UPU,14) published a detailed master plan deliverable report over the existing and future state of the Peshawar District drinking water supply infrastructure. The purpose of this master plan was to evaluate the current drinking water supply and recommend the future options to improve the water supply deliveries. A detailed survey was carried out to see the current working pattern and condition of the existing water supply system. The selected area included 67 union councils out of which 45 union councils are within the urban area and the other 22 union councils lie within the rural area. The total area where these service deliveries are provided is 339 km^2. Based on the detailed field investigation 773 tube wells are under operation in the project area, out of which 42% are 15 years old and may not be a reliable source of water abstraction. 398 tube wells are operational in the area having an age less than 15 years and out of this only 21 tube wells have the new pumps of 7 years old. The flow meter is working in only 6 tube wells out of the 398. The report is rather comprehensive with the hydrogeology, rainfall and population of the project area explained in detail. The groundwater of the Peshawar aquifer has been classified in two layers. The top layer classed as an unconfined aquifer while the bottom as a semi or leaky aquifer. The depth of the first layer is 61m while the thickness of the leaky or semi confined/unconfined aquifer is 120m. The report suggests that the hydraulic conductivity of the upper unconfined aquifer ranges from 1.64 to 4.75m/day while for the leaky aquifer it ranges from 0.047 to 0.298m/day. Taking into account the estimates of future population, the drinking water demand per capita has been recommended for urban and rural union council as 246 and 136 litres/capita/day (lpcd) respectively. The future proposed pumping and the drinking water consumptions have been estimated. In the years 2013, 2022, and 2032 the total drinking water demands of 806,000, 995,000 and 1,214,000 m^3 per day have been proposed.

Muhammad and Khalid (2017) assessed the part of the Peshawar basin for groundwater potential. They carried out hydrophysical investigation at Nowshera area which is situated at the southeastern side of the Peshawar District. The authors used 30 vertical electrical points (VEP) and made the resistivity profile map in conjunction with the pumping test data. The data showed consistency with the borehole data and based on this they argued that the area is consisted of the alluvium deposits with alternate layers of clay, silty clay, coarse sand and gravel. High resistivity values were corelated with the coarser sediments and the lower values were related with the fine materials. The studies carried out are supposed to be an important study because they could be helpful in identification of the hydrogeological units of the Peshawar District basin.

In 2017, Urban Policy Unit Planning Development (UPU, 2017) published a comprehensive land use planning report from the year 2018 to 2037. In the report the groundwater management has been highlighted with great stress. Demography and the land use distribution of the district has been highlighted in detail. The report suggests that the groundwater recharge is continuously increasing along the areas of the river and unlined canals which effect the agricultural capacity. The report has shared some interesting facts that out of the total area of the Peshawar District 336 km^2 is water logged, which is 27% of the total area. Salinity Control and Reclamation Project (SCARP) was initiated in the years 1980 to 1997. The SCARP team pumped water by installing 200 tube wells which led to vertical drainage. The report suggests that the practice of this vertical drainage was not successful because the water table did not recede.

The groundwater system of the Peshawar District has been disturbed because of the haphazard withdrawal to fulfill the drinking, commercial, industrial and agricultural need. The abstraction of water in the densely populated areas of the district may deplete the water table resulting in an excessive cost for supply. Also, from the literature the monitoring data is limited and discontinuous and access to this data is extremely difficult for the water managers and the farmers. Detailed groundwater modelling of the Peshawar District has not been made, and if any models exist they have been placed in offices without access to common research students and water managers. The necessity of groundwater modelling has been realised in that it would be a helpful tool to predict the groundwater behavior in response to the pumping.

1.8 Methodology and Materials

The methods are based around the objectives which have been set. Several steps are included in the methodology which is illustrated in the flow chart in Figure 1. To understand the general groundwater concept different literature on the international, national and the regional level were reviewed and studied. The consolidated materials which were studied thoroughly includes the topographical, hydrogeological, geological and groundwater modelling studies from different areas regionally and globally.

The data required for the model was obtained from the concerned public departments which include Water and Sanitation Services Peshawar (WSSP), Irrigation Department Peshawar, Water and Power Development Authority (WAPDA) and Peshawar Development Authority (PDA). The meteorological data was obtained from the concerned websites as well as from the latest updated public publications. Besides these data other related data was obtained from the consolidated previous literatures which include books, journals, conference papers, masters and PhD theses. The data obtained from the WSSP office includes the pumping data, log data and the observed water table depths, which were obtained for the year 2017.

The data obtained was screened and analysed to use for modelling of the proposed Peshawar District groundwater. Geographical Information system (GIS) Arc Map 10.4.1 was used for the preparation of the project area map and boundaries. Digital elevation model (DEM) data was obtained from the Shuttle Radar Topography Mission (SRTM) website with earth explorer. Georeferenced Tagged Image File Formats were downloaded, which are compatible with the GIS applications. Based on the DEM, the topographical contour map of the area was prepared. The hydraulic boundaries of the area were set and demarcated based on the hydrogeological features. Similarly, the groundwater abstraction rates obtained were imported to the GIS ArcMap10.4.1 and were converted and saved as a shape file so that they could be imported to ModelMuse (Winston, 2006), the user interface used in this study, which is based on the numerical model code MODFLOW 2005 (Harbough,2005).

The computer code used for modelling of the Peshawar District is ModelMuse-Modflow 2005. ModelMuse works as a graphical user interface for MODFLOW-2005 (Harbough,2005). The spatial data in ModelMuse is independent of the grid and the temporal data is independent of all the stress periods. ModelMuse has the built-in capability to import the DXF and shape files while inside the interface it has many interpolation methods, which makes the work easier. MODFLOW-2005 is a computer code that solves the three-dimensional finite difference equations for groundwater flow, it can simulate steady state and transient situations and the aquifer layers can be defined as either unconfined, confined or confined/unconfined. The spatial inputs can be graphically displayed, which makes it easier to debug or detect the error. Once the shape files were created using the GIS ArcMap 10.4.1 , they were imported to ModelMuse and the surface layer was generated for the upper and lower aquifer layers.

The boundary conditions were set based upon the conceptual model, and the solver criteria for the model were defined. Once the numerical model design was made the model was run in the steady state condition. Calibration was made by tweaking the sensitive parameters like the hydraulic conductivities of top and bottom layers. The model was calibrated through manual trial and error calibration. The process of calibration was performed manually by comparing the simulated heads with observed heads, which were obtained for the year 2017. The main output results included the hydraulic heads and groundwater budget. The results of the model were evaluated and discussed to draw several conclusions, upon which recommendations for future studies and investigations were proposed. In Figure 1 the flow chart shows the general methodology that is followed in the groundwater modelling process.

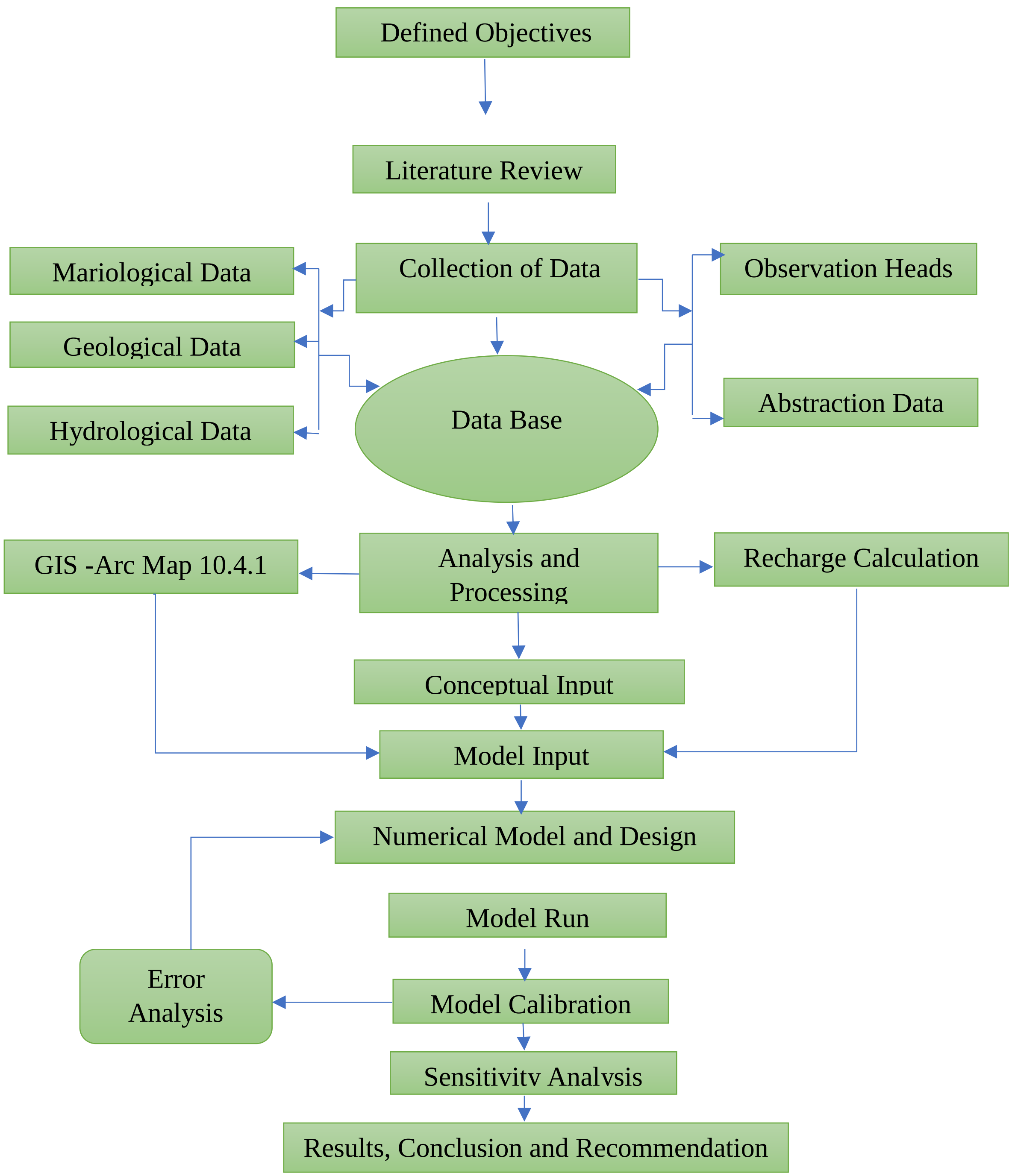


Figure 1. Flow chart explaining the methodology in the ground water modelling process

Chapter 2. Study Area

2.1 Description of the Peshawar District

The selected study area is the Peshawar District, which is the metropolitan city serving as the capital of the Khyber Pakhtunkhwa province in Pakistan. It has a great historical importance and serves as the hub for commercial, historical, industrial and political activities in the region of the Khyber Pakhtunkhwa province. Peshawar city is situated near the Pakistan and Afghanistan border at an altitude of 360 m above mean sea level. It is situated in the southern foothills of Himalaya between 33° 44′ to 34° 15′ northern latitude and 71° 22′ to 71° 42′ eastern longitude. Peshawar District is located 160Km away from the capital city Islamabad and is the biggest city in the Khyber Pakhtunkhwa (KP) province of Pakistan.

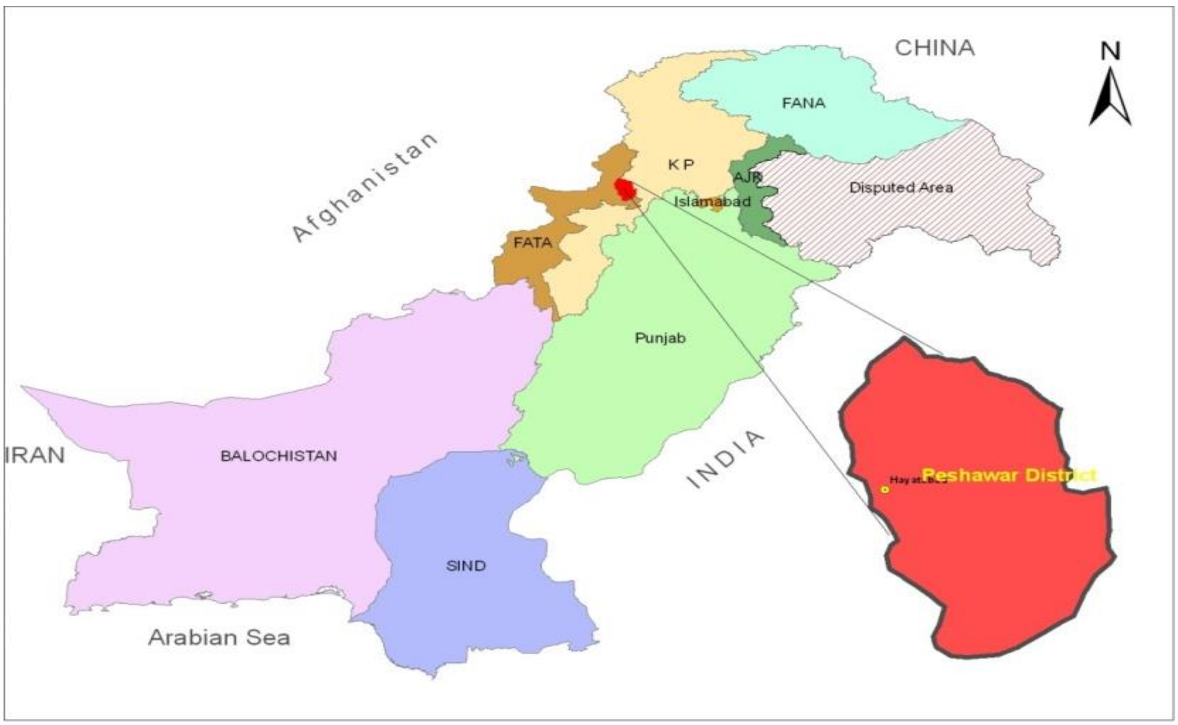


Figure 2. 1 Location map of Peshawar District
Source: UPU, 2014

Two agencies called Khyber and Mohmand agencies (out of the 7 Federal and Tribal Agencies (FATA)) are situated in the west and north west of the Peshawar. In the south, Kohat is situated while the districts of Charsadda and Nowshera are situated in the north and north east respectively (see Figure 2.1)

2.2 Administrative Division of the Peshawar District

The total area of the Peshawar District is 1257 km^2, which contributes only 1.69% of the total province area (Adnan & Iqbal, 2014). Administratively the district has been divided into 4 towns which include town 1, town 2, town 3 and town 4. From Figure 2.2, we can see that town 4 is bigger in size and contributes around 45%, of the land area while town 2 is 35%, town 3 is 16%, and town 1 including the cantonment areas is comprised of only 2% of the total district area. The total number of union councils in the district is 92 out of which 25 are situated in each of town 1 and 2, and 21 each in town 3 and 4. According to the urban master plan report (UPU, 2014), 48 union councils are declared as rural areas while the remaining union councils are considered as urban areas. There is only one tehsil (Tehsil is further division of district) called Peshawar Tehsil while there are total of 279 mauzas (villages) out of which 15 are declared as urban, 236 are rural while 28 are partly urban.

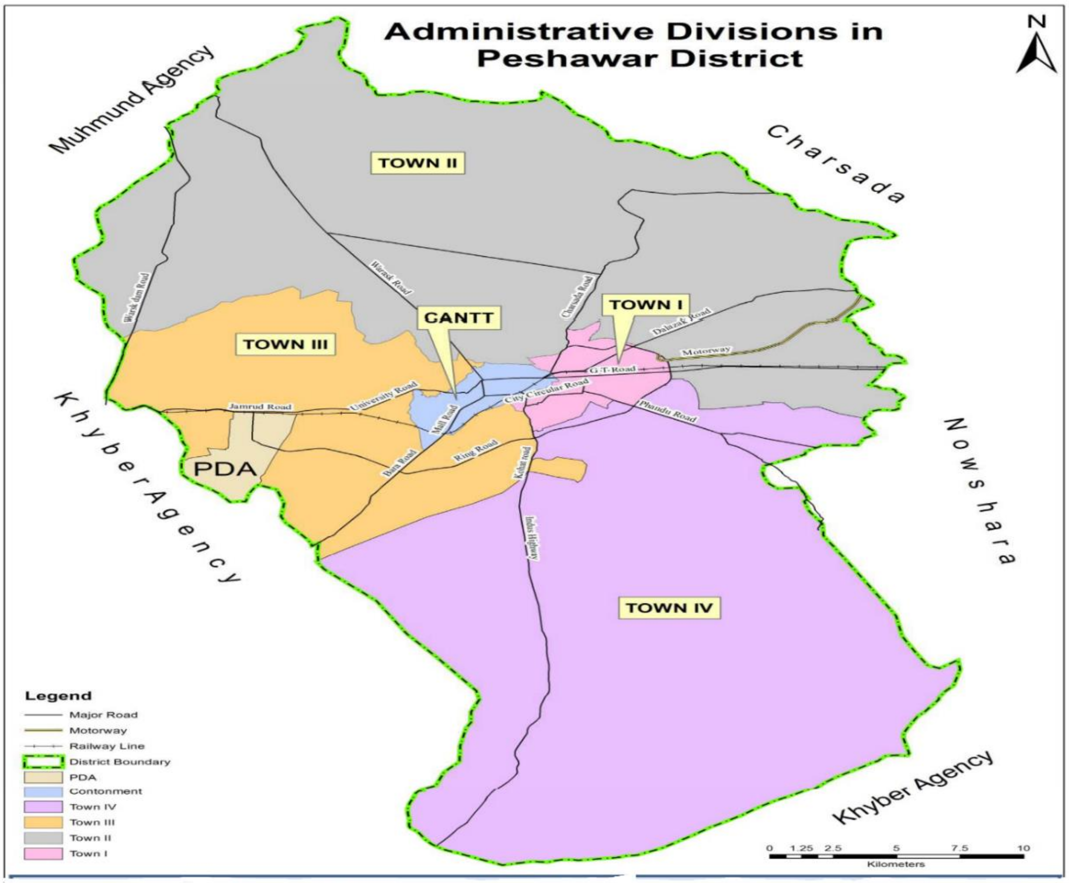


Figure 2. 5 Administrative division of Peshawar District
Source: UPU, 2014

2.3 Demography

2.3.1 Population

The population of Peshawar is growing rapidly and according to the census carried out in 2017, the population of the city is 4.27 million (PBS, 2017). As a whole 99% population is Muslim while Christians, Hindus and Sikhs also live in minority. Peshawar District serves as the economic hub in the province, therefore the influx of the migration from the rest of the rural areas has increased due to push and pull factors (Usman 2009). Push factor are those circumstances which compel the people to migrate to a specific area, while pull factors like employment, good health and good education are attractions which influence the people in rural areas to migrate the urban areas.

The population trend in the Peshawar District in various decades has been shown in Table 2.1. From the year 1972 to 1981 the growth rate in the population was 3.64%, from 1981 to 1998 the growth rate increased to 3.7% while from the year 1998 to 2017 it further increased to 4% and more than doubled. The bar graph shown in figure 2.2 also indicates the same growth trend.

Table 2. 1 population growth trend in decades

District Name	Population Census	Population Census	Population Census	Population Census
	9/16/1972	3/1/1981	3/1/1998	3/15/2017
Peshawar	807,012	1,113,303	2,026,851	4,269,079

Source: Pakistan Bureau of Statistics 2018.

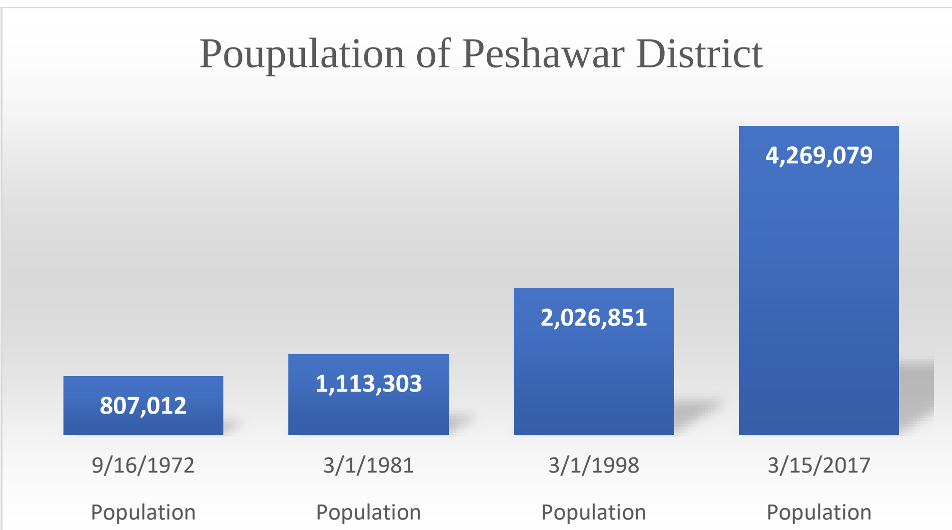


Figure 2. 11 Population trend in Peshawar District since 1972.

From the same source the proportion of the urban and the rural population of the Peshawar District as of 2017 census is tabulated in Table 2.2. Similarly, the pie chart in Figure 2.4 shows that 46% of the people are residing in the urban area while 54% are living in the declared rural area of the Peshawar District.

Table 2. 2 Urban & rural population proportion

Urban & Rural population (Census 2017)	
Rural	2,299,037
Urban	1,970,042

Source: Pakistan Bureau of Statistics 2018

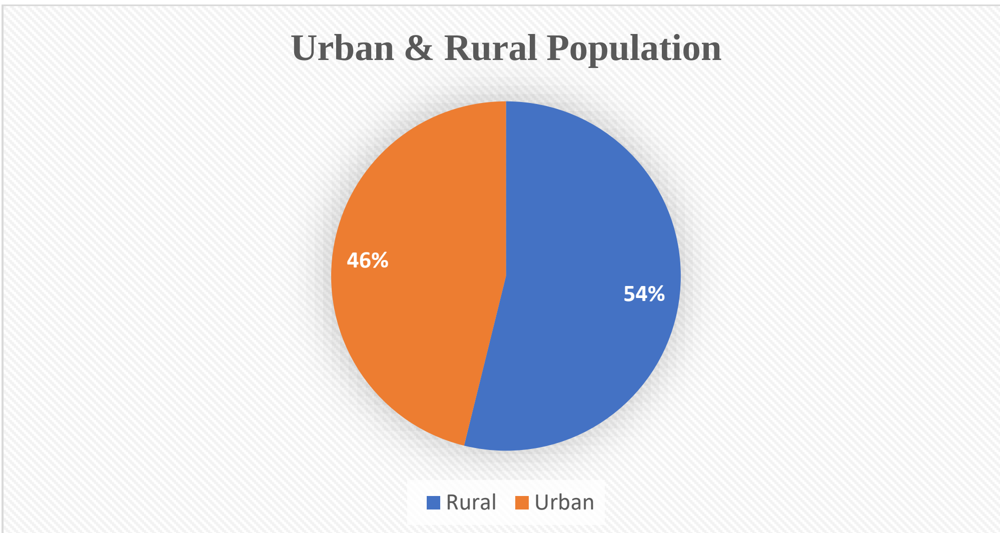


Figure 2. 12 Rural and urban population in Peshawar District

The male, female and the transgender population as of 2017 census is shown in Table 2.3 while the pie chart in Figure 2.5 shows 51.56% male, 48.43% female and 0.005% of transgender population in the district.

Table 2. 3 Gender population classification

Male	Female	Transgender
2,201,257	2,067,591	231

Source: Bureau of Statistics Khyber Pakhtunkhwa 2018

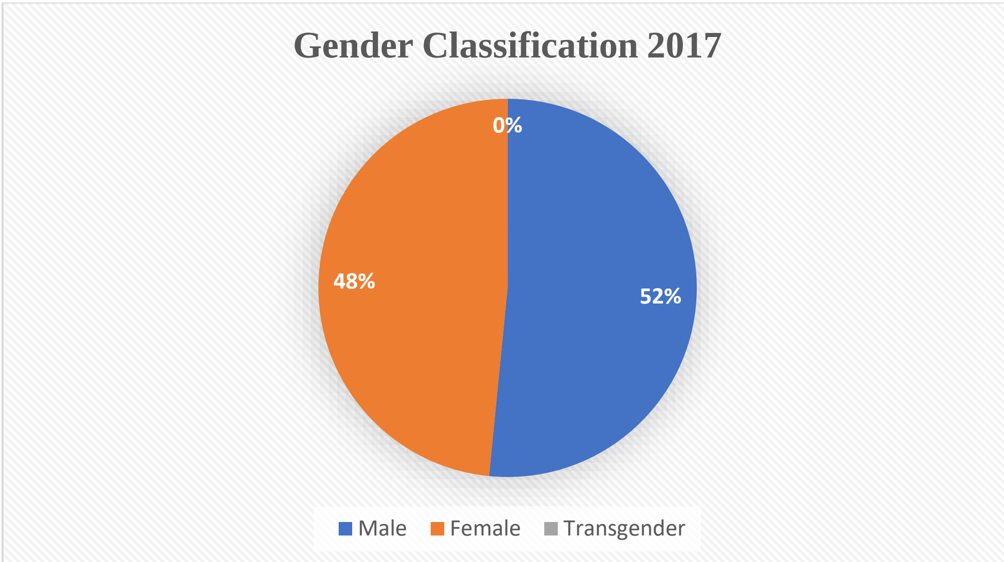


Figure 2.17 Male, female and transgender percentage

The increase in the population of the district is more compared to the other districts of the province which indicates that the city has attracted people from other districts because of the increased economic activities and attractive facilities (Naveed Khan, 2017). Beside the conventional migration, there is transient movement of people especially from upper hilly districts like Chitral, Sawat and Dir, which sees an increase in the winter season. The families visit the city for medical checkups, tuition, visiting relatives and to get warm due to the frozen winter weather in the upper districts. Thus, this temporary stay also puts extra pressure on the water resources. Current population density of the city is 3395/km^2 and the transitional movement puts extra burden over the resources and the local government has no facilities to cope with the situation**.**

The water supply to the population of the district is provided from groundwater except the part in the cantonment area where surface water from the Bara River is provided after filtration. The water treatment plant over the Bara River was constructed in 1918 providing water to the cantonment area as well as the three union councils in the town 1 but now it provides drinking water only to the cantonment area because of the reduced capacity and increased population (UPU, 2014).

2.4 Land Use Distribution

Proper distribution of land use is essential for the survival and development of people living in any part of the world (UPU, 2017). The endless human demand and the rapid urbanisation in the district of Peshawar has pushed the land resources to the extreme. The sprawl of industrialisation and urbanisation may affect the agricultural land and also the socio-economic condition of the area because most of the land is still dependent on agriculture. The current government has prepared a rational land use plan based on the natural resource's potential and the population requirements.

According to the latest land use report (UPU, 2017), existing land use distribution of the Peshawar District is divided into three categories. The zonation categories of the whole district have been shown in Figure 2.7, which include a northern or agricultural zone, an urban zone and a southern zone. Referring to Table 2.3 and Figure 2.6 the northern or agricultural zone covers a total area of 451 km^2 which is about 36% of the total area. Similarly, the urban area is 144 km^2 covering a total of 11% of the area. The southern zone is the largest one which covers an area of 662 km^2 or 53% of the total area from the table and figure respectively.

Table 2.3 land use distribution in zones

Northern Zone (km^2)	**Urban Zone (km^2)**	**Southern Zone (km^2)**
451	144	662

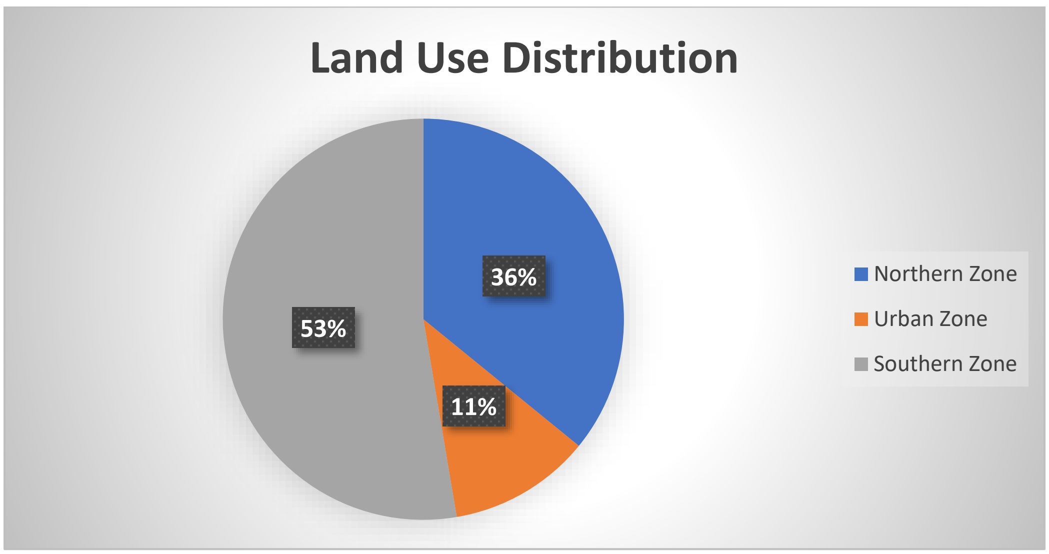


Figure 2. 26 Peshawar District Land Use in %

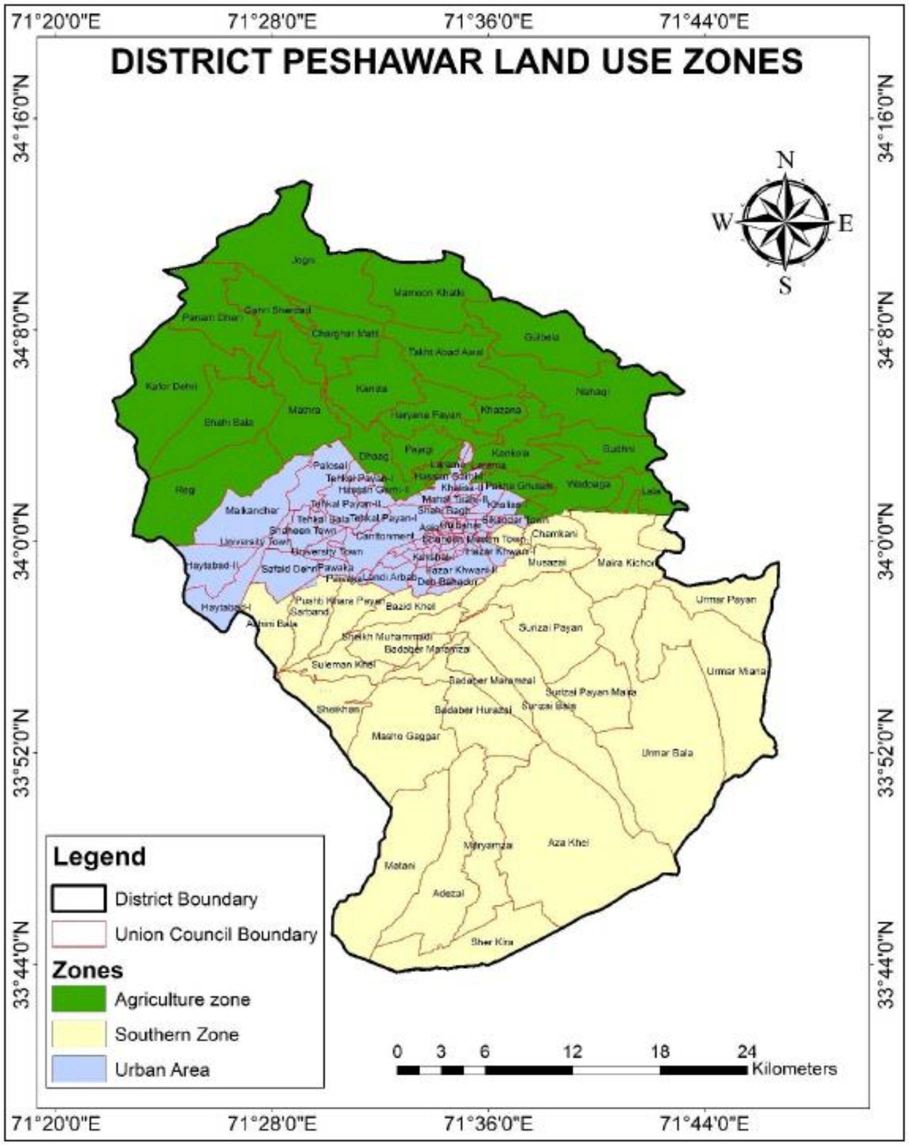


Figure 2.27 Land use zonation

Source: UPU, 2017

2.4.1 Land Use Distribution in Peshawar District

The Peshawar city acts as capital city of the Khyber Pakhtunkhwa (KP) province but still its major part has rural characteristics (UPU, 2017)**.** The urbanisation is rapidly stretching in all directions but referring to Table 2.4 and Figure 2.8 out of the total area of 1257 km^2, 62 % of the total area is used for agriculture. 11% is the open land while the country side settlement is occupied by 10%. Similarly, 6% is urban settlement, 4% is covered by water bodies, 1% is reserved for industries and commerce while the remaining 6% is covered by roads, railways and their terminals, and graveyards.

Table 2. 7 Land use distribution of Peshawar District (km^2)

Agriculture	Open Land	Rural Settlement	Urban Settlement	Water Bodies	Industries, Commercials	Roads, Terminal, Grave yards etc.
785	139	120	70	50	15	78

Source: Provincial Land Use Plan Planning & Development Department KP, 2017

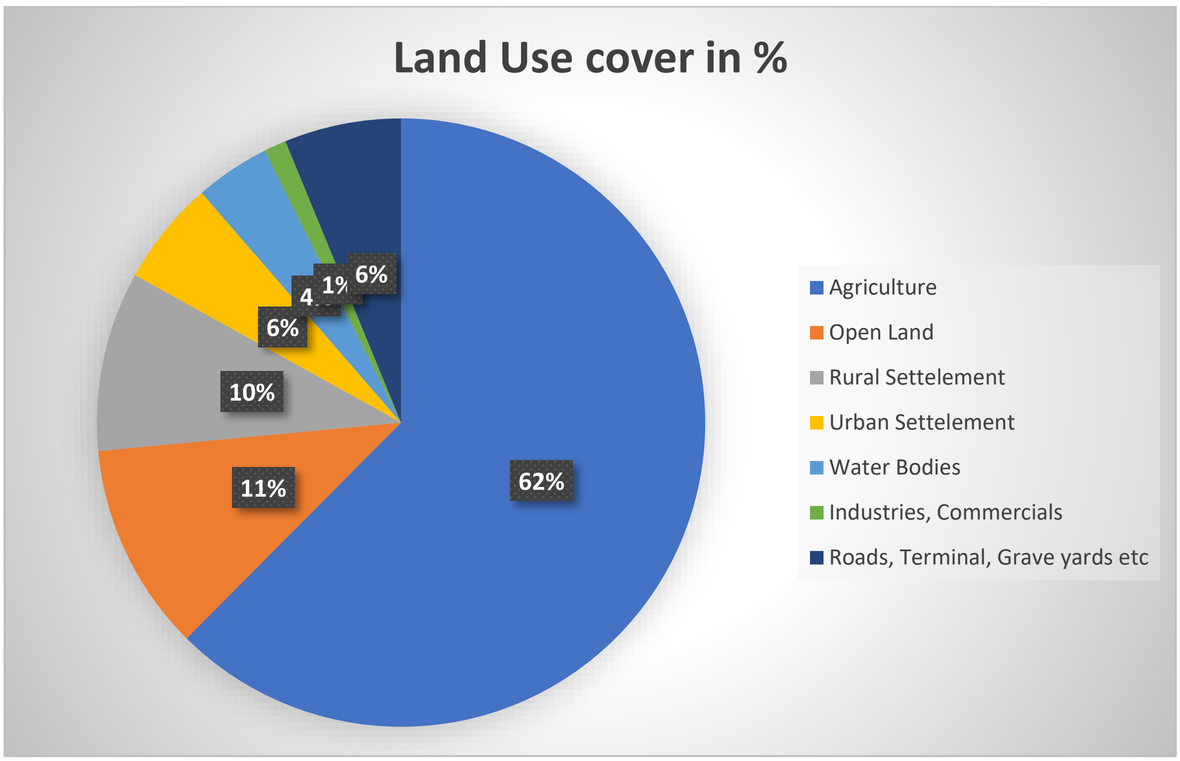


Figure 2. 36 Land use coverage in Peshawar District

The agricultural component is the biggest land cover and the irrigation is mainly done from surface canals and tributaries, which infiltrate down into the groundwater and raise the water table (UPU,2014). However, in the past couple of decades the construction of rigid concrete structures in the form of roads, buildings, commercial areas in urban and rural sectors has been increased without considering the recharge areas. The water infiltration in to the ground can therefore be assumed to be blocked, which may affect the groundwater table's vertical position.

2.5 Climate

Physical conditions like temperature, rainfall, humidity and pressure, which have a direct or indirect impact on the biosphere are all aspects of the weather and the weather pattern in a region over a period of time is referred to as the climate (Cunningham et al, 2005). The climate of Peshawar is semi-arid, consisting of a very hot summer from the months of May to September and a mild winter from November to March. The maximum temperature in the summer season, hot in May and June in particular, exceeds 42 degrees centigrade (C°), while the mean temperature is 25 C°. In the winter season the mean minimum temperature drops to 2 C° while the maximum is 18 C°. The most pleasant season is the start of the March where the spring sets in and the flowers start blooming. The influence of the monsoon rainfall and the western disturbances result in the increase of humidity but for most of the time it remains under the average level of 42 to 70% during the year (UPU, 2014).

The land of Peshawar District receives rainfall both in winter and summer. Figure 2.9 shows 50 years rainfall data from 1967-2017. From the pattern the average annual rainfall calculated is 420mm. The highest annual rainfall was recorded in the year 2003, which saw 904.5mm of precipitation. The lowest rainfall of 200 mm took place in 1972. Similarly, 236mm was the highest monthly winter rainfall recorded in 2007 while the highest monthly summer rainfall was recorded in the 2010, which was 402mm. The surface wind speed is variable and ranges from 2 to 6 knots. Table 2.5 shows maximum and minimum mean monthly temperature data from 1981-2010 and while figure 2.10 is the plot of that data. From figure 2.10 maximum mean temperature recorded is in month of June while the minimum mean temperature recorded is in the month of December.

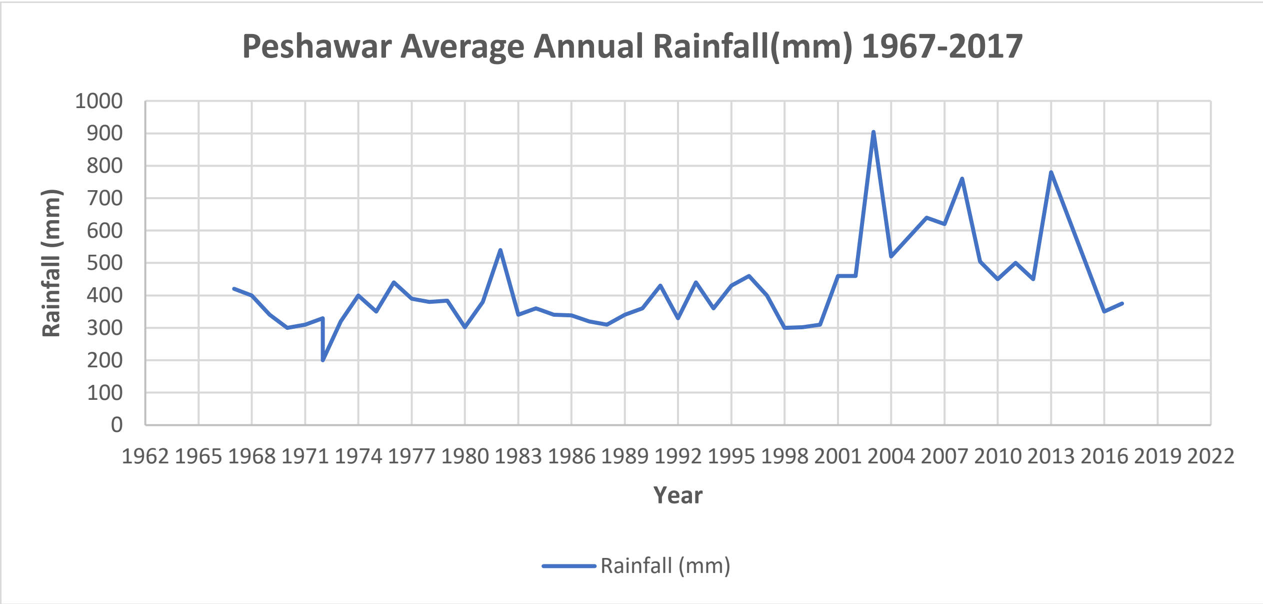


Figure 2. 37 Mean annual rainfall profile of Peshawar District (50-year averages data)

Source: Pakistan Meteorological Department (http://www.pmd.gov.pk/)

Table 2. 8 Mean monthly temperature data (1981 to 2010)

Parameters/Months	Jan	Feb	Mar	Apr	May	Jun	Jul	August	Sep	Oct	Nov	Dec	Annual
Mean Max Temp (C◦)	18.6	20.2	24.5	30.6	36.9	39.9	37.8	36	35	31.3	25.6	21	29.8
Mean Min Temp (C◦)	4.3	7	11.8	16.7	21.7	25.3	26.5	25.9	23	16.1	9.8	5.3	16.1

Source: Pakistan Meteorological Department (http://www.pmd.gov.pk/)

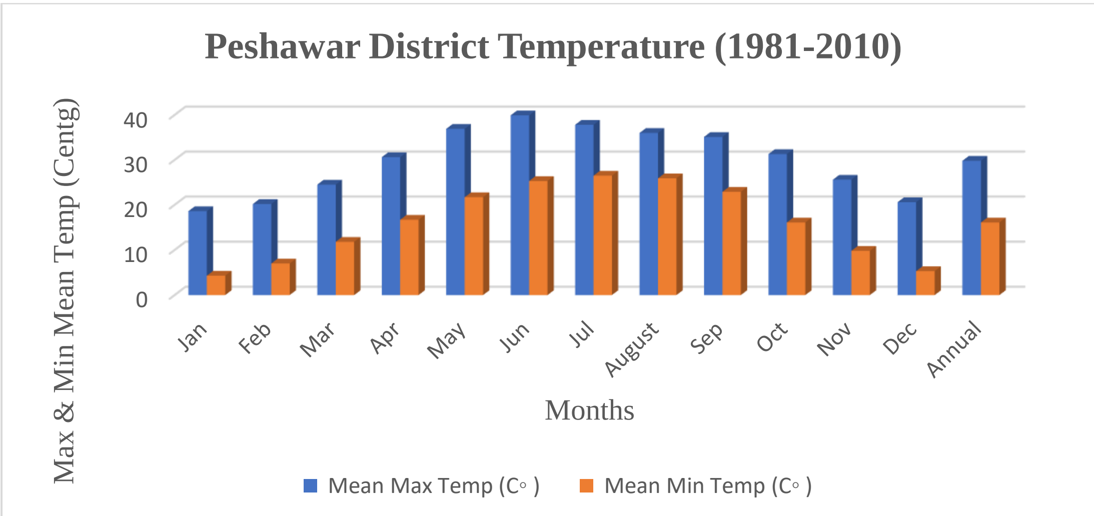


Figure 2.10 Mean monthly temperature profile of Peshawar District (30-year averages)

2.6 Groundwater

Main drinking water supply to Peshawar District is provided by abstracting the groundwater by pumping. The groundwater, which is called Peshawar basin groundwater, prevails over an area of 6270 km^2 (Naqvi, 1988). The flow direction is from southwest to the northeastern side and drains to the Kabul River, which flows along the eastern edges of the Peshawar. The valley is comprised of alluvial deposits which have been eroded from the near surrounding mountains. These fills make the Peshawar District aquifer, which provides groundwater to the Peshawar region.

The groundwater was investigated in 1968 when the re-regulating (regulating the flow rate) of the Warsak reservoir was started. The investigation was carried out on the right bank of the Kabul River by WAPDA and indicated that two aquifers exist in the area. The upper aquifer is the unconfined water table aquifer with a depth of 61m while the bottom aquifer is a semi-confined aquifer having a thickness of 120m. Permeability of the lower aquifer is 10 times lower than the shallow upper unconfined layer. The recharge to the groundwater takes place from infiltration of rainfall from the surrounding mountains and the seepage taking place from irrigation practices. The quality of the water from the last 40 years has remained good but with rapid urbanisation and man-made activities, E-Coli has been reported from different points in the shallow aquifer (Bacha, 2017).

2.7 Surface Water

The surface water of the Peshawar District comes from the Kabul River, Bara River and the streams draining from mountain sides (UPU,2014). The main source of water supply for the irrigation purpose is the Kabul River, which enters in to Peshawar District boundary from near the north edge and moves across the area in a south easterly direction. It further divides in to Adizia and Naghuman Rivers. The Adizia River flows on the southern boundary of the Charsadda district. Naghuman river splits into two rivers and then they both join up again further downstream in the eastern part of the Peshawar district. The Bara River originates from the Tira Valley and enters the Peshawar District from the southern boundary, moving across the district to join the Kabul River at on the eastern side of the region near Nowshera district**.** There are a series of ephemeral streams originating in the mountains in the western and southern part of the district, which eventually drain towards the eastern side and finally to the Kabul River. The agricultural land of the Peshawar District, which constitutes around 62% of the total land area is irrigated by five canals, which take water from the Kabul River. These canals are the Kabul River canal, Hazar Khani canal, Warsak Gravity Lift canal, and Joe Sheikh canal.

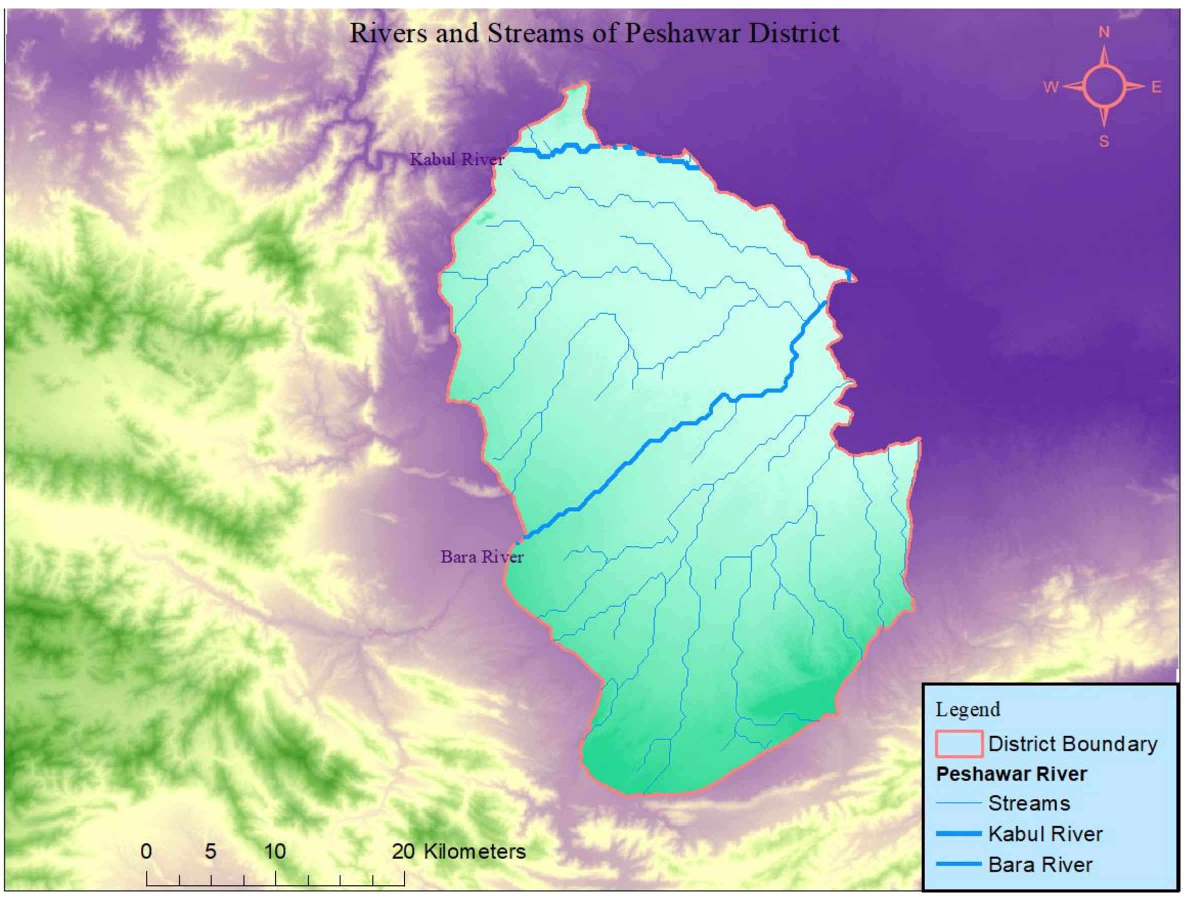


Figure 2.11 Surface water of Peshawar District

Chapter 3.

Topography, Geology and Hydrogeology

3.1 Topography

Peshawar District is surrounded by mountains at its western and south western edges. The major central and the eastern part of the Peshawar District is flat. Referring to figure 3.1 the gentle slope can be seen from the south towards west and then from the north towards the eastern direction. Bara River and all the streams originating from the southern and the western part slope towards the north east and drain to the Kabul River, which flows on the eastern edges of the Peshawar District**.** The surface elevation of the flat central part varies from 300 to 330m while the highest elevation may vary from 450m to 600m as seen on the topographical map in figure 3.1**.**

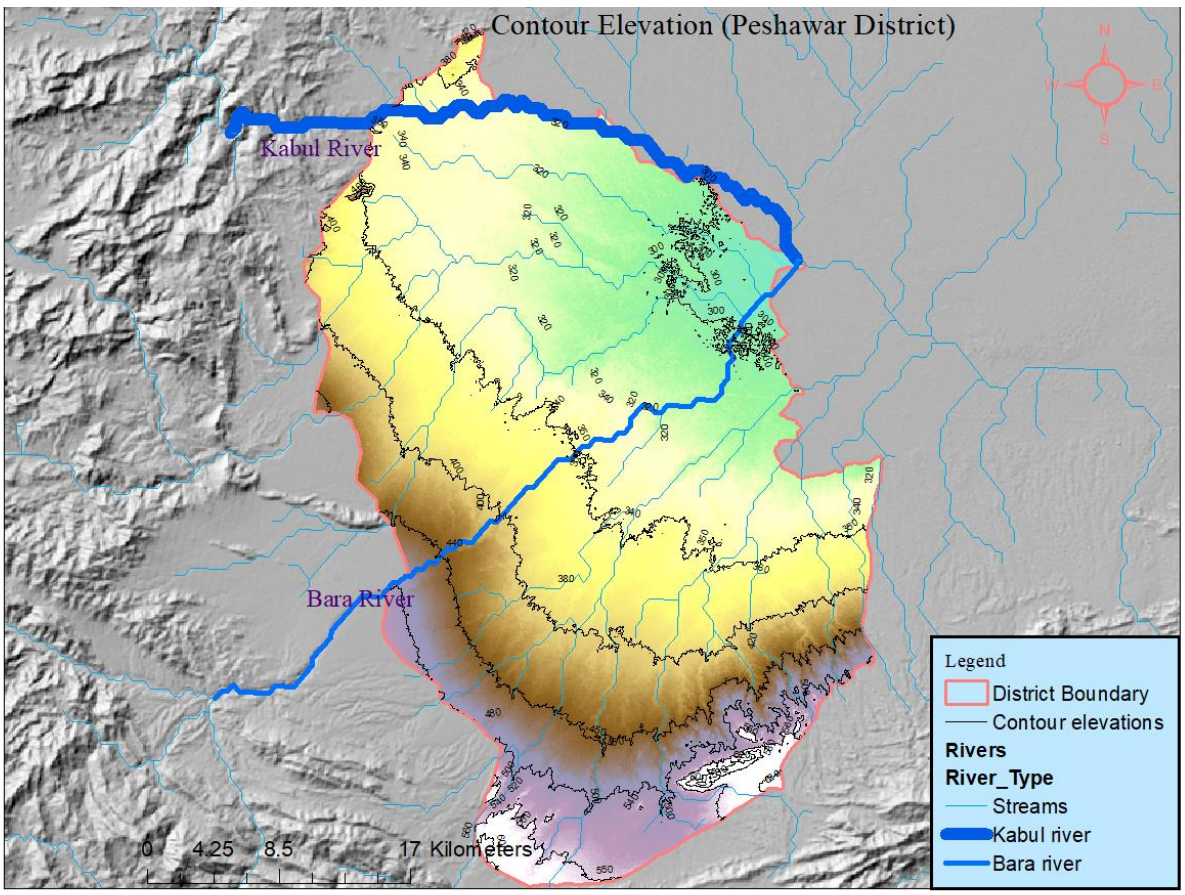


Figure 3. 1 Ground surface contour elevations of Peshawar District

3.2 Geology

The Peshawar district is one of several within the Peshawar vale, the vale basin area covers more than 6270 km^2 and forms part of the Indo-Gangetic foredeep (Kruseman and Naqavi, 1988). The valley is surrounded by high mountains at its three sides. The mountains are ranged in the southwest, southeast and in the west of the Peshawar making a complex of undulated and deformed metamorphic and sedimentary rocks. According to Burbank and Tahirikheli (1985) it became an intermountain basin around 2.3 million years ago when the Attock Ridge was cut off from the northwestern corner of the Indo-Gangetic plain. The surrounding exposed ridges of the Peshawar vale range from the Precambrian to Tertiary ages (Rafiq et al. 1983). The Peshawar area has remained under various transformations, which resulted in the formation of the current state as shown in the Figure 3.1. During the middle Pleistocene, the Peshawar area formed several lakes several times due to the outflow blockage of the Indus River (Nizami, 1973). Alternate layers of sand and silt can be seen because of the deposits of the lake. Intercalation of the loess and lacustrine strata at some places also give an indication of the dry period between the two lake periods. Once the area was drained properly the shifting rivers formed the sandy and silty alluvial deposits. The loess cover was removed by several erosion cycles in the middle Pleistocene.

Slate, silty shale, sand stone and hard shale are the major constituents of the Pre-Cambrian sequence (UPU, 2014). Throughout the Cretaceous, Jurassic, Eocene and Pleistocene ages various sandstone, limestone, clay stone and shale units were deposited. The dominant exposed rock at the southern margin of the Peshawar Basin are the Precambrian to Devonian rocks of the Himalaya. The basin sediments were folded and faulted during the deposition process (Nizami 1973). According to Naqvi (1988) the western and the northern area of the Peshawar valley consists of metamorphic rocks with igneous intrusion.

In the Safed Koh range, the area of the Warsak is included, which forms the Cretaceous-Tertiary Himalayan orogenic system. A syncline structural feature of the area is obscured partially towards the north eastern direction by alluvium. The rocks have been dipped at different angles varying from 30 to 70 degrees and the syncline plunges to the north. The alluvial deposits consisting of sand, gravel, clay, boulders and silt are products of the erosion process, which saw the surrounding rock weathered and then transported by the stream flow. The central part of the Peshawar basin is comprised of the flood plain deposits along the river which are filled with clayey lacustrine deposits with sandy intercalations overlain by younger alluvial deposits. Coarser sediment is found at the mountain front, having been left behind as the river removed the finer material(UPU,2014).

The project area consists of the alluvial deposits, which contain boulders, gravel, sand, silt and clay. The foot hill is separated by the courser materials of the cemented conglomerates, which are classified as piedmont deposits, while the rest of the area consisteds of alluvial deposits of clay and sandy materials. The land to the west and south west of the Peshawar vale is covered by cemented gravels and sand, with recharge to the groundwater resulting from percolation through these sediments. The land bordering the mountains in the west and south west of the project area are permeable and have a significant impact on the recharge to the ground. The piedmont deposits of the Pleistocene age are distributed to south (UPU, 2014). The flood plain deposits are laid down by the Kabul River and consist of clay and silt with thin beds of sand and gravel.

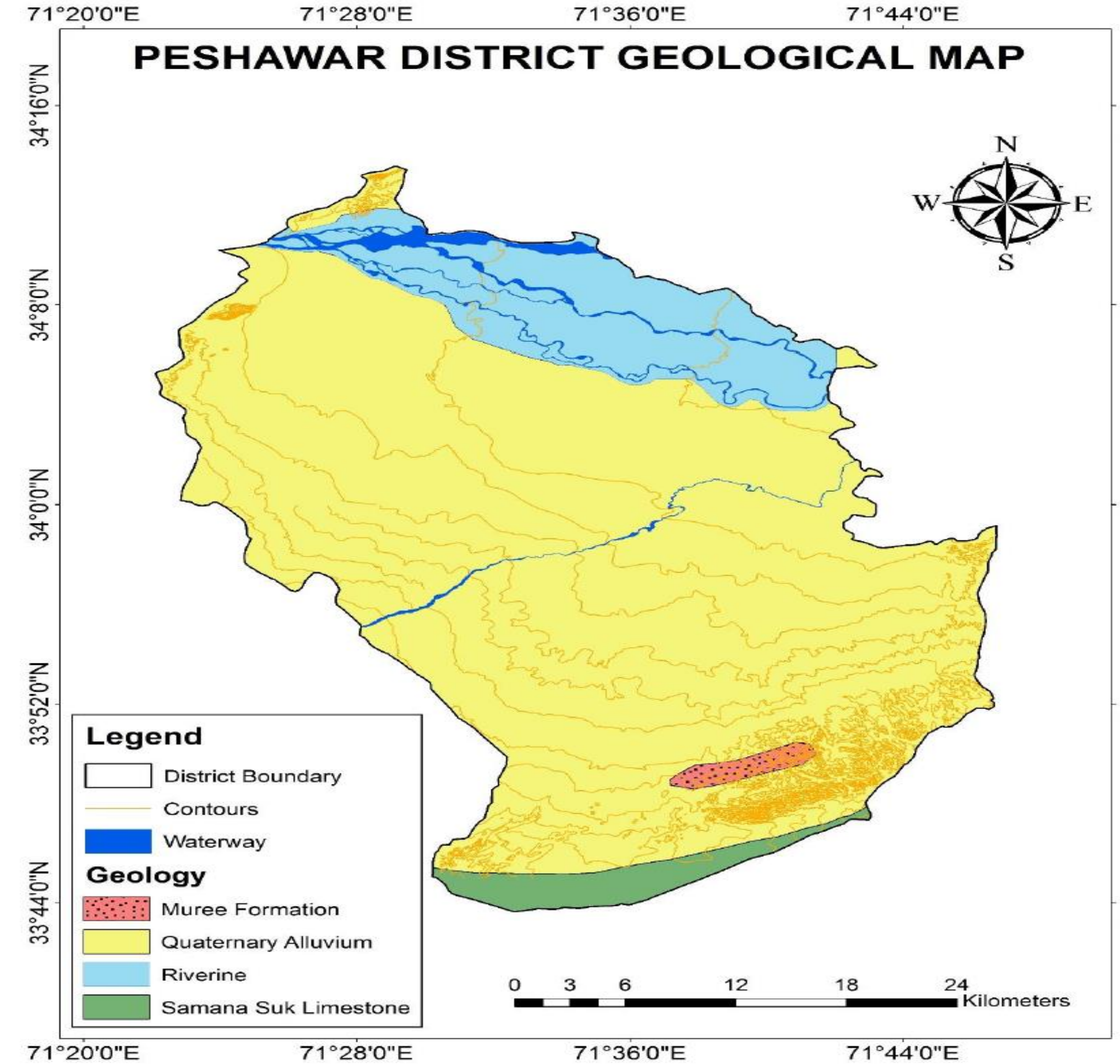


Figure 3. 3 Geological map of the Peshawar

Source: Geological Map of North-West Frontier Province Pakistan-2006, Geological Survey of Pakistan,

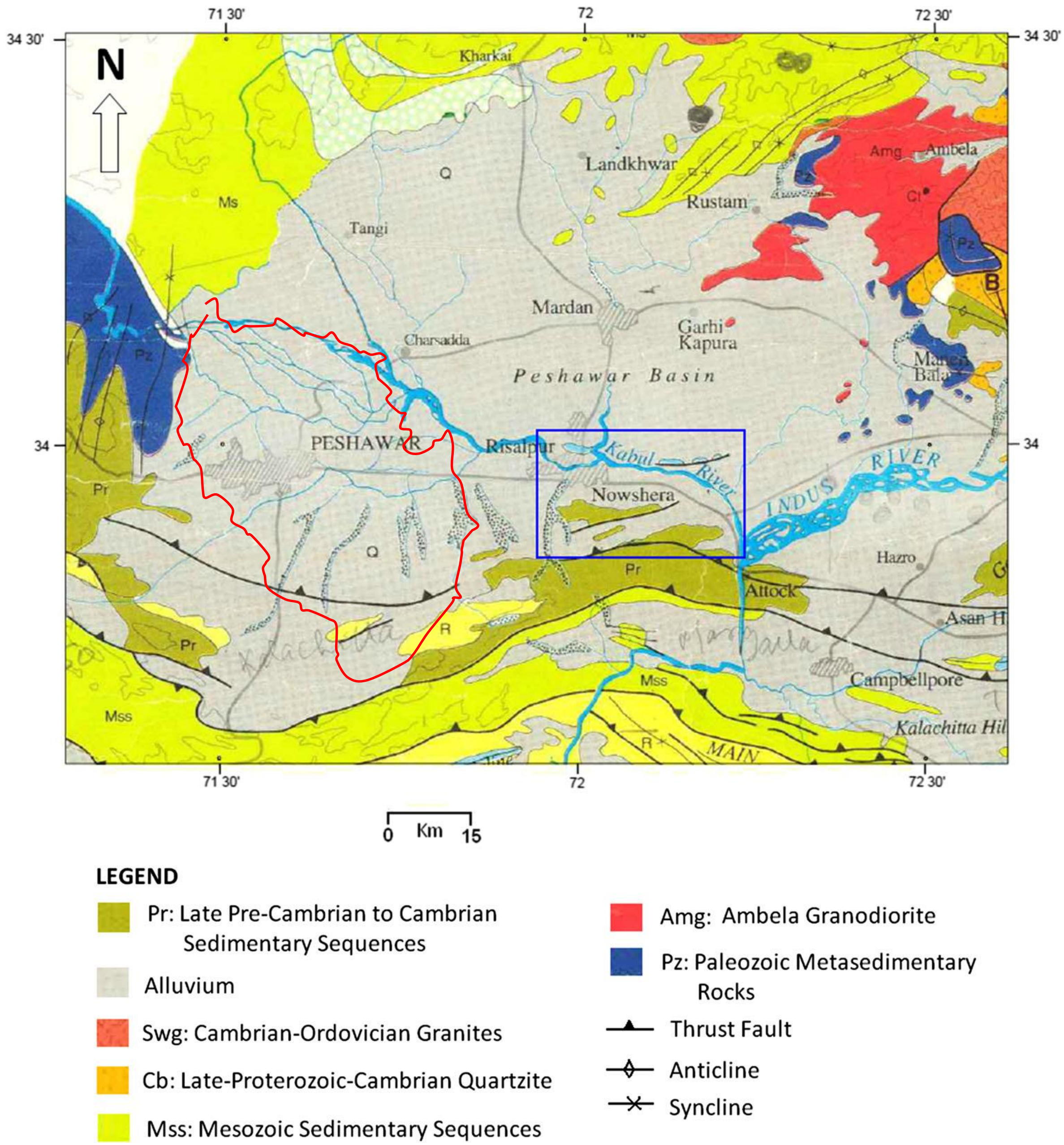


Figure 3. 5 Geological map of Peshawar District study area is highlighted in

Source (modified from Searle et al. 1996)

Figure 3.2 shows the generalised geological map of the area obtained from the geological survey of Pakistan where the whole district is categorised as Riverine, quaternary alluvium, Murree formations and Samana Suk limestone series. In Figure 3.3 the boundary highlighted with red colour represent the selected Peshawar District.

3.3 Principal Hydrogeological units

The geological formation has been subdivided in to hydrogeological units for groundwater modelling and analysis. Based on the available borehole log data and their properties, layers and sediment deposits have been identified. The geological units of the area are not uniform and show heterogeneity both in the lateral and vertical extent (Kruseman and Naqavi, 1988). According to the studies carried out by (UPU, 2014) two hydrogeological units have been identified for the Peshawar District which is shallow and deep aquifer based on their hydrogeological properties, borehole studies. The shallow aquifer is an unconfined aquifer of 61m average thickness. The lower or deep aquifer is a leaky or semi-confined aquifer which extends from 61m to a depth of about 180m and this means its saturated thickness is 120m. The cross section of the project area shows the distribution of the sediment's layers and although the stratification varies from borehole to borehole, the absence of prominent change in groundwater level at short distance gives an indication that hydraulic continuity between layers exists and based on this it can be assumed that hydraulic interaction occurs between the gravel and sand layer to form the large regional aquifer (Kruseman & Naqavi, 1988).

Along the Kabul river various escarpment could be seen which are predominantly composed of alluvial fan deposits and in addition to that sand, silt and clay which are bedded horizontally are present throughout the Peshawar basin (Cornwell, 1998). Southeastern part of Peshawar extending to the Nowshera area has been studied in detail by Muhammad and Khalid (2017). This area studied is the part of the Peshawar basin which covers the central flood area near the Kabul river and is considered as gravel sand sediments belonging to an alluvial fan environment. The sediments have been transported by the weathering and erosional process suggesting a low degree of sorting in the sediments and ranging a composition of the sand, gravels, and pebbles interconnected with clays and other fine materials (Mohammad & Khalid, 2017). The subsurface lithology of the Peshawar basin at Nowshera has been corelated to the Peshawar District by studying seven number of boreholes (W1- W7) in the Nowshera area . The major lithological logs from the seven boreholes is shown in Figure 3.4. From the borehole in Figure 3.4 it is evident that the sediments at shallow subsurface up to more than 5m is silty clay, clay and gravel mixed. However below 10m and up to 60m it shows a variety of interconnected layers ranging from courser towards finer. The depth below further and up to 150m it shows finer material of clay and silt mixed with sand and gravel.

Based on the above studies the subsurface lithology of the Peshawar District has been divided into two main Hydrogeological units for the modelling purpose. This has been done by assigning the upper layer up to 61m as shallow unconfined aquifer and the lower layer of 120m thick as semi-confined aquifer**.**

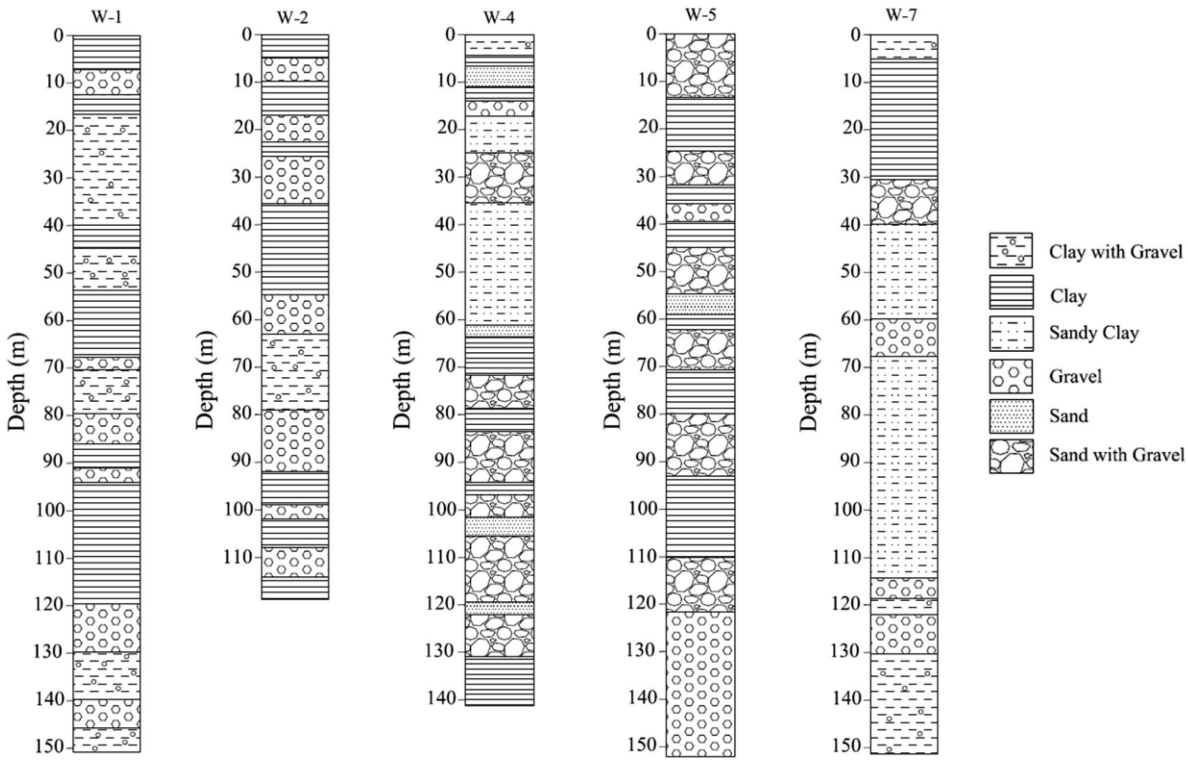


Figure 3. 7 Bore hole lithological logs at Nowshera (southeaster side of the Peshawar District) Source: (Mohammad & Khalid, 2017).

Based on the above discussion two hydrogeological units of the Peshawar District with sediment type are summarized in Table 3.1 below.

Table 3. 1 Principal hydrogeological units classification

Hydrogeological Unit	**Sediments Deposits**
Shallow Aquifer	Gravel, sand, silt
Deep Aquifer	Sand, , silt and clay

3.4 Hydraulic Properties

Horizontal and vertical hydraulic conductivities are the sensitive parameters, which are key for calibrating the groundwater model (Reilly, T.E. & Harbaugh, A.W., 2004). Water and soil investigation division (WASID) drilled 38 test holes in the area varying in depth from 30 to 215m. To determine the aquifer parameters like hydraulic conductivity (K), transmissivity (T) storage coefficient (S) and specific storage, WASID converted 12 test holes into test wells (UPC, 2014). Thus, based on the laboratory tests the values have been tabulated in Table 3.2. The hydraulic conductivity of the shallow aquifer varies from 1.64 to 4.75m/day while for the semi-confined aquifer it varies from 0.074 to 0.298m/day. The sand size ranges from 0.18-0.33 mm while for the gravel it varies from 1.1 to 3.1mm. Specific yield for the gravel deposits is 37% while for the silty clay it is 13%. The transmissivity of the upper aquifer is high ranging from 200 to 500m^2/day but it starts reducing as the grain size starts diminishing (UPU,2014).

Table 3. 2 Hydrogeological properties of the Peshawar District aquifers.

S.NO	**Description**	**Unit**
1	Sand size	0.18-0.33 mm
2	Gravel	1.1-3.1mm
3	Porosity	42%
4	Specific yield for silty clay	13%
5	Specific yield for sand gravel	37%
6	Hydraulic conductivity for sand and gravel mixed	1.64-4.75m/day
7	Hydraulic conductivity for clay, silt and gravel mixed	0.074-0.298m/day
8	Transmissivity	200-500m^2/day

Source: (Urban Policy Unit master plan report , 2014)

3.5 Surface and Groundwater Interaction

When rainfall occurs some of the water gets infiltrated into the ground while the remaining water flows as runoff or sheet flow in the Peshawar District. According to Kruseman and Naqavi,(1988), the rainfall recharge to the ground takes place from the elevated edges near mountains where the strata is coarser. As the Bara River flows into the district from the south western part and the River Kabul flows along the eastern part, the influence of these rivers over the recharge of the groundwater is also a key factor. Around 62% of the Peshawar is an agricultural area, which is being fed by four canals taken from the Kabul River. About 25-30% of water is being infiltrated back into the water table within the irrigation land of the Peshawar area while from the annual precipitation of 420mm more than 4% gets infiltrated and also provides recharge to the groundwater resource(Kruseman and Naqavi, 1988).

Recharge from rainfall and surface irrigation practices has been calculated and tabulated in Tables 3.3 and 3.4 respectively. The agricultural activities in the Peshawar District are performed during two seasons called Rabi season and Kharif season. Rabi crops are cultivated before the winter season begins and harvested in early summer while the kharif crops are sown at the beginning of the summer and harvested in the start of winter**.** The calculation of surface irrigation water losses for the model area has been made based on the tentative estimation methods followed by Robert (1988). According to the studies carried out by (Saeed and Khan, 2014) on the Warsak irrigation canals in Peshawar, total percolation losses from the surface irrigation amounts to 35% of the total diversion from the inlet canals. The calculation of recharge taken place by irrigation in Table 3.3 has been made based on the winter and summer crop season water requirement which was proposed by Robert (1988) and followed by Kazmi & Naqvi (1988) when the hydrogeological investigation Peshawar basin was carried out.

The calculation in table 3.3 has been made based on the following assumptions

1. The water depth in Rabi and Kharif crop season is known to be 0.16m and 0.786m respectively.
2. As 1 hectare covers an area of 10000m^2, therefore the volume required per hectare for Rabbi and Kharif season would be
   $V = 10000(m^2/hac) * water\ depth\ (m) = 1600m^3/hac\ and\ 7860\ m^3/hac$
3. The total cropped area is 111,680 hectares
4. Half of the total area is cropped in Rabbi season and half during Kharif season, so the cropped area in Rabbi is 558,40 hectares and 558,40 hectares in Kharif.
5. The total water requirement is obtained by multiplying the cropped area in hac/year with the water volume per unit hectare (m^3/ha).
   Thus, Total water requirement= Cropped area in (ha /year) * water volume per unit hac (m^3/ha)= m^3/year
6. The summation of the Rabi and Kharif water requirement is the total water quantity in m^3/year which is converted into m^3/day and 30 % of this amount is assumed as the water percolation losses.

The detailed calculation of the above explanation is tabulated in table 3.3 which is given below

Table 3. 3 Calculation of annual water recharge from the surface Irrigation

Surface water Irrigation percolation losses				
S.No	**Description**	**Rabi**	**Kharif**	**Units**
1	Water depth	0.16	0.786	m
2	Water volume in (m^3/ha)	1600	7860	m^3/ha
3	Cropped area hectares (ha/year)	558,40	558,40	Ha/year
4	Total water (2*3) m^3/year	949,280,00	441,136,000	m^3/year
	Total water quantity in m^3/year	536,064,000		m^3/year
5	Total water quantity per day	1468668.5		m^3/day
	Total 30 % percolation loses		**440,601**	**m^3/day**

The water depth (m) and crop area is known and the quantity that percolates as water loss from the irrigation area and irrigation canal is termed as the groundwater recharge.
Referring to table 3.3, the total cropped water requirement in the area is 1468,669 m^3/day

and in order to have this quantity available 30% of water gets infiltrated by seepage, which is 440,601 m^3/day.

The recharge area for the precipitation has been taken as equal to the model area which is 1745 km^2. Few studies have been made to estimate the groundwater recharge from the rainfall in study area. The Water and Power Development Authority (Kruseman & Naqavi, 1988) took groundwater recharge as 4% of rainfall whilst carrying out their investigative study of the Peshawar area. In Table 3.4 the recharge flux has been shown and thus the total recharge from the rainfall has been assumed to equate to 4% of the total annual rainfall (Kruseman and Naqavi, 1988).

The calculation detail is given below

Total mean annual rainfall in Peshawar District =420mm/year or 0.42m/year

4% as groundwater recharge= 0.42 m/year *0.04= 0.0168m/year

or

Groundwater recharge in (m/d) = **0.00005m/day**

Similarly, the water losses by irrigation practices as explained in table 3.3 is converted into m/day as below

Total water losses in (m^3/day) = 440,601 m^3/day

Total area (Model area) = 1745000000 m^2

Recharge (q)= V/A

Recharge = 440,601 m^3/day/1745000000 m^2 = **0.000253m/day**

The above calculated recharge values have been tabulated in table 3.4 which is given below.

Table 3. 4 Total recharge to the groundwater

S.No	**Recharge**	**Total model area in km^2**	**Recharge in m/day**
1	Precipitation	1745	0.00005
2	Losses by surface irrigation	1745	0.00025
	Total Recharge		**0.0003**

Evapotranspiration takes place in the eastern part of the district where the water table is high, and this area includes the areas near the Kabul River where an evapotranspiration depth of up to 5m has been reported (UPU, 2017). According to Roberts (1988), the total groundwater discharge from the SCARP area (2000km^2) is 1Mm^3/year. Out of the total evapotranspiration from the SCARP area, Peshawar District area contributes a total of 25000 m^3/day. This amount of evapotranspiration takes place over an area of around 200km^2, where the water table depth is shallow. Table 3.5 refers to the evapotranspiration value applied over the entire model.

Table 3. 5 Evapotranspiration

S.No	Description	Total Area (km^2)	ET in m/day
1	Evapotranspiration	1745	0.000014

3.6 Groundwater Abstraction

The abstraction of groundwater takes place for the purpose of domestic, agricultural, commercial and industrial use. The amount of water abstraction of the different line departments and private users is discussed.

1. Government tube wells

Guldaraz, Mujahid and Akbar (2014) mentioned the total number of submersible and turbine tube wells operating in Peshawar District. Table 3.6 gives the total number of tube wells and their abstractions operated by different line departments.

Table 3. 6 Water abstraction by public wells

Government pumping wells in Peshawar District			
S. No	Description	Total no of tube wells	Abstraction in m^3/day (12 hours operation)
1	Public wells	670	386,699

These tube wells are being operated by Water & Sanitation Services Peshawar (WSSP) and Peshawar Development Authority (PDA), Public Health Engineering Department (PHED), Military Engineering Service (MES), Cantonment Board and Irrigation Department. Table 3.7 is the fragmented list of the 670 tube wells being operated in four administrative towns and one cantonment area within Peshawar District.

Table 3. 7 Fragmented public wells list

S. No	Location	No of tube well	Discharge m^3 per day
1	Town I	222	119052.8
2	Town II	76	47924.8
3	Town III	205	123720
4	Town IV	123	73116
5	Cantonment area	44	22885
Total		**670**	**386,699**

Out of the above 670 tube wells, 494 of them have their exact coordinates plotted and are being operated by WSSP as urban unit areas while the remaining tube wells have been lumped and placed on the model area based on their respective distribution within the administrated towns. Figure 3.5 shows the distribution of the 494 number of tube wells within the jurisdiction of the urban area. Urban area covers town I, the major area of town III, Cantonment area, PDA area and some area of town III and town IV.

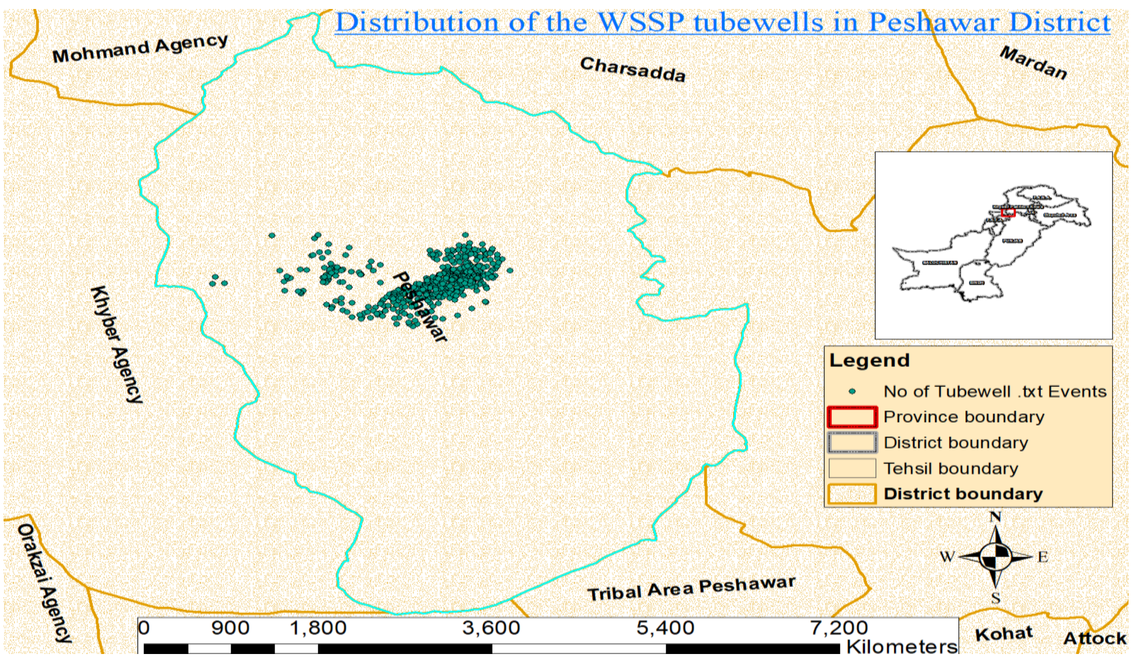


Figure 3. 8 WSSP tube wells with known coordinates in the urban area of Peshawar District

2.Commercial, private or community tube wells

On average there are 6 commercial tube wells in each union council having an individual average commercial well discharge of 0.209 m^3/sec (Guldaraz, Mujahid & Akbar, 2014). Since there are 92 union councils in the district the total number of tube wells operating is approximately 592. From Table 3.8, the total discharge in m^3/day indicates that the tube wells operate approximately for 4 hours in a day.

Table 3. 8 Commercial tube wells

Commercial tube wells in Peshawar District				
S. No	Description	**Total no of tube wells**	**Total discharge in m^3/sec**	**Abstraction in m^3/day (4 hours operation**
1	Commercial	552	0.209	2903

3.Hand Pumps in Peshawar District

People in the rural parts of the district have no access to government tube wells and therefore have to use their own manual hand pumps. The government usually does not hold a proper record of these pumps**.** Guldaraz, Mujahid and Akbar (2014) carried out a survey to find out the total number of hand pumps in the Peshawar District. They selected 5 union councils each from town 2, 3 and town 4 and came up with the calculation that 25% of the population in each selected town consume water by using the hand pumps which is 0.0477 l/s. As the hand pumps on average operate for two hours a day, the conversion of 0.0477 l/s gives an average daily demand of 343 l/day per capita. By assuming that 40% of the population of the three towns consumes water with an average daily demand mentioned as above then a total abstraction of 422,378 m^3/day is required**.** From Table 3.9 we can see that there are 67 union councils within the three towns, so if there are 7 hand pumps operating in each union council in town 2, and 6 hand pumps in each union council for towns 3 and 4 then a total of 428 hand pumps are required as total for the model. The hand pumps have been plotted on the GIS-ArcMap 10.4.1 in the respective union councils of the towns 2, 3 and 4. Figure 3.6 is an administrative division map of the project area where all the towns are visible with demarcated boundaries.

Table 3. 9 Water abstraction by hand pumps in town 2, 3 & 4**.**

Towns	Area (km^2)	Population 2017	Discharge of the hand pump per day (l/day)	Consumption by 40% population (m^3 /day)	No of Union Councils	Distributio n of hand pump	Discharge (m^3/day) per hand pump
Town 1	26	1,047,342					
Town 2	414	1,131,669	343	155,464	25	175	888.37
Town 3	171	983,667	343	135,132	21	126	1072.48
Town 4	632	959,276	343	131,782	21	127	1037.65
Cantonment Area	15	147,125					
Total	**1258**	**4,269,079**		**422,378**	**67**	**428**	

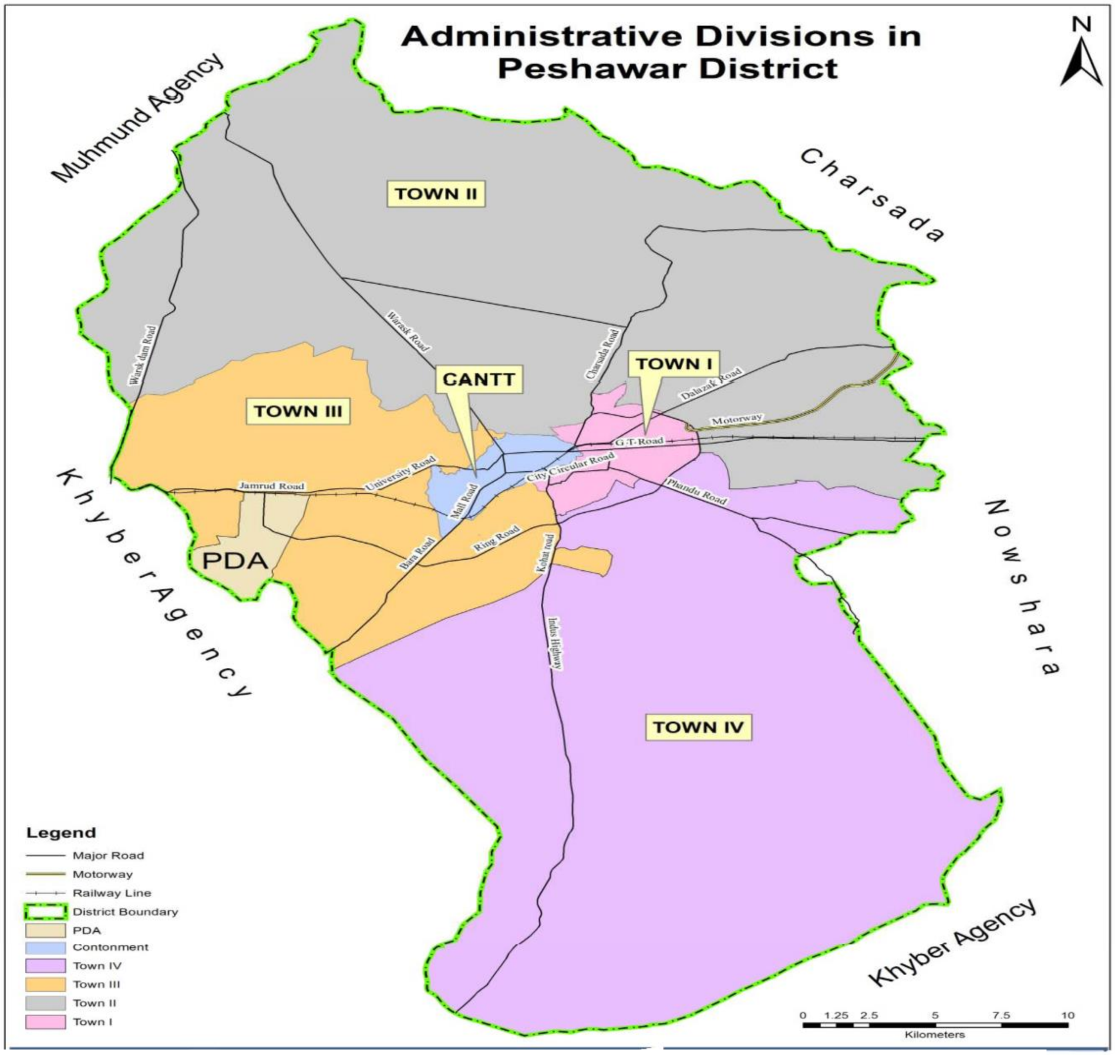


Figure 3. 11 Administrative divisions of Peshawar District
Source: http://puf.urbanunit.gov.pk

4.Abstraction by dug wells

The dug well data is maintained by the irrigation department and according to Guldaraz, Mujahid and Akbar (2014) a total of 63 dug wells are being operated with an average discharge of 0.01 m^3/sec each. Table 3.10 shows the total pumping rate which normally operate for 12 hours a day.

Table 3. 10 Dug Well in Peshawar District

Dug wells in Peshawar District				
S. No	Description	Total no of dug wells	Total discharge m^3/s	Abstraction (m^3/day)
1	Dug wells	63	0.642	27,734

The total water pumping from the various sources as discussed above is tabulated in Table 3.11. We can see that a total of **839,715m³** of water is being abstracted per day from the ground**.** Figure 3.7 is a GIS map representing the total number of wells over the project area.

Table 3. 11 Groundwater abstraction detail in Peshawar District

S. No	Description	Total no of tube wells	Abstraction (m^3/day)
1	Public wells	670	386,699
2	Private wells	552	2,903
3	Hand Pumps	428	422,378
4	Dug well	63	27,734
Total			**839,715**

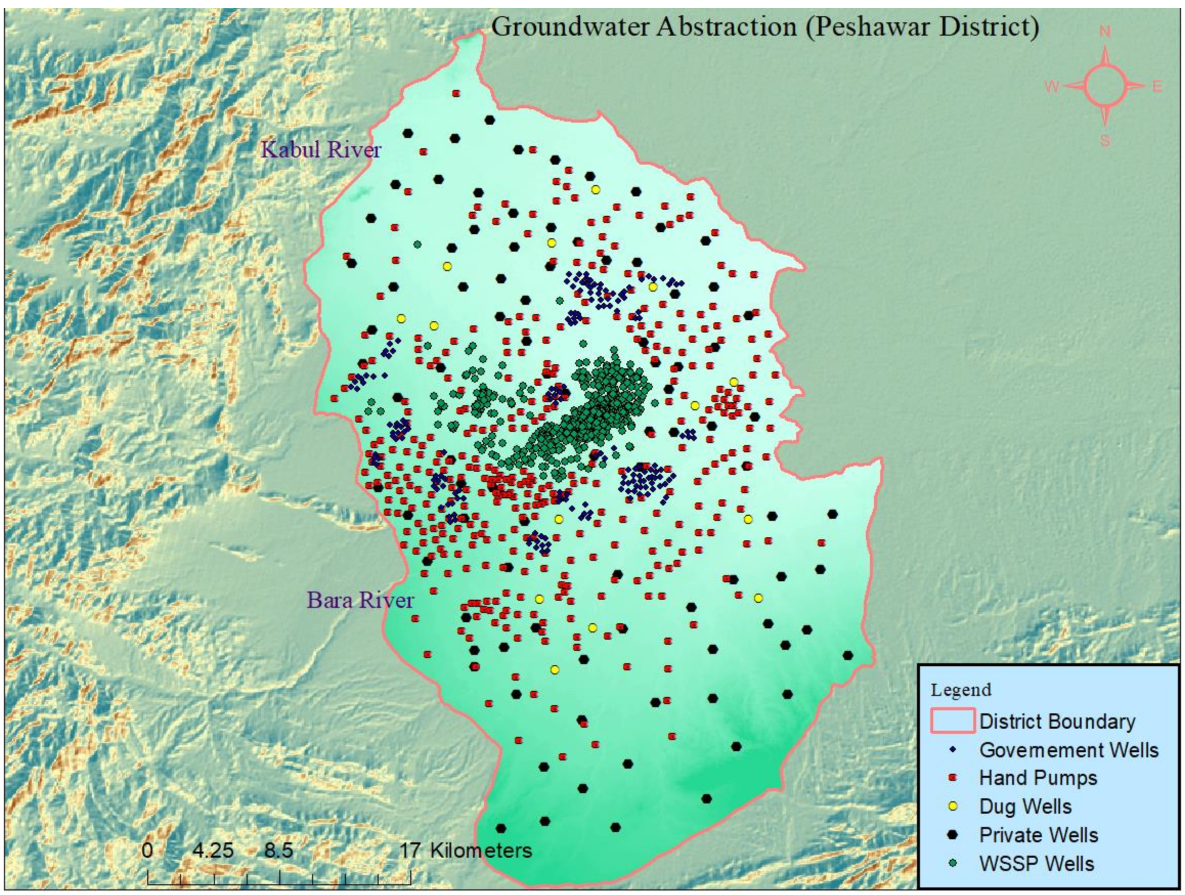


Figure 3. 14 Groundwater abstraction from various sources (Peshawar District)

Chapter 4

Groundwater Flow Modelling

Groundwater models represents a simplified form of the real word situation and are based on simplifications and assumption with an intention to investigate certain phenomenon or predict the future behavior of water(Baalousha et al, 2013). In every branch of science including hydrogeology, models are helpful and widely used to understand and test the responses of the real-world systems. The significant demand to predict the impacts of human involvement on groundwater systems and the environment has resulted in the advancement of groundwater flow modelling approaches (Pathak et al, 2018). Groundwater models can have a wide range of applications such as the evaluation of regional groundwater resources management, which includes the prediction of hydraulic heads in response to abstraction, possible migration of contamination and its control, and to develop groundwater monitoring tools.

4.1 Governing Equation in Groundwater Flow Modelling

The rate of flow of water is proportional to the water properties, porous material and the hydraulic gradient, which was show by French engineer Henry Darcy in the form of an equation. The Darcy law is given below

$$q = -K(\frac{dh}{dl}) \qquad \text{eq. 4.1}$$

Here q is the specific discharge or the Darcian velocity vector, K is the hydraulic conductivity while dh/dl is hydraulic gradient, which represents the change in head between two points per unit distance between those two points. The velocity vector q could be represented in terms of its components in qx, qy and qz, while the gradient vector can be represented as $\partial h/\partial x$, $\partial h/\partial y$, $\partial h/\partial z$.

The second important law is the continuity equation and for the steady state condition it is stated that the amount of water flowing or entering the system, or the representative elementary volume, must be equal to the amount of water going out. As the state is steady there is no change in the heads, therefore the continuity equation can be written as

$$\frac{\partial qx}{\partial x} + \frac{\partial qy}{\partial y} + \frac{\partial qz}{\partial x} = 0 \qquad \text{eq. 4.2}$$

When Darcy's Law and the continuity equation are combined we are left with a resultant second order differential equation that is the Laplace equation. By putting the Darcy law into equation 4.2

$$\frac{\partial}{\partial x}\left\{-k\frac{\partial h}{\partial x}\right\} + \frac{\partial}{\partial y}\left\{-k\frac{\partial h}{\partial y}\right\} + \frac{\partial}{\partial z}\left\{-k\frac{\partial h}{\partial z}\right\} = 0 \qquad \text{eq. 4.3}$$

For homogeneous and isotropic conditions, the value of K would be independent of the directions in X, Y and Z. By this assumption the equation 4.3 becomes

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \qquad \text{eq. 4.4}$$

Under homogeneous isotropic and steady state conditions, equation 4.4 is the governing equation for groundwater flow, which is also called the Laplace equation (Wang and Anderson, 1995).

In the transient state conditions, the derivation of the governing equation is modified with inclusion of the rate of change of storage. The change in storage is equal to the difference between water flowing into and out of the representative elementary volume. A positive change in storage equates to a higher volume in than out, and a negative change in storage the opposite. In this connection a new term called the storage coefficient, S is introduced, which is volume of the water released from a storage per unit surface area per unit decline in the water head. Mathematically the storage coefficient can be written as

$$S = -\frac{\partial Vw}{\Delta x \Delta y \Delta z} \qquad \text{eq. 4.5}$$

The volume of water released from storage can be written as $\frac{\boldsymbol{\partial Vw}}{\boldsymbol{\Delta t}}$ but from the equation 4.5 $\boldsymbol{\partial Vw = -S\Delta x\Delta y\Delta z}$ therefore as change in time or Δt approaches 0 then $\partial Vw = -S\Delta x\Delta y(\frac{\Delta h}{\Delta t})$. Therefore, for transient conditions the continuity equation becomes the following if equation 4.2 is used.

$$\frac{\partial qx}{\partial x}\Delta x(b\Delta y) + \frac{\partial qy}{\partial y}\Delta y(b\Delta x) + S\Delta x\Delta y\left(\frac{\Delta h}{\partial t}\right) = R\,(X,Y,Z)\Delta x\Delta y \qquad \text{eq. 4.6}$$

Simplification of equation 4.6 further by using T=Kb

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S(\Delta h,)}{T\,\partial t} - \frac{R(X,Y,Z)}{T} \qquad \text{eq. 4.7}$$

Equation 4.7 can be simplified by

$$\frac{\partial}{\partial x}\left\{kx\frac{\partial h}{\partial x}\right\} + \frac{\partial}{\partial y}\left\{ky\frac{\partial h}{\partial y}\right\} + \frac{\partial}{\partial z}\left\{kz\frac{\partial h}{\partial z}\right\} + R = Ss\frac{\partial h}{\partial t} \qquad \text{eq. 4.8}$$

Darcy's law + continuity: Head as a function of x,y,z + Change in storage with time

Sources & sinks

Equation 4.8 is the 3-dimensional governing equation for the transient flow.

4.2 Developing the Model

The aim of developing the model is to investigate and describe the Peshawar District groundwater basin aquifers flow system by using numerical groundwater flow equations. The powerful computer system availability coupled with user friendly modelling software and GIS as a map tool has enabled the fast growth of regional groundwater modelling **(**Zhou, and Li , 2011). The numerical model has been developed based on hydrogeological data and other related information gathered and described in the previous chapters. Based on the input data availability and their screening, the model will be run in response to the stresses imposed and results in the form of changing hydraulic heads could be examined for the different time intervals and stress periods.

4.3 Conceptual Model

Construction of the conceptual model of the aquifer system and highlighting the associated problems is the first important procedural step. Based on the objective of the model the assumptions are setup with the view to simplify the real-world problems and it is critical that the hydrogeological conditions are represented appropriately (Barnett et al, 2012). As the spatial variation in the real geology makes the real-world groundwater system complex, the need of simplification is always required. Sometime over simplification may result in innapropraite realisation while sometime the reductionist approach may result in making the modelling work costlier. Therefore, the development of a rationale appropriate conceptual model based on the simplified assumptions is important (Poeter and Anderson 2005). As the grid design and the dimensions of the model are determined by the conceptual model, the failure or inability to make predictions is often attributed to the conceptual model (Kahsay,2008).

The conceptual model is the step or the stage, which is developed by using the knowledge and available data of interest in a region. This includes the description of the physical features of the area and flow process in the groundwater. The understanding of the key groundwater process and influence of the stresses such as sources and sinks will assist the model to predict the future changes **(**Barnett et al., 2012).

The Peshawar District conceptual model has been developed based on the available data obtained from the concerned departments and from consolidated literature. This includes the hydrogeological data, well logs and cross sections of the maps. The project area is represented by a schematic diagram in Figure 4.2, which shows the aquifer systems information and the discretization. The conceptual model is a key step in which the groundwater flow and the associated hydrogeological information is provided in order to allow the modeler to produce a model behaving like the real-world situation.

The development of the Peshawar aquifer conceptual model includes the following.

1. Defining the model area and identifying the boundaries

The modelling area is the Peshawar District of the Peshawar basin as discussed in the previous chapter number 3. The model boundaries represent the interface between the model domain and the surrounding environment. Therefore, the description of the hydrogeological features and their influence over the model boundaries must be understood with great care. The boundaries largely determine the pattern of the flow; therefore the correct selection of boundary conditions is a critical step in the design of the model (Anderson and Woessner, 1992). Boundary conditions that are wrongly assigned can lead to large differences in fluxes into and out of the model domain, which strongly impact the output results in the water balance of the model.

In the groundwater flow modelling process the boundaries may include a physical boundary, which could be determined by geological formations and surface water bodies, or it could be hydraulic boundaries like groundwater flow divides or flow lines. Figure 4.1 shows the generic sketch of the conceptual model of the Peshawar District where streams, active and non-active cells, constant head and the no flow regions have been shown.

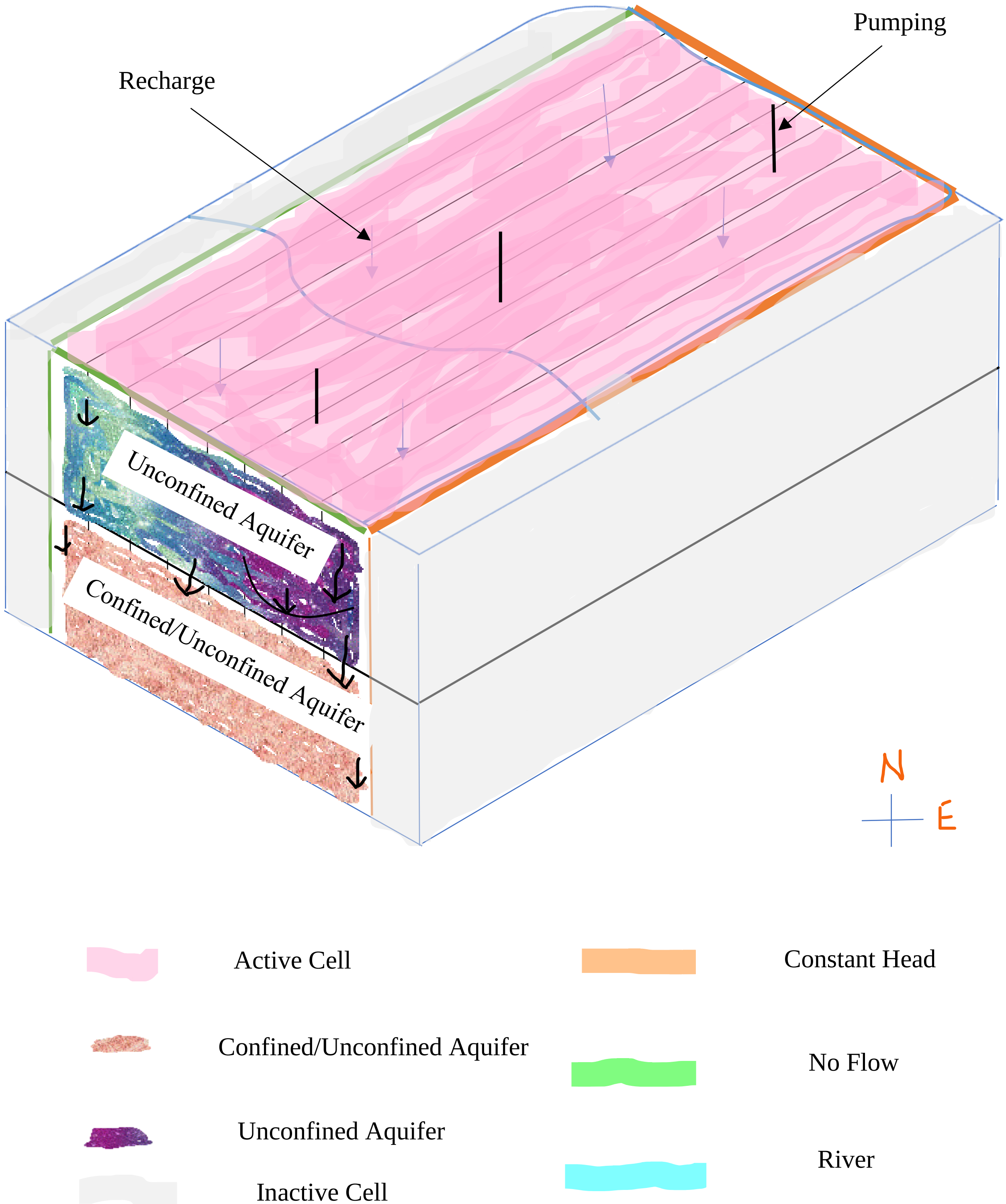


Figure 4. 1 Conceptual model of Peshawar District (boundaries and aquifer system)

The Project area of the Peshawar District is surrounded by the mountains along the west and the southern sides. Based on the available data and the investigation of the previous literary references the boundary conditions of the Peshawar area have been selected and have been shown in Figure 4.2. The north and eastern model edges have been selected at the Kabul River and classed as a constant head boundary whilst the southern and western edges have been classed as a no flow boundary due to the presence of impermeable rocks.

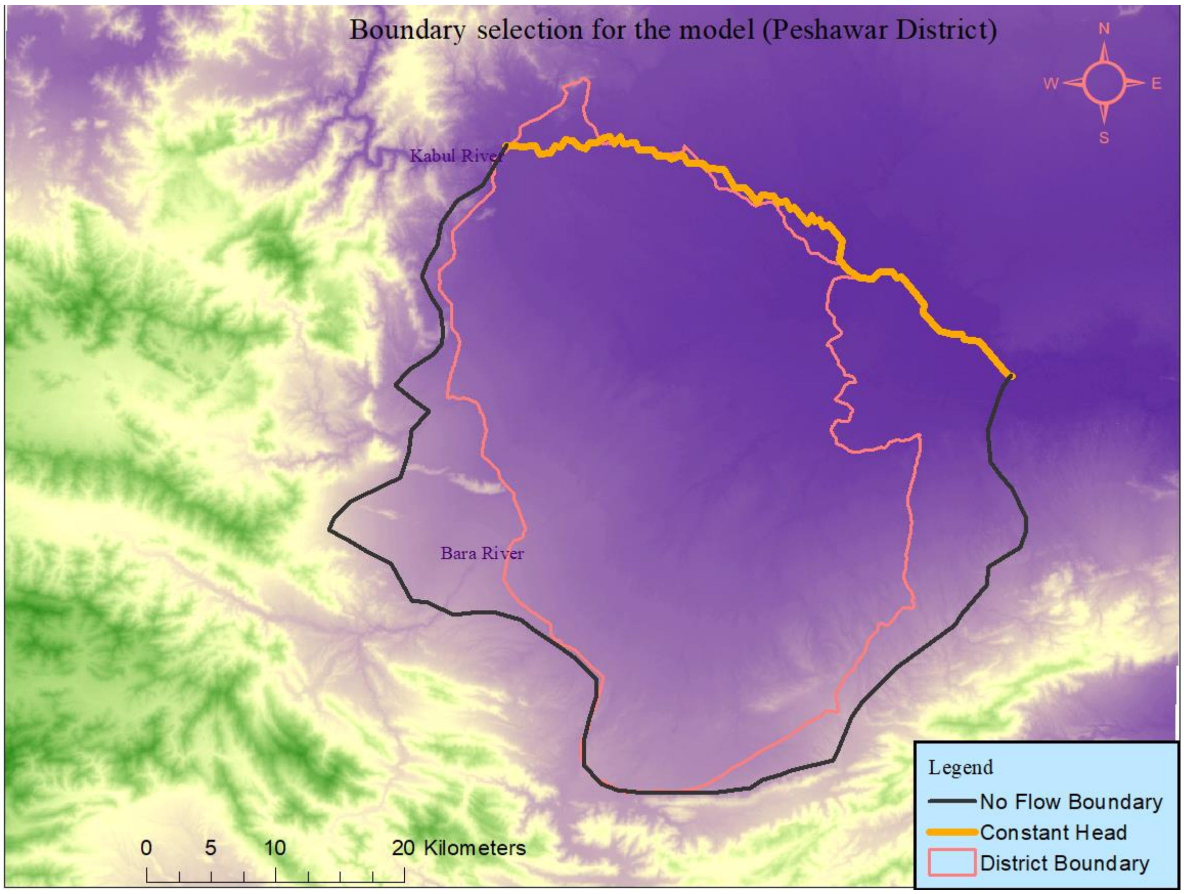


Figure 4. 2 Boundary selection for the model (physical & hydraulic)

2. Defining the Hydrogeological Units

Understanding of the horizontal and vertical extent of the geological formations and their relationship with each other is an important consideration for the accurate construction of the groundwater model **(**Barnett et al., 2012). Similar hydrogeological units of the same properties can be lumped as one unit, or a single hydrogeological unit can be subdivided in to aquifers and layers. In Figure 4.3 the map has been shown as drawn by Kruseman and Naqavi,(1988). The project area has been highlighted by the pink line colour. Similarly, the Section D-D, which runs from the north to south has also been shown in figure 4.4. Table 4.1 has been tabulated based on the understanding of the hydrogeology discussed in Chapter 3 where the hydrogeological and lithostratigraphic units and layers have been shown.

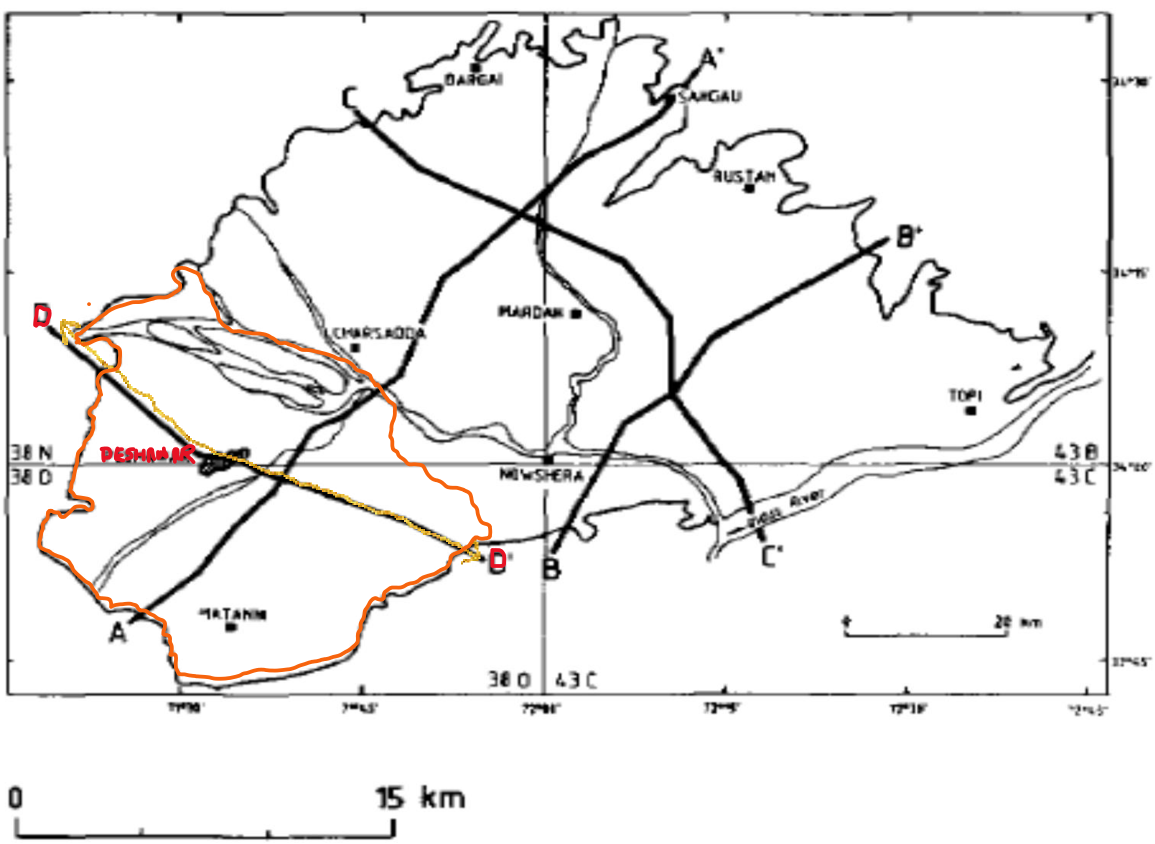


Figure 4. 3 Hydrogeological sections for Peshawar District (applicable sections D-D)

Source: Ammended (Kruseman & Naqavi, 1988)

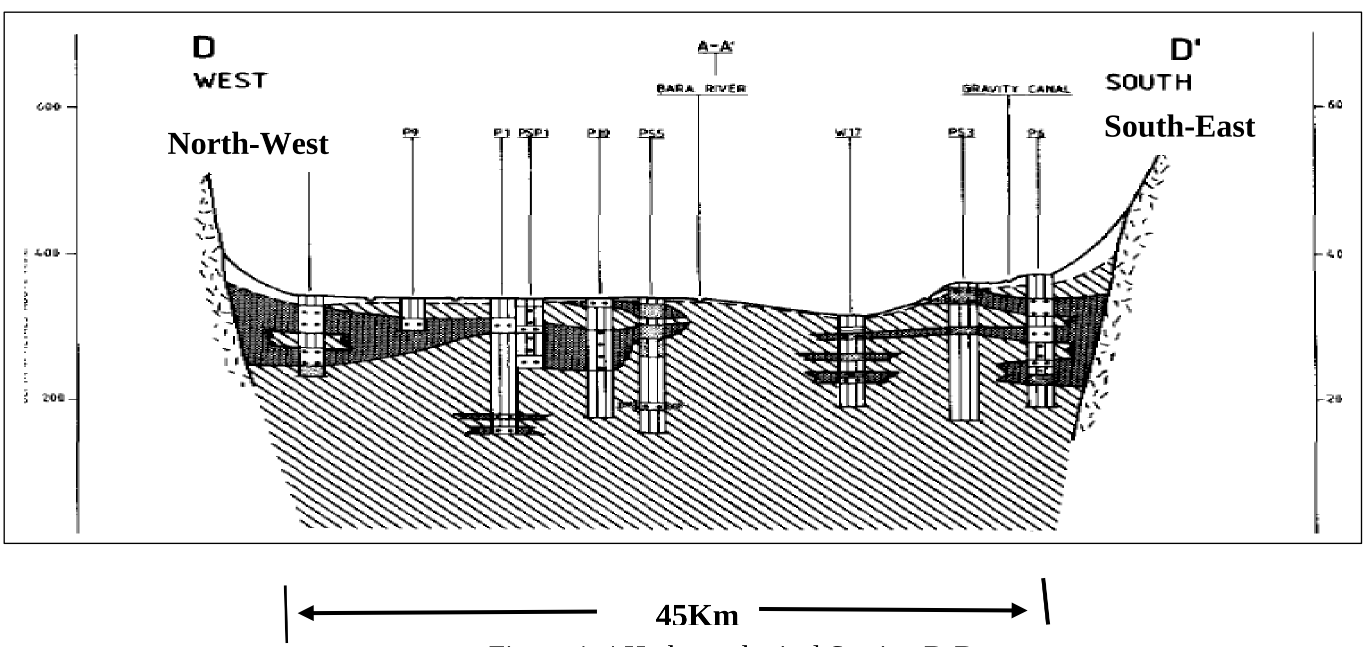


Figure 4. 4 Hydrogeological Section D-D

The presence of the borehole in the area investigated in the late 1980s by the WAPDA indicates that a silty layer divides the Alluvial sequence in to the upper unconfined aquifer and the lower leaky confined/unconfined aquifer**.** The cross section in Figure 4.4 shows the distribution of the coarse layers. From borehole to borehole the stratification also differs. From the cross sections it seems like the coarse layer occurs as lenses, which are not interconnected, however, the absence of significant water level change between nearby wells indicates that the gravel layers could be interconnected with each other and subsequently with the sand layer below (Kruseman and Naqvi, 1988).

Table 4. 1 Hydrogeological and lithostratigraphic units

Stage	Hydrogeological Unit	Lithostratigraphic Unit	No of layers
Middle Pleistocene	Unconfined	Gravel, Sand, silt	Layer 1
Pleistocene	Confined/Unconfined	Sand, , silt and clay	Layer2

3. Flow System

The flow system represents the flow pattern, flow paths and the areas where recharge and discharge take place. The development of an accurate model ensures that how and where water gets into and out of the system is accurate in terms of recharge and discharge. The geology and the topography of the Peshawar District controls the flow system, which has been discussed and shown in Figure 3.1 in Chapter 3. The streams originating from the western and the south western mountains drain the water to the north east and finally to the Kabul River. The discharge of the groundwater takes place by two ways, one is by pumping and the second by drainage to the Kabul River by the down-gradient flow. The direction of flow is towards the north east from the west and south western part. The recharge is by rainfall infiltration into the upper unconfined aquifer, which trickles down to the lower bottom aquifer. The agricultural area where surface irrigation water from the canal is extensively used causes the water to percolate down due to irrigation losses and recharge the groundwater table. The influence of the river is also an important discussion point and it is believed that the hydraulic connection between the Kabul River is responsible in replenishing the aquifer at times (UPU, 2014).

4.4 Model surface and layer generation

The conceptual model of the Peshawar aquifer consists of the two-layers, the upper shallow layer and the bottom deep layer. The elevation data of the layers has been developed based on the available logs data. The surface of the model has been prepared using the GIS ArcMap 10.4.2 software. The DEM and the shape file of the area were downloaded using the Shuttle Radar Topography Mission (SRTM) from the U.S. Geological Survey website. Digital elevation model is a representation of the raster model where each grid holds the elevation value (Shafique et al., 2014). Based on the DEM, the elevation contours were generated at the contour interval of 20m, which has been shown in Figure 4.5. However, the same spot height data were also obtained from google earth and then converted from a KML file to a CSV file by using the TCX converter software. A maximum of 8360 points were selected to produce the spot heights of high accuracy. The contour map generated by using Surfer 15 is also shown in Figure 4.6

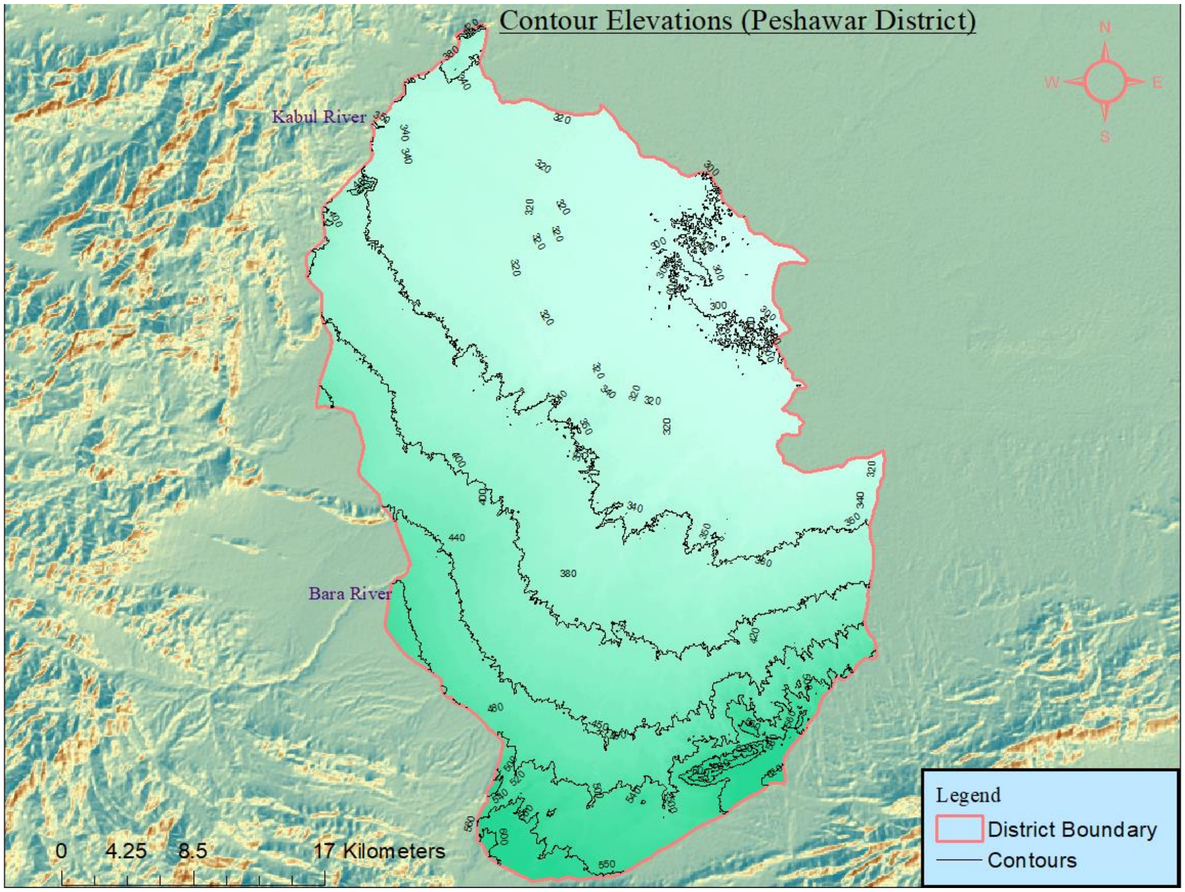


Figure 4.5 Contour elevations of the project area

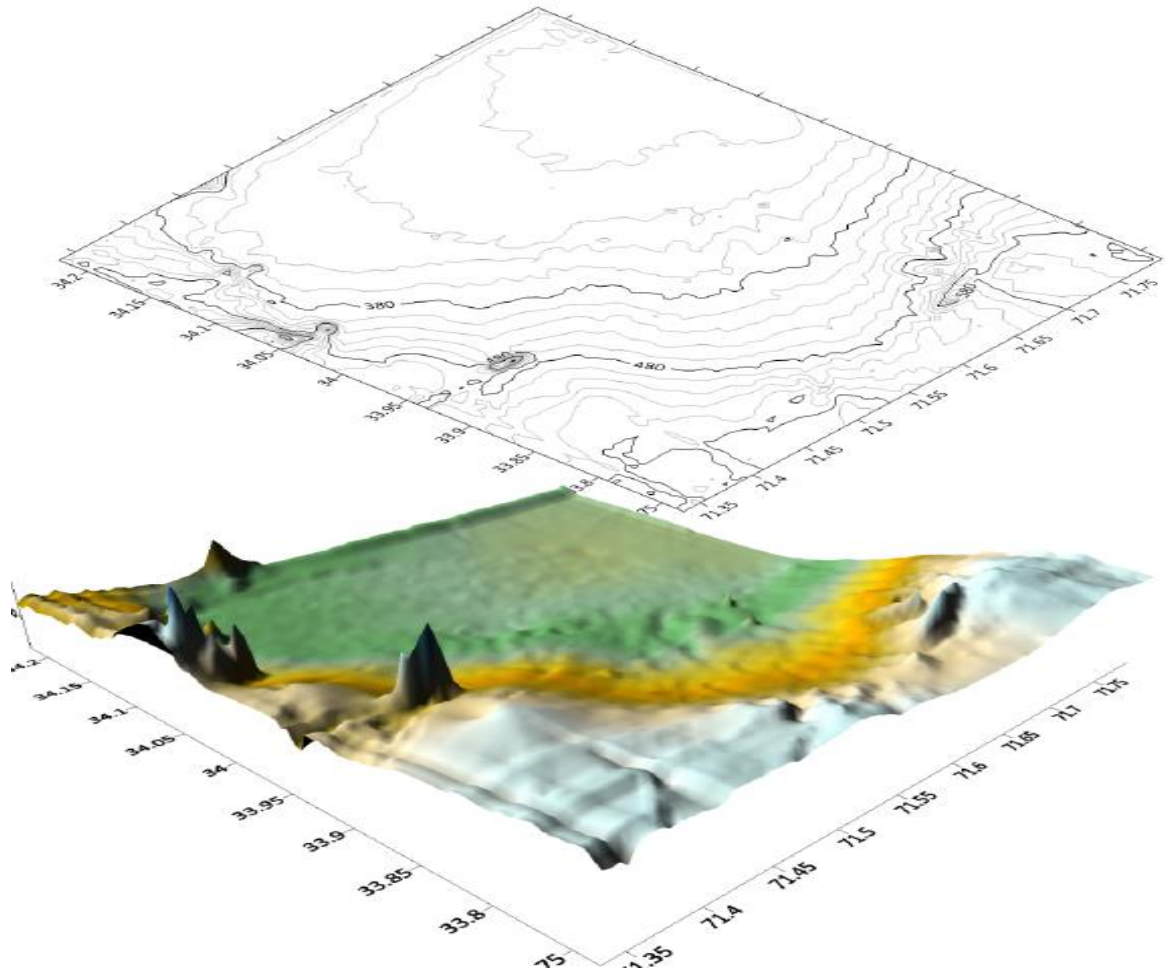


Figure 4. 6 Shade relief and contours lines of Peshawar District (developed from google earth & surfer 15)

4.5 Model Assumptions

A conceptual model is an attempt of representing the key features and behaviour of the physical system in a simplified manner. However, sometimes due to data scarcity, field conditions complexity and the limited resources it becomes necessary to make some assumptions in order to make the model easy and solvable. The following assumptions have been made in the construction of this model.

1) The Peshawar basin is a stretched basin, which comprises of more than 7000 km^2 and includes several districts other than Peshawar. Due to the complex sedimentary nature of the basin, the administrative boundaries of the Peshawar District were extended in the eastern, southern and western directions and some area to the north deemed unnecessary and so reduced, these changes were done to make boundary conditions justifiable and rational. Therefore, the model area is slightly increased compared to the administrative district boundary area.

2) The complex sediments of the selected model area have been divided into two layers for the sake of simplicity. The hydraulic conductivity of the upper layer is more than the lower layer. The hydraulic conductivity values in the x and the y direction have been assumed as same while for the z direction Kz is taken as an order of magnitude lower.

3) The exact location of the abstraction wells is not known except for the 492 wells in the urban area, therefore for simplicity the locations of remaining wells have been considered based on the literature and rational understanding then placed on model area.

4) The recharge due to precipitation has been assumed the same throughout the stress period irrespective of the soil type and topography. In the model it has been distributed equally to the top active cell of the model domain. Similarly, the irrigation losses contributing to recharge to the ground have also been equally distributed across the model area.

4.6 Design of the Model

4.6.1 Model Grids

The model domain is 35km in the x-direction and 50 km in the y-direction. In ModelMuse the actual map in the form of a shape file has been imported to the model with no grid and then the grid option within the map area has been activated with a grid size of 50m x 50m. The orthogonal set of rows and columns in ModelMuse is formed by the intersection of the cells. There are 1020 rows and 1083 columns including the active and inactive cells. The rows and columns of each cell occupy an area of 0.0025 km^2 ($2500m^2$). The area outside the selected boundary area has been defined as inactive, while the rest of the cells are active lying inside the model area. The total active area of the model is 1744.59 km^2. The reason of the extension of the model area from 1257 km^2 is because of the boundary conditions which have been discussed in the section above. Figure 4.7 shows the model area where active and inactive cells are located, but the grids are not visible because of the zoom out (increased number of rows and columns). The black line (colour) indicates the inactive cells while the area inside the cells inside the blue area is active.

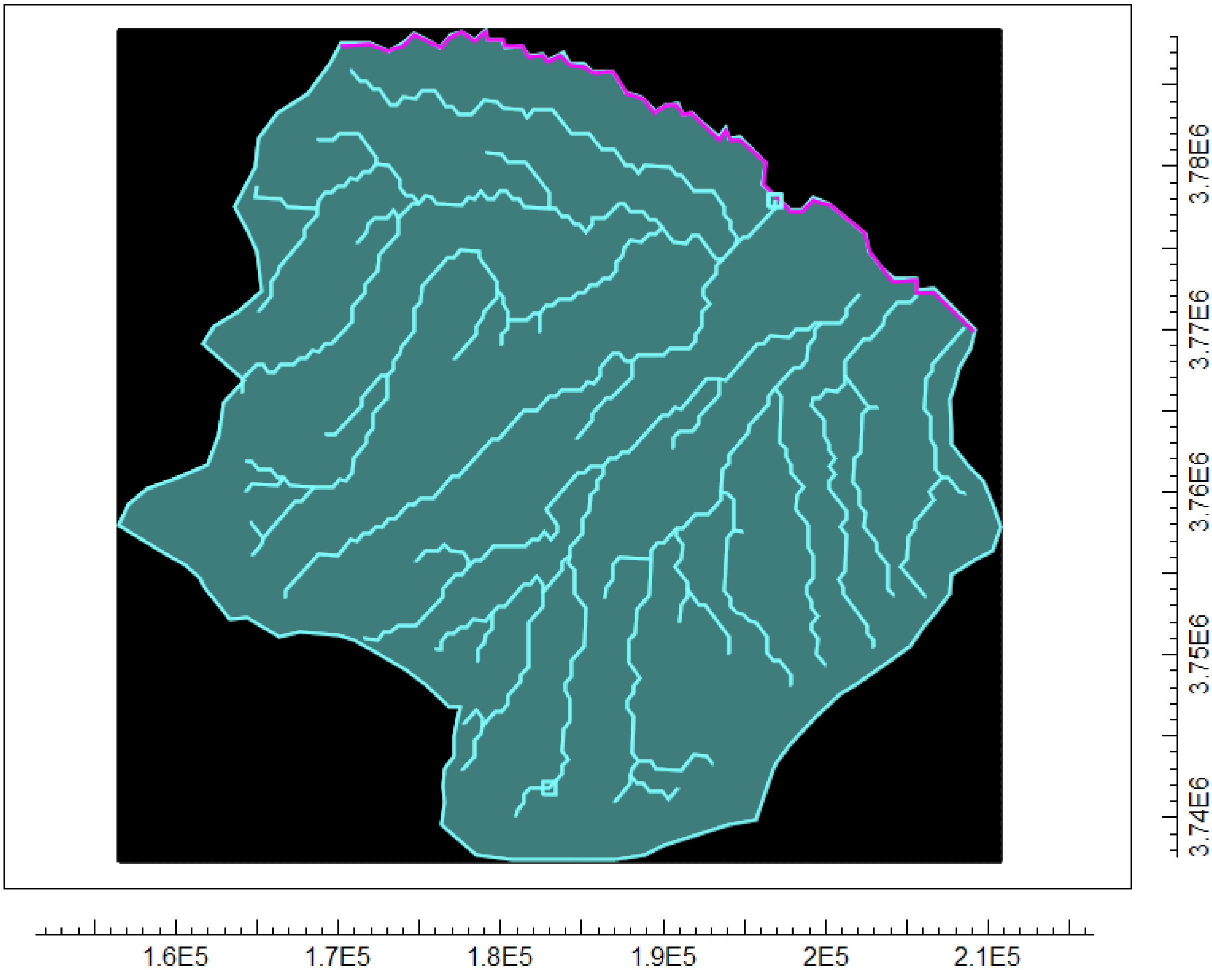


Figure 4. 7 Model area and the grids in x and y direction

The model area has been divided in to two layers based on the hydrogeological stratification. The surface of the top layer has been generated by importing the shape file from GIS ArcMap 10.4.1 and then inside ModelMuse fitted surface interpolation methods have been applied to generate the surface. Maximum number of points had been selected to generate the real surface. The two layers with top surface are shown in cross section in Figure 4.8. Layer 1 is 61m thick while layer 2 is 120m thick. The top layer is the shallow aquifer with increased hydraulic conductivity while layer 2 is the confined/unconfined layer with lower hydraulic conductivity.

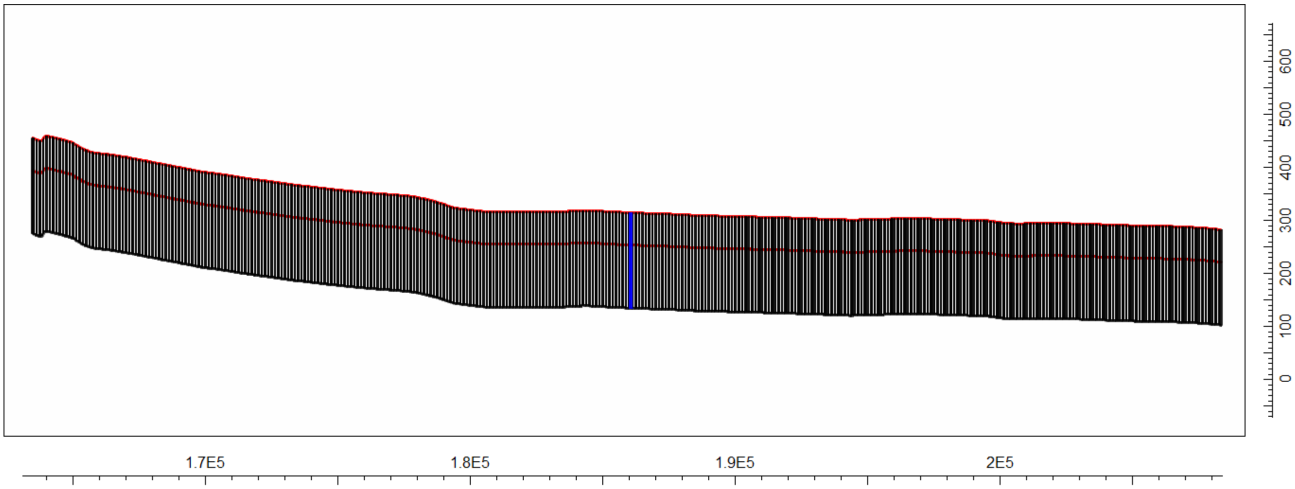


Figure 4. 8 Front section of the model (the section has been taken from the center (West to East)

4.6.2 Model Parameters

1. Hydraulic conductivities and the storage parameter

Hydraulic conductivity is the most sensitive and critical parameter and great care is made to apply a realistic value of the hydraulic conductivities. Because of the complexity and the heterogeneity of the geological units the exact values of the hydraulic conductivities are difficult to find out for the majority of the scattered area. However, based on the available bore tests and the published literature, possible realistic values have been applied that range from 4 to 48m/day.

4.6.3 Setting the Boundary Conditions.

Based on the study area the following boundary conditions have been set and discussed below.

a. Constant Head (CHD)

Kabul River, which flows along the north eastern edge of the model has been taken as constant head. The water head in the Kabul River is maintained at different fixed heads according to the river bed elevation.

b. No flow boundary

By assigning no flow boundary MODFLOW assumes zero flux around the grid perimeter. In ModelMuse if no object other than general head boundary or constant head boundary has been mentioned then ModelMuse automatically assumes those edges as no flow boundary. The edges in the west, south and south eastern part has been considered as no flow boundary as visible in Figure 4.9.

c. Specified flux

The recharge and well packages have been activated to designate specified fluxes. The recharge has been applied equally to the top active cells. The total recharge to the aquifer is the recharge by rainfall and irrigation losses summing to a total of 0.0003m/day. The wells have been imported to the model by point in ModelMuse, which penetrate in to layer 1 and layer 2.

d. Head dependent flux

In the head dependent flux, the flow rate is calculated based on the head difference between the boundary cells and the aquifer adjacent cells. This package includes the drain and evapotranspiration. Evapotranspiration depth of 3 m has been taken while the drain packages depth has been considered as the model top surface level. The drain package removes the water only if the water head is more than the specified drain head. However, it is not affected and remains dry if the head in the aquifer falls below the fixed head of the drain. Referring to Figure 4.9, we can see the network of the drains that originate from the high elevated areas and drain the water to the Kabul River.

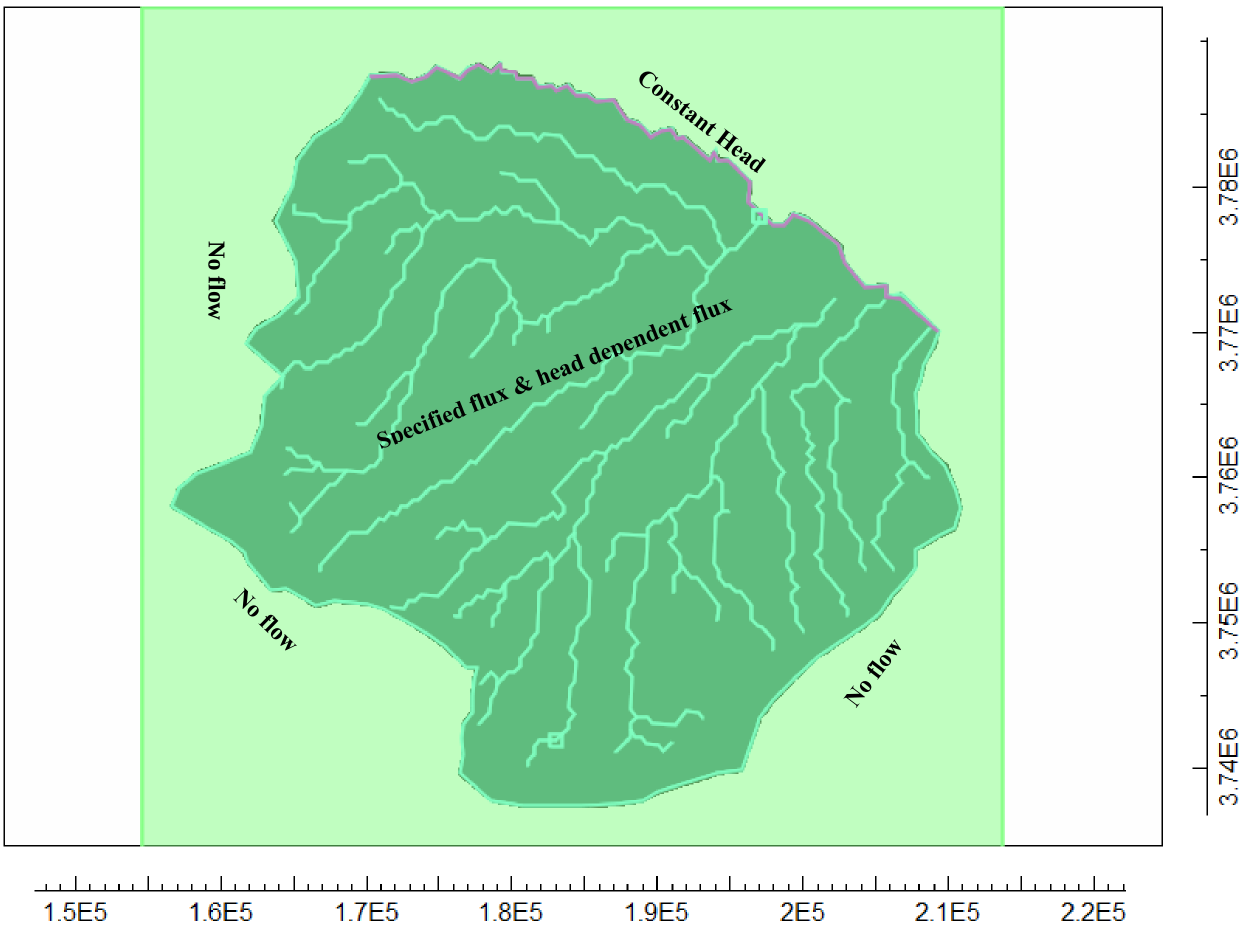


Figure 4. 9 Model boundary conditions

4.6.4 Initial Conditions

Initial heads represent the distribution of the hydraulic heads in the beginning for running the initial steady state (Anderson & Woessner, 1992).The initial heads could be any reasonable heads to fulfil the convergence criteria. In ModelMuse the initial head selected for the steady state run is the model top.

4.6.5 Groundwater Abstraction

The groundwater abstraction in the Peshawar District takes place by abstraction wells, which are used for drinking, commercial and industrial purposes. The number of abstraction wells is increasing with demand and at present more 1000 wells are operational in the district (UPU , 2017). The total groundwater abstraction from the government wells, hand pumps, dug wells and commercial wells has been discussed in detail Chapter 3. The total abstraction rate is 839,715 m^3/d while the abstraction wells locations based on the conceptual model are shown in the Figure 4.10.

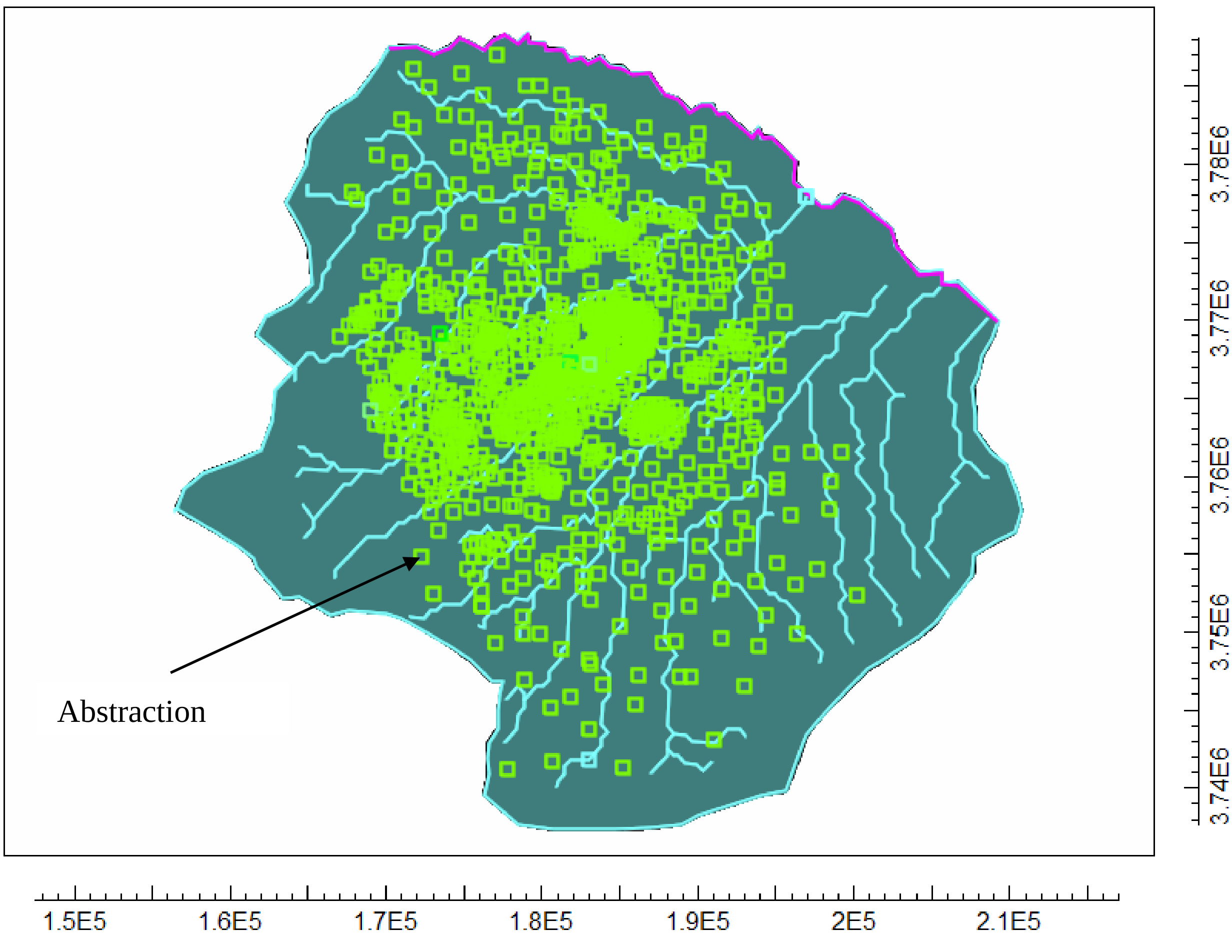


Figure 4.10 Groundwater abstraction wells in the model domain

4.7 Solver

In MODFLOW the head is calculated based on the finite difference equation at the center of the cell and in the six adjacent cells. The solver package for the model used is the preconditioned conjugate gradient package (PCG). The maximum number of outer iterations is 20 while the inner iterations is 150. Maximum absolute head change, and the maximum absolute residual change taken are 0.001.

4.8 Model Run

Once the setup of the models is made the next stage is to run the model. Running the model was done under the steady state conditions. In the steady state the model is run, and many iterations are made to get the rational heads. The model was run under the steady state condition and the calibration process was carried out with the most sensitive parameter hydraulic conductivity, was tweaked until suitable results were obtained. In the model output water budget, water heads, water table, and flow direction were obtained. In the calibration process 34 observation heads were compared with the simulated heads. The observation heads have been selected based on their distribution with a view to encompass and represent maximum model area to increase and enhance the model credibility. The transient model is useful when prediction is required in response to the stresses and for that purpose the availability of the continuous observation heads is necessary.

4.9 Models Limitations

The assumptions and simplifications of the physical system in the numerical groundwater model may not represent the real-world situation and may not be valid. Undoubtedly any model, which represents the real nature would be non-unique, so it may possess shortcoming and errors (Rojstaczer, 1994). The degree of uncertainties in the groundwater model results are because of the input parameters, time discretisation and grid spacing. The lack of information in the geological condition of the subsurface, mainly that the hydraulic conductivities and transmissivities are assumed to be uniform over large areas, results in error and uncertainty that is important to recognize. Some of the limitations of the model are summarised below.

i). Heterogeneity of the Hydrogeology

The lack of a detailed description of the hydrogeological conditions created difficulties in the conceptualisation of the model. The heterogeneity of the subsurface geology and the lack of studies has made the model very complex in nature. The sediment distribution in different layers and the limited number of borehole logs in the study area also added to the challenge. Therefore, the simplification of the model may add uncertainties to the output results.

ii) Input Parameters

The poor-quality data and gaps were the main constraint in developing the model. The hydrogeological investigation of the area had been made early in 1970 when the Warsak Dam was under construction. The data which play a key role in defining the model parameters are not well documented. The old records have either been misplaced or not updated in soft forms by the concerned departments. The discontinuity of available water head records results in difficulties in the calibration process and hence may add uncertainties and error to the model output.

iii) Boundary Conditions

The boundary conditions may also lead to uncertainties because they represent the physical features in terms of rivers, impervious beds, streams etc. The boundary conditions may not coincide with the real features exactly, leading to errors and uncertainties.

iv) Scale

Proper transfer of the regional scale to the local determines the accuracy of the model. The scale of the model can add limitation to the accuracy of outputs, this can lead modelers to choose smaller grid spacing, which increases the number of cells and can help to improve accuracy due to increased resolution.

4.10. Steady State Model Calibration

The calibration of the model refers to the process of adjusting the model parameters to match the simulated heads with the real world observed heads. Various techniques of model calibration are used in groundwater modelling of which parameter estimation (PEST) and trial and error are the most common (Doherty, 2000). Adjustment of the input data is required to improve the reliability of the model.

During calibration target, groundwater hydraulic heads have been used as calibration values, which means that the heads obtained from the model were matched with observed heads at specified points. The observation heads have been obtained from 34 monitoring points measured in the year 2017. Trial and error calibration procedure has been used by manually adjusting the input parameters. The calibration has been made under the steady state condition under constant pumping rate, evapotranspiration and recharge. The seasonal fluctuations have also been neglected so that a natural steady state condition for the model could be achieved.

The hydraulic conductivity of layer 1 and layer 2 was modified manually during the calibration process and after each run the simulated heads were compared with the observed heads. Different error parameters like residual mean and root mean square error (RMSE) were calculated to reduce the error quantitatively. Table 4.2 shows the observation points with their description and coordinates while Table 4.3 shows a quantitative way of minimising the error. We can see from Table 4.3 that the root means square error (RMSE) has been calculated as 1.09, which is a rational value. The observed vs. simulated head scatter plot from the model result has been shown in Figure 4.11 while the plot of the two data series is shown in Figure 4.12 respectively.

Table 4. 2 Groundwater Observation heads in Peshawar District (RSWL)

S.No	Description	Longitude	Latitude	Ground Elevation (m)	Observed Heads (m) (msl)
1	Afghan Colony Chowk	71.581	34.027	321	318
2	Shaheed Abad No.1	71.517	33.970	382	335
3	Audit colony Kohat road	71.560	33.990	351	324
4	District council Nothia	71.547	33.997	347	326
5	Sheikh Abad	71.436	34.061	357	340
6	Hayatabad D4 super market	71.435	33.978	410	342
7	Hayatabad PHASE 3 k4 Park	71.459	33.981	389	337
8	Zargar Abad	71.581	33.998	344	321
9	Land Arbab	71.548	33.982	362	331
10	Achini Payeen	71.475	33.961	409	340
11	Pishtikhara	71.511	33.968	385	336
12	Kakshal	71.567	33.998	344	321
13	Dheri Baghban	71.557	33.994	354	325
14	Mushtarzai	71.495	33.908	435	360
15	Forest Land	71.486	34.017	356	334
16	Nursery Area	71.488	34.020	353	332
17	Football Ground	71.487	34.021	358	333
18	Works Directorate	71.479	34.022	359	334
19	Professor Colony	71.470	34.019	360	336
20	Biotechnology Land	71.471	34.023	360	336
21	Malakhandir Farm	71.463	34.021	368	335
22	Military Farm	71.459	34.021	373	338
23	Veterinary Hospital	71.459	34.015	378	338
24	Kacha Garhi near A	71.460	34.007	375	337
25	Kacha Garhi near B	71.456	34.001	378	336
26	Phase 4 Drain	71.452	33.990	380	339
27	Phase 3 Civil Quarters	71.458	33.982	385	340
28	Phase3 Police Post	71.452	33.988	387	340
29	Phase 3 Ring Road	71.454	33.972	406	341
30	Phase 3 Drain	71.452	33.970	411	340
31	Phase 7 F-7	71.429	33.956	429	343
32	Phase 7 IM Sciences	71.417	33.961	437	350
33	Phase 7 Haji Camp	71.417	33.968	434	345
34	Phase 7 Behram Market	71.424	33.967	427	343

Table 4. 3 Goodness of fit

Observation Name	Observed Value (m) (msl)	Simulated Values (m)	Mean Error	RMSE
OBS1	318	320.238	2.238	5.01
OBS2	335	335.589	0.589	0.35
OBS3	324	326.472	2.472	6.11
OBS4	326	326.330	0.330	0.11
OBS5	340	339.069	-0.931	0.87
OBS6	342	341.130	-0.870	0.76
OBS7	337	338.434	1.434	2.06
OBS8	321	321.841	0.841	0.71
OBS9	331	330.672	-0.328	0.11
OBS10	340	340.082	0.082	0.01
OBS11	336	336.235	0.235	0.06
OBS12	321	321.958	0.958	0.92
OBS13	325	325.415	0.415	0.17
OBS14	360	360.738	0.738	0.54
OBS15	334	333.433	-0.567	0.32
OBS16	332	333.301	1.301	1.69
OBS17	333	333.395	0.395	0.16
OBS18	334	334.089	0.089	0.01
OBS19	336	334.891	-1.109	1.23
OBS20	336	334.868	-1.132	1.28
OBS21	335	335.572	0.572	0.33
OBS22	338	336.016	-1.984	3.94
OBS23	338	336.051	-1.949	3.80
OBS24	337	336.239	-0.761	0.58
OBS25	336	337.044	1.044	1.09
OBS26	339	338.242	-0.758	0.57
OBS27	340	338.433	-1.567	2.46
OBS28	340	338.369	-1.631	2.66
OBS29	341	340.077	-0.923	0.85
OBS30	340	340.544	0.544	0.30
OBS31	343	343.905	0.905	0.82
OBS32	345	345.328	0.328	0.11
OBS33	345	344.734	-0.266	0.07
OBS34	343	343.527	0.527	0.28
Mean Sum				1.19
Sq. Root				**1.09**

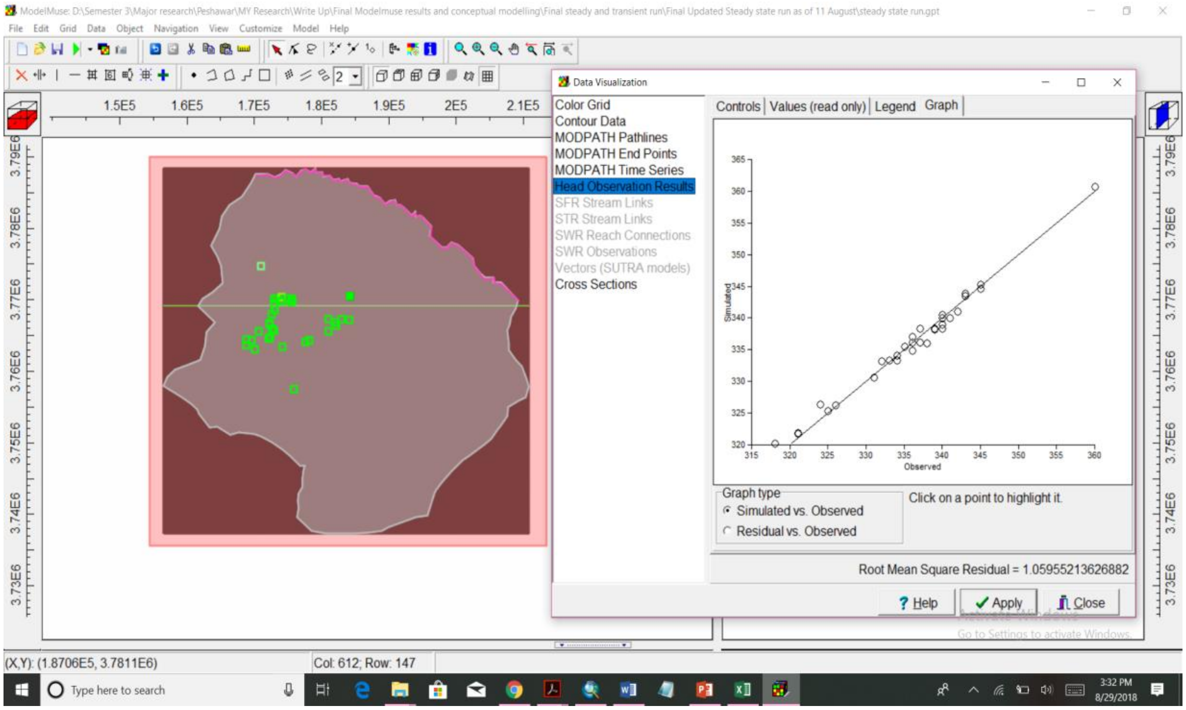


Figure 4.11 Comparison of observed head and the simulated head under steady state

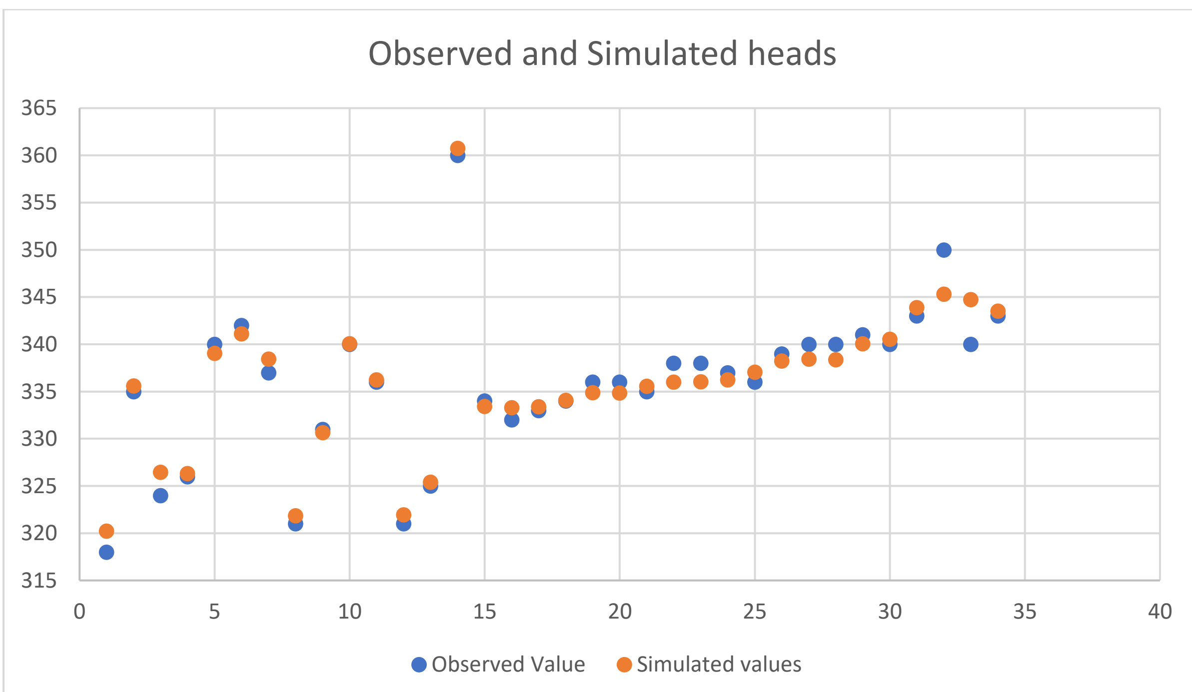


Figure 4.12 Plot of observed head and the simulated head under steady state

The following results have been obtained from the evaluation of the calibrated model.

i. Maximum number of the simulated heads are very close to the observed heads
ii. In the volumetric water budget, the water balance discrepancy error is only 0.398%, which is quite small if compared with the total area.
iii. The quantitative measured error calculated is also small with a RMSE of 1.09m.
iv. The hydraulic conductivities of the layer 1 and the layer 2 is calibrated whose ranging values are shown in the Table 4.4.

Table 4. 4 Calibrated ranges of the hydraulic conductivities in layer 1 and 2.

S.No	Layer	Kx Range (m/day)	Ky Range (m/day)	Kz Range (m/day)
1	Unconfined shallow layer	48	48	4.8
2	Confined/Unconfined deep layer	18	18	1.8

4.10.1 Discussion on the Calibration Results

The calibration procedure has been performed by comparing the simulated heads with the observed heads. Some of the reasons that may influence the results are given below.

i. The observed heads are limited to 34 specific sites, which could lead to inaccuracy in representing the large area of the model.
ii. The measurement and operator errors may also influence the calibration.
iii. During the calibration some assumptions are made, which also influence the model results.

4.11. Modelling Results under Steady State Conditions

The model was run in steady state by considering precipitation and irrigation losses as recharge, and pumping and evapotranspiration as discharge. The results of the run include the simulated hydraulic heads, volumetric water budget, vertical and horizontal flow within the groundwater system, and the dry cells, which remain dry in the upper layer of the model.

4.11.1 Simulated Heads

The hydraulic heads are the main output from MODFLOW-2005 and represent the distribution of the water heads of each cell in the model domain. Based on the hydraulic heads the water table of the aquifer can also be shown by interpolation of these heads. The hydraulic heads have significant importance based on which important observation about the flow system can be made. If the water table is depleting it is an indication that more water is being mined or abstracted compared to the recharge. The simulated hydraulic heads from the steady state run for each of layer 1 and layer 2 is shown in Figures 4.13 and 4.14 respectively.

The hydraulic head contours shown in Figure 4.13 indicate variation from 290-390m. The hydraulic head is high in the western side and tends to decrease in an eastern direction. The heads in the high-altitude areas of the western and the south western part of layer 1 are not visible (dry) because of the high gradient and elevations of the mountainous areas.

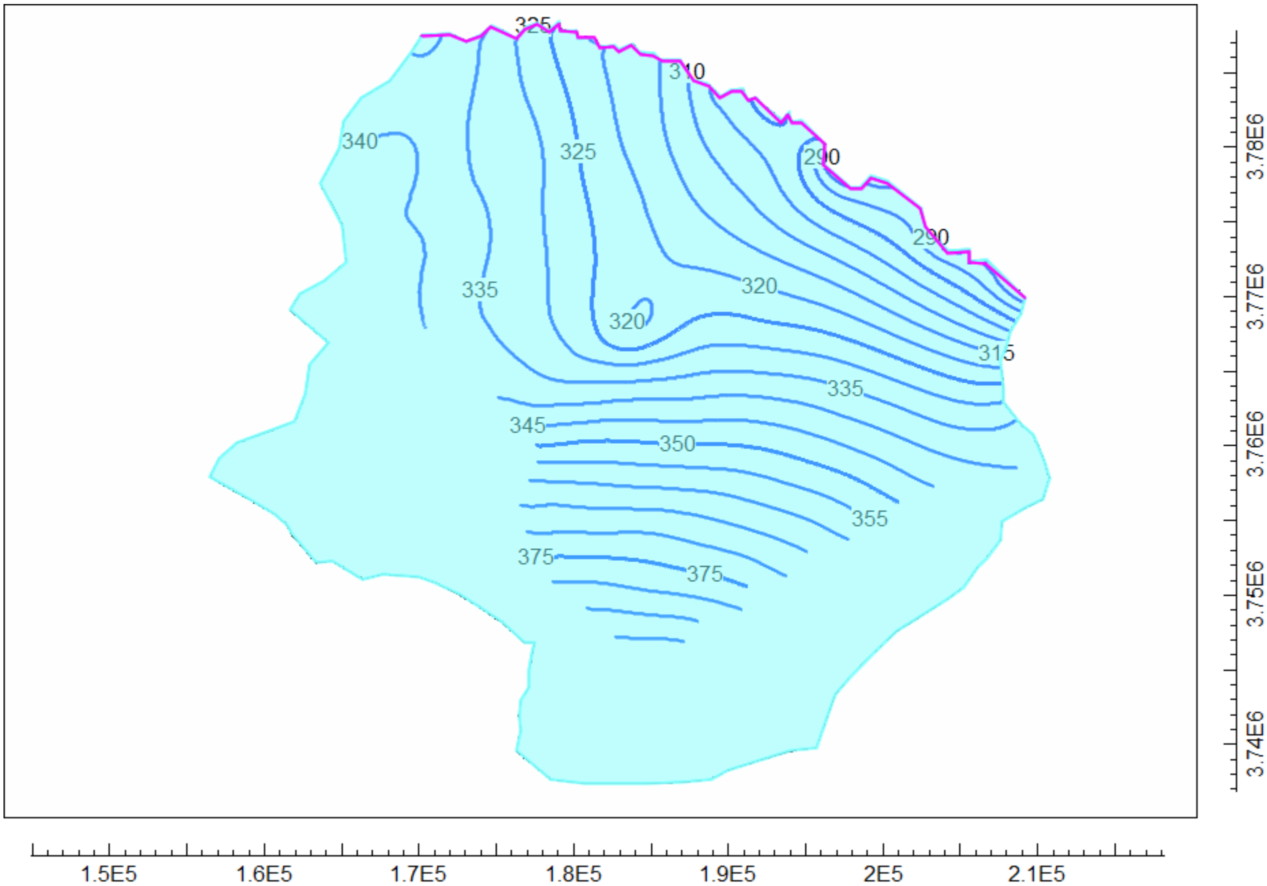


Figure 4.13 Hydraulic heads in layer 1

The simulated hydraulic heads of layer 2 are shown in Figure 4.14. The heads range from 290m to 420m. It can also be seen that a smaller number of cells are dry in layer 2 if compared to layer 1. Groundwater flows towards the north-east from the higher altitude regions in the south and west. The flow is towards the Kabul River constant head boundary along the north eastern edge

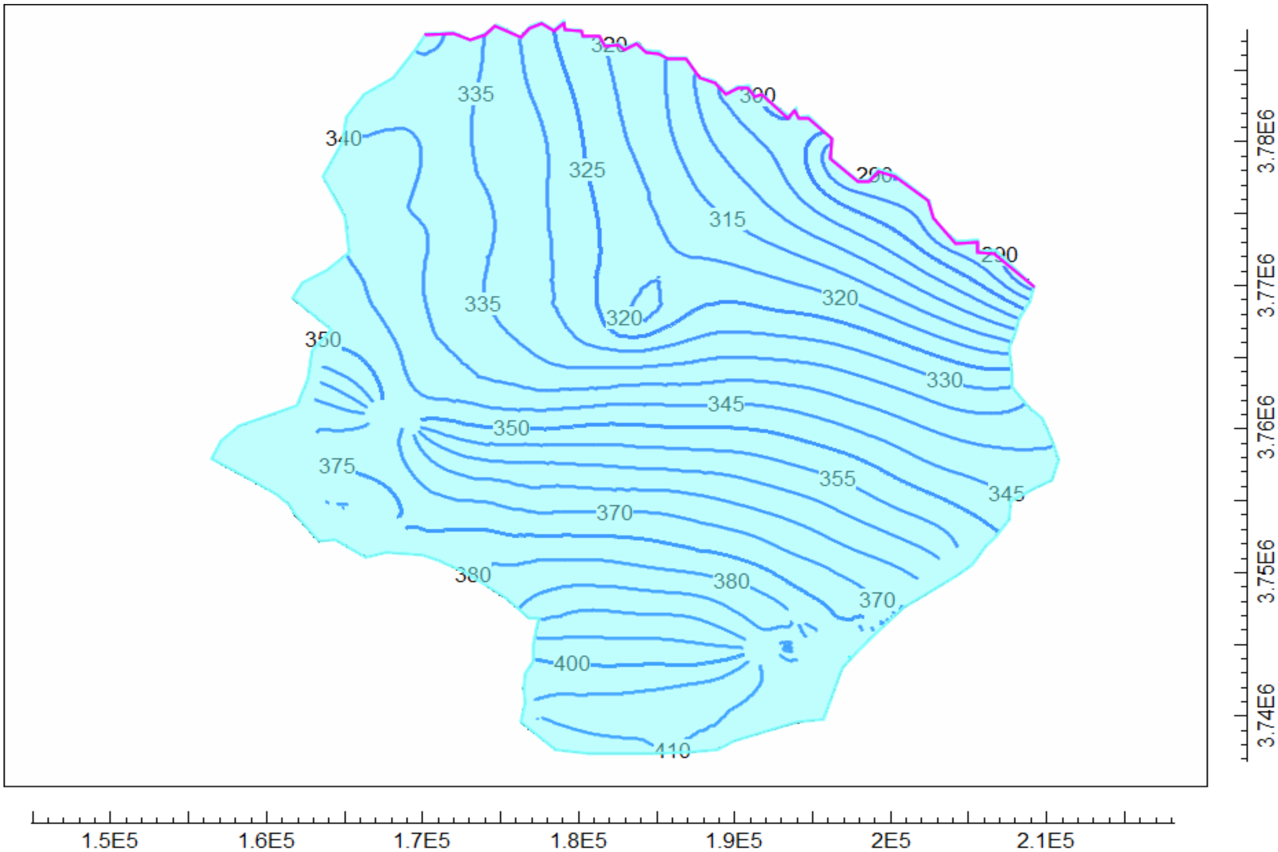


Figure 4.14 Hydraulic heads in layer 2

4.11.2 Dry Cells

During the simulations, some cells became dry in layer 1, a smaller number of cells also became dry in layer 2. The presence of dry cells in layer 1 indicates that the water table lies below the bottom of the cells, meaning the cells have no more available water and are no longer saturated. Layer 1 is thinner and at the top of the modelled profile, the cells that run dry are those in the elevated regions of the model area. Around 35% of the cells are dry in layer 1 while in layer 2 about 10% are dry. The dry cells in both layers occur in the areas where the land surface elevation is high and the slope changes drastically. The western and south western areas are situated in high elevations. From the topography of the area, the ground surface elevation along the eastern part on average is 300m while in the western and south western edges it is more than 550m on average.

4.11.3 Horizontal Flow directions and velocity in Layers

The determination of the horizontal flow direction of groundwater is a useful indication based on which it is possible to determine the flow paths of possible contaminants in the groundwater system (Salam et al., 1999). From Figure 4.15 it is evident that horizontal flow of groundwater in layer 1 is from the north towards the east and from the south wester towards the lower lying eastern region. Similarly, 4.16 refers to the flow directions in layer 2 where flow direction is also almost the same, except in the western edge where the divide line diverts half of the water towards the northern side while rest towards the south.

The velocity of the flow represents the distance covered by the water in time. In both layers maximum velocity of water occurs is in the western and the southern edges due to the steep hydraulic gradient. The low velocity component in the central and eastern edges is because of the low gradient. The Darcy equation has been used to calculate the average linear velocity by dividing the Darcy flux by the effective porosity. The travel length of 24.64km was taken from the west elevated area to the Kabul River in the east with a calculated hydraulic gradient of 0.0018 and effective porosity of 0.3. Thus, the average linear velocity in layer 1 is 0.292m/day while for layer 2 it is 0.0976m/day. The lower velocity in layer 2 is due to the low hydraulic conductivity in layer 2.

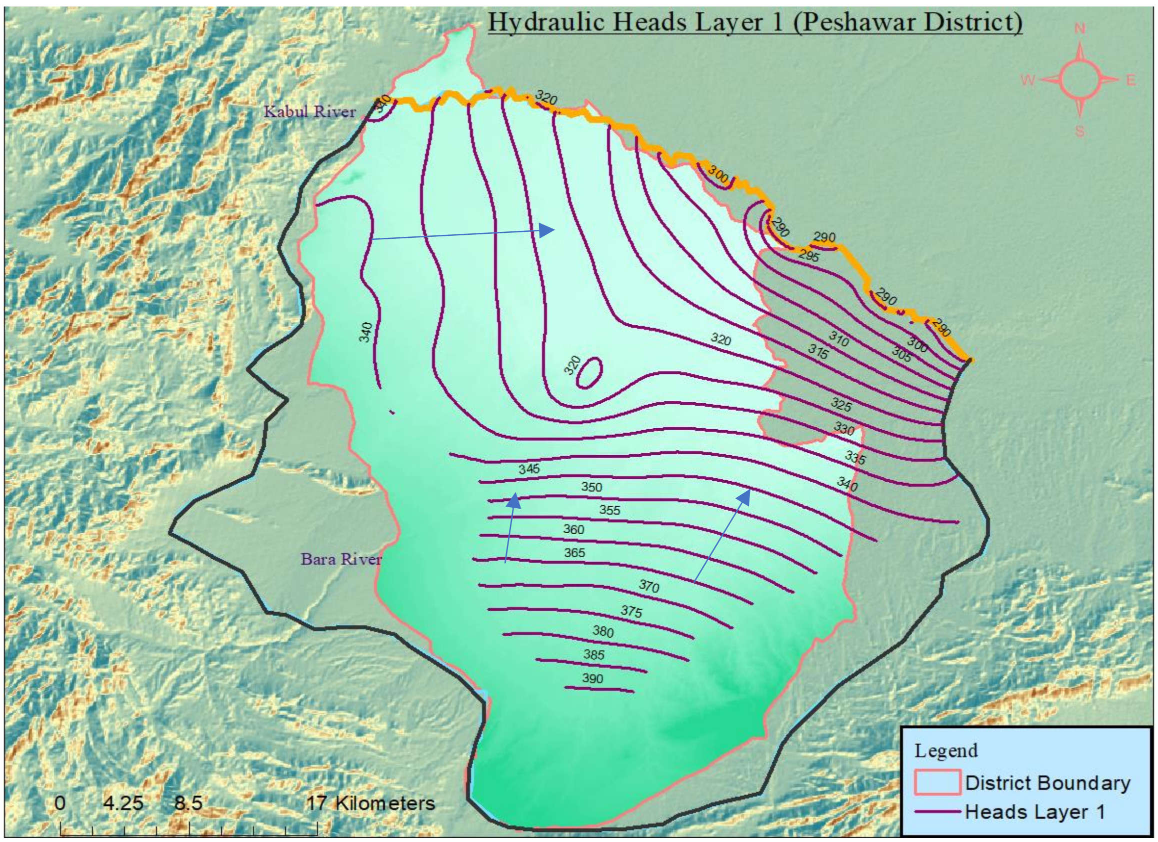


Figure 4.15 Flow direction and average horizontal velocity in layer 1

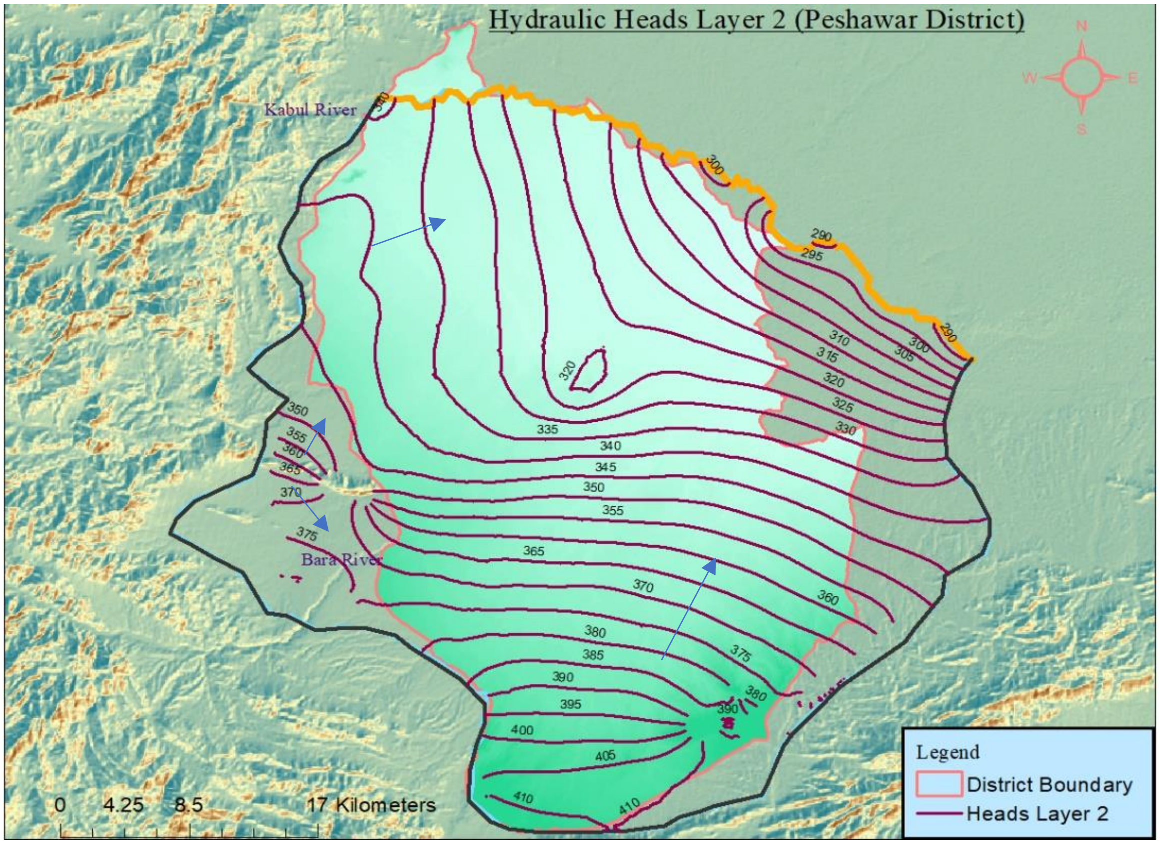


Figure 4.16 Flow direction and average horizontal velocity in layer 2

4.11.4 Water Budget

The water balance of the project area can be evaluated based on the water budget. The volumetric water budget describes the inflow and outflow of the groundwater aquifer system. In the recharge component, precipitation and irrigation water losses have been considered as inflow to the aquifer while groundwater abstraction by pumping and the evapotranspiration taking place from the ground have been considered as the outflows from the aquifer system.

The balance equation of the groundwater system is given below

Inflow – Outflow = Rate of change in storage

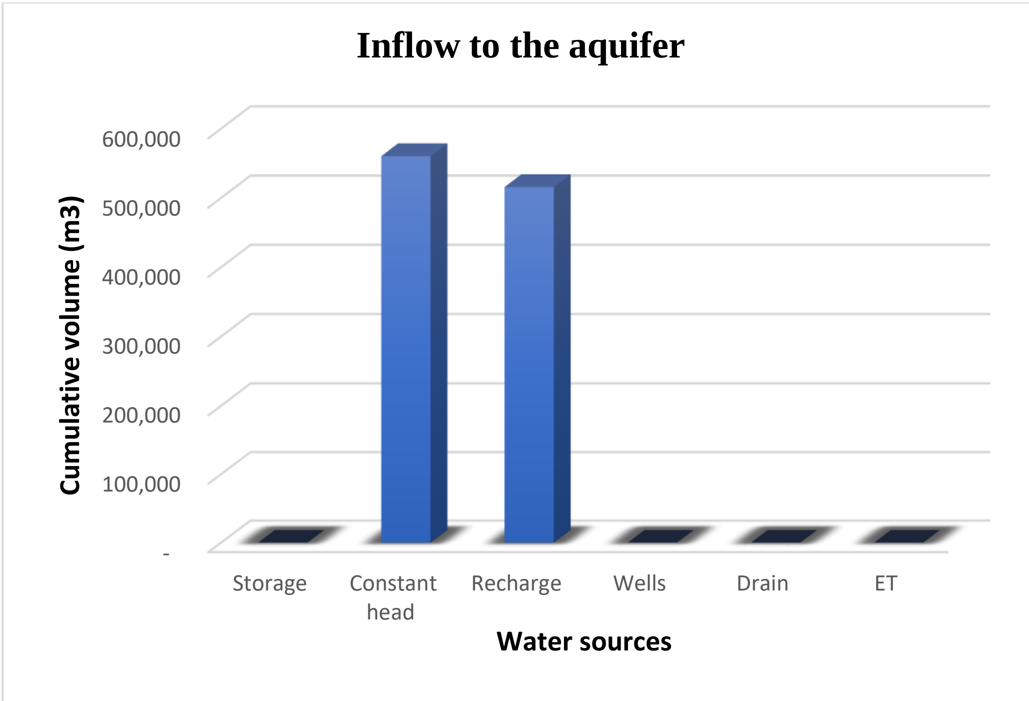
As the simulation is under steady state conditions, the change in storage is considered as negligible.

$$\text{Inflow} = \text{Outflow}$$

The volumetric water budget has been shown in Table 4.5. The total flow rate in to the aquifer is **107,585,7.03m^3/day**. This total volume into the aquifer is contributed by the constant head boundaries and the recharge. From the constant head, everyday 560257.0312 m^3 of water is added to the aquifer. From the recharge, 515600 m^3 of water is added to the system every day. Thus, the total inflow into the Peshawar aquifer is 1075857.0312 m^3/d. In the outflow, the maximum quantity of water that goes out is due to pumping, which is **826949.375 m^3** per day. Similarly, 237908.6250 m^3 of water is drained back into the Kabul River, (constant head) which is about 29% of the pumping rate every day. From the evapotranspiration, about 15241.9844 $m^3$of water goes back to the atmosphere every day as an outflow. 49.9792 $m^3$of water is drained every day from the system into the Kabul River by the drains in the project area. Thus, a total of 1080150 m^3 of water leaves the aquifer every day with a total percent discrepancy of 0.398. For a better visual understanding same values have been plotted on a bar graph and shown in Figure 4.17. The cumulative volume refers to a 5 years stress period but as the run is on steady state therefore the discussion refers to only m^3 per day only.

Table 4. 5 Volumetric water budget under a steady state condition

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1, STRESS PERIOD 1	
CUMULATIVE VOLUMES L**3(m^3)	RATES FOR THIS TIME STEP L**3/T (m^3/day)
IN:	IN:
STORAGE = 0.0000	STORAGE = 0.0000
CONSTANT HEAD = 1023169403	CONSTANT HEAD = 560257.0312
WELLS = 0.0000	WELLS = 0.0000
DRAINS = 0.0000	DRAINS = 0.0000
ET = 0.0000	ET = 0.0000
RECHARGE = 941614504	RECHARGE = 515600.0000
TOTAL IN = 1964783907	TOTAL IN = 1075857.0312
OUT:	OUT:
STORAGE = 0.0000	STORAGE = 0.0000
CONSTANT HEAD = 434480626.000	CONSTANT HEAD = 237908.6250
WELLS = 1510216296.0000	WELLS = 826949.3750
DRAINS = 91274.4453	DRAINS = 49.9792
ET = 27835674.0000	ET = 15241.9844
RECHARGE = 0.0000	RECHARGE = 0.0000
TOTAL OUT = 1972623870.5	TOTAL OUT = 1080149.96360
IN - OUT = -7839934	IN - OUT = -4292.93
PERCENT DISCREPANCY = -0.398	PERCENT DISCREPANCY = -0.398



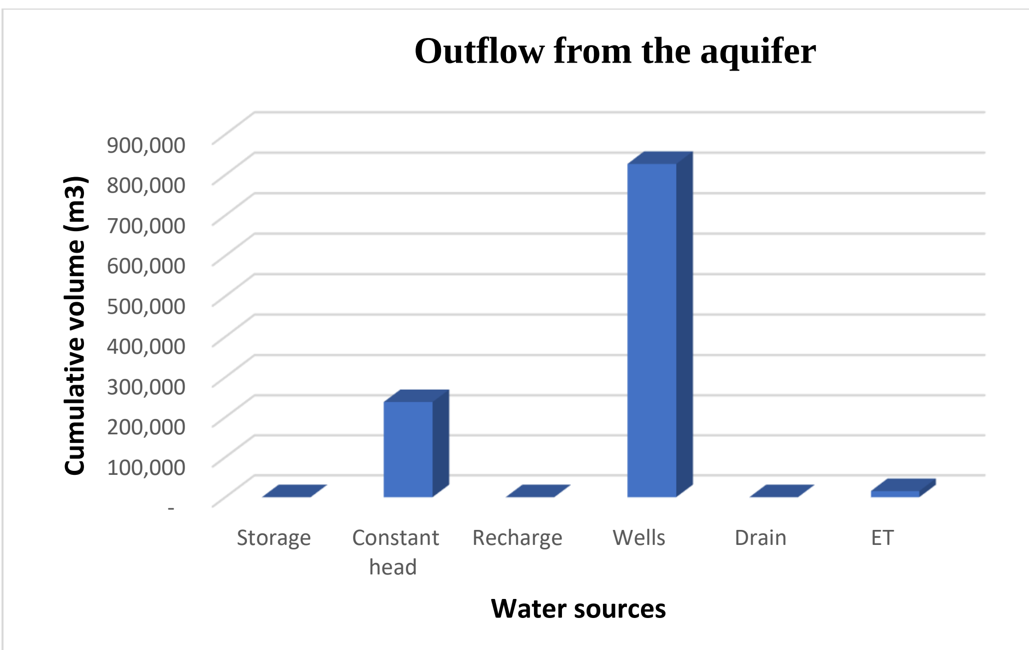


Figure 4.17 Daily inflow and outflow from the aquifer

4.11.5 Modelling Results Summary

The results of the calibrated steady state groundwater model of the Peshawar District can be evaluated based on several indicators. The model results produced are realistic because of the following reasons.

i) Out of the 34 observed heads around 98% of the simulated heads are very close to the observed heads.
ii) The inflow and outflow balance each other with negligible discrepancy error.
iii) The hydraulic contour heads in layer 1 and layer 2 are reasonable
iv) The groundwater flow direction is in good agreement with flow direction indicated in the conceptual model.

From the analysis of the modelling results it is evident that recharge is less than the discharge taking place in the aquifer. The Kabul River contributes around 40% of the total and recharge to compensates for a deficit of recharge in the aquifer that is evident from analysis of the modelling results. Pumping from urban settlements close to the Kabul River reduces the potentiometric level in the aquifer, however, due to the resulting reduced pressure, induced recharge from the river takes place. It means that the locally lowered potentiometric surfaces due to pumping create a gradient in the water table that induces lateral recharge to the aquifer from unstressed areas and vertical recharge from the constant heads (Kabul River), tributaries and irrigation channels. This discussion however leads us to the understanding that the aquifer may not be a sufficient water resource for the population, which is increasing with a rate of 3.9% annually, if there is any interruption to the flow of the Kabul River. The groundwater resource has the potential to supply the future demand, but with the caveat that the Kabul River continues to provide recharge. The district is confronted with climate change and increasing population so it is hard to say that the water abstraction taking place is sustainable.

4.11.6 Uncertainties

Incomplete knowledge of the system and the complexities of the geological conditions cause the groundwater model to display the uncertain results. In the modelling process three sources of uncertainty are categorized which are conceptual uncertainty, uncertainty of parameters, and stochastic uncertainty (Sing et al., 2010).

The imperfect and incomplete knowledge of the system is attributed to the conceptual uncertainty while insufficient and rough field data applied to the model contributes to the parametric uncertainty. The stochastic uncertainty may arise because of the natural variability of the field conditions.

Chapter 5

Conclusion and Recommendations

5.1 Conclusion

This study sought to investigate the impacts of increased abstraction due to population growth as well as commercial and industrial activities on the groundwater resource of the Peshawar District. This investigation was done by developing a groundwater model and then calibrating it in order to see how the system responds to various stresses imposed upon it. For this purpose, all the necessary available data including physiography, meteorology, geology and hydrogeology of the system has been unearthed and evaluated to develop a conceptual model for the project area. The data scarcity across the project area is a major challenge and the lack of data does not allow precise determination of all components of the groundwater budget. The hydrogeological investigation of the area has provided the basis for observing groundwater flow direction, velocity, distribution and budget in response to high volumes of pumping.

Based on the analysis of the model results the following conclusions have been made, which are summarized below.

i) The Hydrogeology of the Peshawar basin is complex and therefore the hydrogeological investigation of the aquifers needs to be handled carefully. The thickness of the aquifers and layers both horizontally and vertically must be studied and divided carefully in the model to have accurate results.

ii) The model has been divided into two aquifers with the top layer defined as unconfined and the bottom thicker layer defined as a confined and unconfined aquifer. The hydraulic conductivity of the top layer is higher compared to layer 2 and both aquifers are interconnected

iii) The recharge calculated from rainfall is 4% of the total annual rainfall, which is 17mm/year while recharge from the surface water irrigation losses is 92mm/year.

iv) The Kabul River contributes 40% of the water balance to the aquifer, which helps to compensate the abstraction of 826,949 m^3 per day. This suggests that pumping taking place from the aquifer relies on the induced recharge from the river which is in strong hydraulic connection with the aquifer. If the river experiences low flow (in the case of climate change for example) it could have a more detrimental effect on the sustainability of the Peshawar District groundwater resource.

v) From the hydraulic heads it is evident that the depth to the water table in the eastern part near the constant head is less, so we can say that maximum water pumping can be diverted towards those areas. However, the hydraulic connection between the river and aquifer may induce more water influx which could affect the Kabul River flow rate.

vi) From the hydraulic heads and the topography of the area we can say that the depth to the water table is increased as we go towards the southern and western sides.

This is because of the high gradient and steep slope. The water table depth at the center of the urban area is 20 m and the water table depth on the Hayatabad side near the hilly area is 70 to 80 m at various locations.

vii) The direction of flow is from the west and south to east, towards the constant head

viii) The maximum concentration of pumping is at the center of the urban area where maximum population density exists.

ix) From the hydraulic heads, it can be predicted that the water table is falling at the central part of the densely populated area where the maximum abstraction of water is taken place

x) The average velocity of water in layer 1 is 0.292 m/day, while in layer 2 it is 0.0976 m/day.

xi) The hydraulic conductivity of the shallow unconfined aquifer is more sensitive to the model output.

5.2 Recommendations

Based on the analysis of the results the following recommendation are made

i) To make the model more refined, collection of additional data is essential. To better represent the hydrogeological framework of the area extensive collection of field-based observation points and log data is an important step to further delineate the area.

ii) The conceptual model of the project area has been made based on the limited available data and to use the model as a tool for the management decision the model needs to be validated temporally in response to the abstraction rate. Adequate field data of the project area can improve the predictive capability of the model.

iii) Based on the limited field observation data the model has only been run under the steady sate condition and calibrated, therefore it does not include the temporal variations in the input and output. To more accurately represent the field conditions and use the model as a management tool it needs to be run in transient scenarios to evaluate the effect of pump density in urban area as well as in surroundings.

iv) The model has been calibrated based on the observed heads, which are distributed in the central and the western parts but does not include the scattered areas of the southern and the northern parts. To improve the modelling results, observation points from these southern and northern regions could be incorporated in the calibration process

v) The hand pumps and the dug wells in rural areas of the Peshawar District are not well documented, therefore their exact location is unknown. To enhance the model results the exact locations of wells in those areas is essential.

vi) The pumping tests in the Peshawar aquifer area were done several decades ago when the construction of the Warsak dam and the distributary canals were in progress. It could be necessary to undertake more pumping tests to have more realistic conductivity estimates of the area, which could help to reduce uncertainties in the model.

vii) There are several surface water irrigation channels and so a detailed investigation of the losses from the unlined portion and their potential recharge to groundwater table is essential to produce a more precise water balance of the area.

viii) The model developed can be used for contaminant transport and by using particle tracking to identify which wells will be affected and in doing so could develop ways to protect them from contamination.

ix) The model can be used as a valuable tool to assess the impact of climate change and will be helpful in groundwater resources planning and management.

x) The water being contributed to the Peshawar aquifer from the Kabul River should be checked in terms of water quality because the contamination in the river from upstream sources can have adverse effects on the quality of the groundwater.

xi) Regarding the sustainability of the Kabul River as well as the Peshawar District, detailed studies on the induced seepage from the Kabul River is recommended.

xii) For the full evaluation of the sustainability of the Peshawar groundwater resource it is suggested that a detailed evaluation of the overall changes in the water table be carried out across the entire basin (Peshawar Basin).

References

Anderson, M.P., Woessner, W.W. and Hunt, R.J., 2015, *Applied groundwater modeling: simulation of flow and advective transport*. Academic press

Anderson, M.P. and Woessner, W.W., 1992, 'The role of the postaudit in model validation', *Advances in Water Resources*, vol.*15*, no.3, pp.167-173

Adnan and Iqbal 2014, 'Spatial analysis of the groundwater quality in the Peshawar District, Pakistan', *Procedia Engineering*, vol *70*, pp.14-22

Arif, A.H. and MA. Khan, 1970, 'Groundwater investigations on the right bank of the Kabul River, Peshawar Valley, with emphasis on waterlogging problems', *WAPDA/WASID*, vol. 84 no. 17,pp. 22-38

Asim, M., 2005, Hydrochemical Characterization and Numerical Modeling of Groundwater Flow in a Part of the Himalayan Foreland Basin, Doctoral dissertation, Kent State University, USA

Barnett et al., 2012, *Australian groundwater modelling guidelines*, Waterlines report, National Water Commission, Canberra

Bundschuh, J., 1992, 'Hydrochemical and hydrogeological studies of groundwater in Peshawar Valley Pakistan', *Geological Bulletin, University of Peshawar*, vol. *25*, pp.23-37.

Basharat, M. et al., 2009, 'Assessment of groundwater development potential in district Nowshera using groundwater modeling', *Pak J Water Resource*, vol. *13*, no 2, pp.17-27.

Bacha, A.A., Durrani, M.I. and Paracha, P.I 2010, 'Physical and Bacteriological characteristics of drinking water of Peshawar', *Pakistan Journal of Nutrition*, vol. *9*, no. 10, pp.1028-1033.

Burbank, D.W. and Tahirkheli, R.K., 1985, 'The magneto stratigraphy, fission-track dating, and stratigraphic evolution of the Peshawar intermontane basin northern Pakistan', *Geological Society of America Bulletin*, vol. *96*,no 4, pp.539-552.

Bureau of Statistics 2017, Government of Khyber Pakhtunkhwa Peshawar, viewed 15 July 2018, http://kpbos.gov.pk/.

Baalousha H., Mckay, G., Haik, Y., Siddique, A., Koç, M., Francis, L., Saleem, J., Abdulrahim, H.K.M. and Al-Adwan, A. 2013, 'FUNDAMENTALS OF GROUNDWATER MODELLING', *Jordan Journal of Applied Science*, vol *15*, no.15, pp.347-360.

Cornwell, K., 1998, 'Quaternary break-out flood sediments in the Peshawar basin of northern Pakistan', *Geomorphology*, vol. *25*, no. 3-4, pp.225-248.

Cunningham, W.P., M.A. Cunningham and B. Saigo 2005, *Environmental Sciences*: *A Global Concern*. 8th ed, New York: Published by McGraw-Hill : 16-316.

Connor, R., 2015, *The United Nations world water development report 2015: water for a sustainable world* ,Vol. 1, UNESCO Publishing.

Doherty, J 2000, *PEST-Model-Independent Parameter Estimation, User's Manual*. Australia.

Farid, A. et al., 2013, 'Hydrostratigraphy and hydrogeology of the western part of Maira area, Khyber Pakhtunkhwa, Pakistan: a case study by using electrical resistivity', *Environmental Monitoring and Assessment*, vol 185, no 3, pp.2407–2422.

Fetter, C., 2001, *Applied hydrogeology*, 4th edn, Pearson new international ed, Harlow, Essex: Pearson, UK.

Fitts, Charles R., 2012, Ground Water Science, 2nd edn, Elsivier Science, Academic Press, US

Ganesh, K., 2011, Numerical modeling of groundwater in Kathmandu Valley Nepal, Master's thesis, Universidad de Aveiro, viewed 5 June 2018, https://ria.ua.pt

Geological Map of North-West Frontier Province Pakistan 2006, Geological Survey of Pakistan, Viewed 15 July 2018, www.gsp.gov.pk

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model—The ground-water flow process: U.S. Geological Survey Techniques and Methods 6–A16, variously paged.

Kazmi, S.A.T., 1968. 'Groundwater investigation in Warsak reregulating reservoir scheme area', *WASID*, Vol. 16, pp. 20-61

Kruseman, G.P. and Naqavi, S.A.H., 1988, Hydrogeology and groundwater resources of the North-West Frontier Province Pakistan. In *Hydrogeology and groundwater resources of the*

North-West Frontier Province Pakistan. Water and Power Development Authority, Hydrogeology Directorate; TNO Institute of Applied Geoscience

Kahsay, H.G.2008, Groundwater resources assessment through distributed steady state flow modeling, Anylam Wellfield (Mekele, Ethiopia) MSc Thesis, International Institute for Geo Information and Earth Observation, Enschede Netherllands, pp. 45-50

Khan, G.D. and Waheedullah, A.S.B., 2013, 'Groundwater Investigation by Using Resistivity Survey in Peshawar Pakistan', *Journal of Resources Development and Management-An Open Access International Journal*, vol. *2*.

Khan, G.D., Ali, M. and Akbar, F 2014, Over Exploitation of Groundwater Resources and Their Influence on Groundwater in Peshawar Valley", *Civil and Environmental Research*, vol. 6, no 2

Malik, M.S., 1967, 'Records of groundwater levels of Peshawar Vale, West Pakistan', *WASID/WAPDA*, vol. 12, pp. 18-40

Morris et al., 2003, *Groundwater and its susceptibility to degradation: a global assessment of the problem and options for management*, Vol. 3, United Nations Environment Programme.

Manzoor Ali, 2007, 'Water is a new battleground', *The Express Tribune*, 16 May, https://tribune.com.pk/story/253359/water-is-a-new-battleground/

Muhammad Shafique Sarmad Israr M. Tahir Shah M. Asif Khan, 2014, 'Remote sensing-based strategy of stream sediment sampling for mineral exploration in Peshawar Basin Khyber Pakhtunkhwa Pakistan', *Journal of Himalayan Earth Sciences,* vol. 47, no 2, pp.141–148.

Masud, T., Ali, A., Hussain, H., Shahzada, K., Alam, B., Masud, N. and Rizwan, M., 2013, 'Estimation of groundwater balance for the Pabbi region, Khyber Pakhtunkhwa;, *Journal of Himalayan Earth Sciences*, vol. *46*, no. 2, pp.113-119.

Muhammad, S. and Khalid, P., 2017, 'Hydrogeophysical investigations for assessing the groundwater potential in part of the Peshawar basin, Pakistan', *Environmental Earth Sciences*, vol. *76*, no. 14, p.494.

Naveed Khan, 2017, 'Peshawar Valley: facing unchecked urbanisation', *The Sunday News,* 10 July, http://tns.thenews.com.pk/peshawar-valley-facing-unchecked- urbanisation/#.

W709S2gzZPY
NATHANSON, J. A 2009, Basic Environmental Technology-Water Supply, Waste Management, and Pollution Control, Upper Saddle River, New Jercy 07458, USA, Pearson Education.
Nizami, M.M.I., 1973, ‘Reconnaissance soil survey of Peshawar vale (revised)’, *Soil Survey of Pakistan, Lahore*, vol.165, pp. 6-13
Nasreen, S., 2006, Monitoring of Surface Water Ground Water Air and Soil in Peshawar Basin Against Time The 3rd Dimension, University of Peshawar, Pakistan
Naqavi, S.A.H. and L. Hamadan, 1978. ‘Planning report of Mardan SCARP, app. C: Groundwater resources’, *WAPDA, Planning Directorate, Peshawar*; pp. 37
Noreema Masud Muhammad Rizwan 2013, ‘Estimation of groundwater balance for the Pabbi region, Khyber Pakhtunkhwa’, *Journal of Himalayan Earth Sciences*, vol. 46, no 2, pp.113–119.
Pakistan Bureau of Statistics 2018, *Population Census 2017*, Islamabad, viewed 5 May 2018, http://www.pbscensus.gov.pk/
Poeter, E. and Anderson, D., 2005, ‘Multimodel ranking and inference in ground water modeling’, *Groundwater*, vol *43*, no. 4, pp.597-605.
Pathak, R., Awasthi, M.K., Sharma, S.K., Hardaha, M.K. and Nema, R.K., 2018, ‘Ground Water Flow Modelling Using MODFLOW–A Review’, *Int. J. Curr. Microbiol. App. Sci*, vol *7*, no 2, pp.83-88.
Pakistan Meteorological Department 2018, *rainfall and temperature data*, Government of Pakistan, viewed 18 July 2018, http://www.pmd.gov.pk/
Rafiq, M., Ahmad, I. and Tahirkheli, T., 1983, ‘A geological map of the surroundings of the Peshawar Plain’, *Geological Bulletin of the University of Peshawar*, vol. *16*, p.189
Robberts, J.H., 1988, ‘Groundwater in the Peshawar Vale, Peshawar District, Mardan District and Malakand Agency, NWFP’, *WAPDA Hydrogeology Directorate Peshawar and TNO Institute of Applied Geoscience, Delft, the Netherlands*, vol. 2
Rojstaczer, S.A., 1994, ‘The limitations of groundwater models’, *Journal of Geological Education*, vol *42*, no 4, pp.362-368.

Reilly, T.E. and Harbaugh, A.W., 2004, *Guidelines for evaluating ground-water flow models*, p. 30, US Department of the Interior, US Geological Survey.

Sajjad, A.M., 1983b, 'Hydrogeological data of Peshawar Valley', *WAPDA Directorate-general of Hydrogeology, Lahore*, vol. 1, no. 11, p. 3

Salama, R.B., Otto, C.J. & Fitzpatrick, R.W., 1999, 'Contributions of groundwater conditions to soil and water salinization", *Hydrogeology Journal*, vol 7, no 1, pp.46–64

Saeed, T.U. and Khan, T.A. 2014, 'Impact of Water Losses and Maintenance of Canal Irrigation System on Agriculture (Case Study: Urmar Minor of Warsak Gravity Canal Pakistan)', *American Journal of Experimental Agriculture*, vol. *4*, no 5, p.550-580.

Siddiqi, M.R., 1972, 'Groundwater hydrology of Mardan area. Reclamation division', *WAPDA*, vol. 8, pp, 62-72

Ślesicki, M., 2009, "Application of mathematical modelling methods in the protection of groundwater environment" *Journal of water and land development*, pp.31-39.

Shahida, N., 2006, Monitoring Of Surface Water Ground Water Air And Soil In Peshawar Basin Against Time The 3rd Dimension (Doctoral dissertation, University of Peshawar, Viewed 7 May 2018,
http://nceg.uop.edu.pk/ResearchPublications/International/2005to2006.html

Searle, M. P., Khan, M. A., Jan, M. Q., DiPietro, J. A., Pogue, K. R., Pivnik, D. A., Sercombe, W. J., Izatt, C. N., Blisniuk, P. M., Treloar, P. J., Gaetani, M., & Zanchi, A. 1996, *Geological map of north Pakistan and adjacent areas of northern Ladakh and Western Tibet*, Salt Ranges, Kohistan, Karakoram and Hindi Kush: Western Himalaya.

Singh, A., Mishra, S. and Ruskauff, G. 2010, 'Model averaging techniques for quantifying conceptual model uncertainty', *Groundwater*, vol *48*, no 5, pp.701-715.

Shah, T., Molden, D., Sakthivadivel, R. and Seckler, D., 2000, *The global Groundwater situation: overview of opportunities and challenges*. IWMI.

The United Nations 2014, *Human Settlements Program (UN-HABITAT)*, Viewed 25th June 2018, https://sustainabledevelopment.un.org/content/documents/9025UN-Habitat.pdf

Usman, M.N., Naeem, M. and Khan, Z., 2009, 'Socio-Economic Determinants of Migration of People from Rural to Urban Areas of District Peshawar', *Journal of Management Sciences*, vol. *4*, no. 2

Urban Policy Unit 2017, *Final Peshawar Land use plan 2017-2037*, Planning and Development Department Government of Khyber Pakhtunkhwa, http://urbanpolicyunit.gkp.pk/wp-content/uploads/2018/03/Final-Peshawar-Landuse-Report-2017.pdf

Urban Policy Unit 2014, Master Plan Vol.1 Water Supply, Treatment and Distribution, Planning and Development Department Government of Khyber Pakhtunkhwa, http://urbanpolicyunit.gkp.pk/wp-content/uploads/2018/02/Water-Sanitation-Peshawar-Report.pdf

Wang, H.F. and Anderson, M.P., 1995, *Introduction to groundwater modeling: finite difference and finite element methods*. Academic Press.

WAPDA, Directorate of planning and investigation 1963, *Sherkera tube well irrigation project*, P & I, vol.6 no. 27, Lahore, Pakistan

Water & Sanitation Services Peshawar, 2018, *groundwater abstraction and log data*, Peshawar Government of Pakistan, viewed 10 June 2018, http://wsspeshawar.org.pk

Winston, R.B., 2006, GoPhast-A graphical user interface for PHAST: U.S. Geological Survey Techniques and Methods 6–A20, 98 p.

Zhou, Y. and Li, W., 2011, ‘A review of regional groundwater flow modeling’, *Geoscience frontiers*, vol. *2*, no 2, pp.205-214

Appendix A

Log based strata classification

Log based strata sequence at, Sector L/2 Phase-03 (Hayatabad), Peshawar			
S #	Depth (ft)	Strata Classified	Thickness (ft)
1	00 – 10	Clay - Gravel - boulders	10
2	10 –207	Gravel – boulders	197
3	207 – 228	Clay	21
4	228 – 316	Gravel – boulders	88
5	316 – 321	Clay	5
6	321 – 407	Gravel – boulders	86
7	407 – 416	Clay	9
8	416 – 445	Gravel – boulders	29
9	445 – 450	Clay	5
10	450 – 466	Gravel – boulders	16
11	466 – 472	Clay	6
12	472 – 505	Gravel	33
13	505 – 508	Clay	3
14	508 – 540	Gravel – boulders	32

Log based strata sequence at Corporation Colony TW # 28 UC-04 Peshawar,			
S #	Depth (ft)	Strata Classified	Thickness (ft)
1	00 – 27	Clay	27
2	27 – 111	Gravel – boulder	84
3	111 – 135	Clay	24
4	135 – 206	Gravel – boulders	71
5	206 – 216	Clay	10
6	216 – 321	Gravel – boulders	105
7	321 – 348	Clay – Sand	27
8	348 – 382	Gravel - Sand	34
9	382 – 390	Clay	8
10	390 – 410	Sand with minor gravel	20
11	410 – 421	Clay	11
12	421 – 443	Gravel – Sand	22
13	443 – 460	Clay	17

Log based strata sequence at, Dir Colony, Peshawar			
S #	Depth (ft)	Strata Classified	Thickness (ft)
1	00 – 20	Clay	20
2	20 – 60	Gravel - boulders	40
3	60 – 69	Clay	9
4	69 – 120	Gravel – boulders	51
5	120 – 137	Clay	17
6	137 – 220	Gravel – Sand	83
7	220 – 233	Clay – Sand	13
8	233 – 266	Gravel	33
9	266 – 321	Gravel – Sand	55
10	321 – 375	Gravel – boulders	54
11	375 – 379	Clay – Sand	4
12	379 – 385	Gravel	6
13	385 – 416	Grave – Sand	31
14	416 – 439	Gravel – Sand	23
15	439 – 503	Gravel - Clay – Sand	64
16	503 - 515	Sand	12
17	515 – Onward	Clay	

Log based strata sequence at Gul Bahar, Peshawar

S #	Depth (ft)	Strata Classified	Thickness (ft)
1	00 – 30	Clay	30
2	30 – 90	Gravel – Sand	60
3	90 – 110	Clay	20
4	110 – 148	Gravel – boulders	38
5	148 – 152	Clay	4
6	152 – 200	Sand with minor clay	48
7	200 – 205	Clay	5
8	205 – 272	Gravel	67
9	272 – 280	Gravel - sand	8
10	280 – 320	Gravel	40
11	320 – 340	Clay – Sand	20
12	340 – 351	Clay	9
13	351 – 362	Gravel	11
14	362 – 382	Clay – Sand	20
15	382 – 430	Gravel – boulders	48
16	430 – Onward	Clay	

Appendix B

Groundwater abstraction data

S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day	S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day
1	185045	3768048	332	242	-435	51	183178	3766784	319	229	-763
2	186263	3769118	330	240	-500	52	183260	3766905	345	255	-754
3	186795	3768885	332	242	-561	53	183283	3766842	325	235	-854
4	187712	3768669	320	230	-549	54	183983	3767004	318	228	-806
5	186611	3768768	318	228	-519	55	184034	3767002	332	242	-610
6	186529	3768616	335	245	-513	56	184446	3767019	336	246	-549
7	186037	3768509	367	277	-511	57	183836	3767225	340	250	-385
8	186106	3768260	339	249	-574	58	184135	3767708	342	252	-349
9	185836	3768639	345	255	-557	59	184163	3767800	336	246	-3720
10	185704	3768551	330	240	-555	60	184239	3767767	326	236	-442
11	185697	3768335	323	233	-684	61	184010	3767065	322	232	-256
12	185696	3768304	320	230	-610	62	183992	3766510	336	246	-161
13	185246	3768690	335	245	-568	63	183216	3766382	335	245	-494
14	185272	3768689	341	251	-557	64	183370	3766376	330	240	-684
15	184825	3769136	345	255	-378	65	183474	3766404	345	255	-4650
16	184955	3769193	344	254	-438	66	183907	3766297	353	263	-360
17	185217	3769338	355	265	-519	67	182660	3765876	352	262	-427
18	185699	3769168	350	260	-549	68	184625	3767013	340	250	-442
19	185699	3769168	320	230	-549	69	184516	3766832	338	248	-488
20	185908	3769254	322	232	-305	70	184655	3767136	334	244	-478
21	186931	3769127	351	261	-808	71	183635	3766614	339	249	-488
22	185491	3769082	346	256	-888	72	183073	3766695	349	259	-549
23	185181	3769031	348	258	-488	73	183223	3767338	352	262	-513
24	185615	3768955	336	246	-220	74	184321	3767918	350	260	-684
25	186053	3769002	318	228	-807	75	183004	3767715	354	264	-4650
26	186369	3768436	335	245	-684	76	183003	3767684	347	257	-2325
27	185768	3768148	338	248	-793	77	182870	3767535	329	239	-467
28	185641	3768183	335	245	-305	78	182348	3767305	327	237	-421
29	185413	3768283	337	247	-317	79	182633	3767388	324	234	-575
30	185415	3768344	340	250	-342	80	182559	3767483	322	232	-472
31	185266	3768504	319	229	-671	81	182585	3767483	324	234	-793
32	185348	3768655	345	255	-687	82	182412	3767674	337	247	-745
33	185345	3768563	355	265	-544	83	182357	3767583	339	249	-427
34	186774	3768268	345	255	-452	84	182459	3767549	335	245	-397
35	186639	3768057	340	250	-574	85	182565	3767638	334	244	-392
36	186356	3768066	330	240	-505	86	182595	3767791	332	242	-2325
37	186539	3768153	332	242	-756	87	182506	3768195	341	251	-274
38	185862	3767867	335	245	-732	88	182630	3768067	342	252	-62
39	186004	3767523	346	256	-613	89	182550	3767977	345	255	-488
40	186176	3767270	337	247	-580	90	182908	3767904	356	266	-625
41	185798	3767499	350	260	-610	91	182938	3768057	348	258	-511
42	183716	3767476	355	265	-366	92	182920	3768274	351	261	-627
43	183792	3767442	354	264	-427	93	183227	3768232	361	271	-915
44	183530	3767297	358	268	-513	94	183146	3768112	360	270	-732
45	183726	3767012	363	273	-549	95	183166	3767957	320	230	-574
46	183471	3767083	361	271	-854	96	183192	3767956	318	228	-671
47	183680	3767168	364	274	-830	97	183271	3768015	317	227	-835
48	183722	3766889	370	280	-592	98	183709	3768031	312	222	-403
49	183797	3766825	365	275	-391	99	183552	3767975	330	240	-598
50	183538	3766772	312	222	-793	100	184341	3768504	335	245	-2674

S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day	S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day
101	184291	3768536	332	242	-795	151	182790	3766704	337	247	-305
102	184237	3768476	331	241	-1012	152	182841	3766672	330	240	-557
103	184166	3768664	336	246	-545	153	182969	3766668	326	236	-488
104	184034	3768545	337	247	-574	154	183106	3766910	332	242	-488
105	183826	3768459	331	241	-652	155	185817	3768084	331	241	-439
106	184020	3768885	328	238	-613	156	185713	3768026	327	237	-439
107	183862	3768767	327	237	-511	157	185663	3768089	338	248	-2325
108	183972	3768979	325	235	-806	158	185422	3767789	336	246	-391
109	183713	3768926	336	246	-536	159	185344	3767761	335	245	-305
110	183897	3769043	337	247	-391	160	185121	3768015	334	244	-610
111	183841	3768921	336	246	-532	161	185226	3768073	326	236	-990
112	183791	3768954	338	248	-405	162	185134	3768385	335	245	-806
113	183681	3768742	342	252	-826	163	185056	3768356	341	251	-881
114	184316	3767764	344	254	-528	164	184949	3768237	342	252	-732
115	184511	3767449	342	252	-482	165	185023	3768142	344	254	-757
116	184641	3767476	340	250	-610	166	184867	3768085	345	255	-610
117	184573	3767755	345	255	-684	167	184845	3768209	346	256	-623
118	184564	3767478	347	257	-580	168	184715	3768152	340	250	-513
119	184377	3767268	351	261	-632	169	184800	3768396	341	251	-610
120	184377	3767268	356	266	-527	170	184589	3768249	352	262	-427
121	184284	3767580	354	264	-5813	171	184658	3768771	353	263	-397
122	184055	3767649	357	267	-235	172	184886	3768671	361	271	-610
123	183945	3767406	358	268	-610	173	184914	3768731	360	270	-872
124	183923	3766759	359	269	-366	174	184914	3768731	365	275	-568
125	184337	3766838	340	250	-5813	175	185014	3768666	366	276	-429
126	184148	3766566	341	251	-732	176	185246	3768690	368	278	-915
127	183599	3767819	338	248	-3720	177	184716	3768954	369	279	-732
128	184523	3767788	336	246	-256	178	184509	3768930	370	280	-610
129	183191	3767925	334	244	-322	179	184513	3768282	345	255	-793
130	183138	3767865	332	242	-385	180	184465	3768376	340	250	-366
131	183208	3767678	330	240	-729	181	184631	3768710	335	245	-397
132	183335	3767612	329	239	-1102	182	184606	3768742	336	246	-281
133	183383	3767518	328	238	-256	183	184606	3768742	335	245	-793
134	183398	3767209	360	270	-909	184	184503	3768745	330	240	-915
135	183162	3767062	315	225	-623	185	184379	3768873	328	238	-641
136	183515	3767637	322	232	-623	186	184640	3768987	340	250	-645
137	183912	3767963	336	246	-685	187	184200	3768909	342	252	-500
138	184015	3767990	329	239	-4650	188	184395	3768594	344	254	-244
139	183111	3767835	361	271	-3720	189	184395	3768594	345	255	-915
140	182570	3767020	362	272	-1163	190	184311	3768381	348	258	-799
141	182487	3766869	363	273	-228	191	184156	3768356	339	249	-366
142	182408	3766810	352	262	-450	192	184156	3768356	338	248	-610
143	182527	3766528	350	260	-2325	193	184156	3768356	320	230	-1129
144	182676	3766369	320	230	-197	194	184154	3768294	325	235	-305
145	182514	3766127	325	235	-439	195	184282	3768290	361	271	-366
146	182729	3766398	328	238	-475	196	184356	3768195	362	272	-843
147	182883	3766393	330	240	-488	197	184330	3768165	322	232	-244
148	182907	3766361	335	245	-366	198	184252	3768136	342	252	-548
149	183194	3766475	339	249	-305	199	184170	3767985	345	255	-549
150	182860	3766486	336	246	-305	200	184067	3767988	338	248	-630

S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day	S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day
201	183770	3768338	342	252	-476	251	185183	3767550	326	236	-500
202	183764	3768153	344	254	-488	252	185243	3767826	336	246	-450
203	183764	3768153	345	255	-1246	253	184912	3767898	340	250	-763
204	183625	3768620	342	252	-732	254	184877	3767622	342	252	-438
205	183599	3768590	337	247	-769	255	184603	3767878	340	250	-501
206	183312	3768476	347	257	-610	256	182052	3767686	337	247	-548
207	183337	3768445	349	259	-537	257	181780	3763950	341	251	-393
208	183375	3768042	355	265	-482	258	181514	3763779	345	255	-340
209	183273	3768077	360	270	-419	259	181689	3764300	352	262	-477
210	183172	3765828	361	271	-297	260	181376	3764734	338	248	-246
211	182804	3765593	362	272	-175	261	181878	3764928	329	239	-329
212	182711	3765103	355	265	-259	262	181315	3763986	362	272	-712
213	182923	3764540	352	262	-471	263	181259	3764165	354	264	-657
214	183381	3764401	344	254	-698	264	180522	3763998	339	249	-678
215	184342	3764678	335	245	-657	265	181709	3765736	320	230	-456
216	184209	3766101	336	246	-383	266	181052	3767235	327	237	-498
217	184299	3766469	338	248	-378	267	181011	3767016	329	239	-565
218	184763	3766515	340	250	-274	268	180773	3767193	334	244	-600
219	185598	3766888	328	238	-246	269	180701	3767125	337	247	-672
220	186129	3765852	322	232	-208	270	180801	3766768	339	249	-720
221	186079	3765916	326	236	-712	271	180960	3766881	341	251	-558
222	186222	3767114	341	251	-383	272	181002	3766706	342	252	-252
223	185513	3767446	345	255	-371	273	181148	3766809	346	256	-444
224	185533	3767261	337	247	-329	274	180737	3766533	349	259	-385
225	182869	3767504	332	242	-674	275	180604	3766437	351	261	-480
226	182869	3767504	330	240	-602	276	180385	3766266	352	262	-766
227	182868	3767473	328	238	-329	277	180398	3766020	362	272	-800
228	182761	3767353	334	244	-383	278	180711	3766156	361	271	-672
229	182605	3767297	341	251	-697	279	180871	3766360	372	282	-396
230	182682	3767294	345	255	-383	280	181021	3766169	368	278	-234
231	182398	3767273	342	252	-438	281	181180	3766132	354	264	-720
232	182093	3767376	357	267	-548	282	181351	3766237	350	260	-660
233	181961	3767257	358	268	-364	283	181608	3766859	348	258	-540
234	181932	3767165	362	272	-356	284	181572	3766601	346	256	-504
235	181914	3767382	361	271	-516	285	181805	3767277	345	255	-766
236	182162	3767127	362	272	-471	286	181679	3766402	344	254	-432
237	182459	3766777	364	274	-335	287	181938	3766228	342	252	-258
238	182454	3766654	366	276	-329	288	181950	3766775	337	247	-312
239	182239	3767124	368	278	-253	289	182008	3766777	327	237	-240
240	181873	3767692	355	265	-881	290	181374	3767069	326	236	-438
241	183067	3767281	336	246	-438	291	180508	3766917	324	234	-480
242	183036	3767128	327	237	-548	292	180307	3766850	322	232	-480
243	184599	3767755	320	230	-219	293	179769	3766278	320	230	-330
244	184599	3767755	318	228	-477	294	179994	3766522	332	242	-564
245	184598	3767724	335	245	-627	295	180185	3766770	330	240	-504
246	184722	3767596	338	248	-627	296	180449	3766776	341	251	-720
247	184973	3767434	340	250	-274	297	180444	3766601	345	255	-840
248	184997	3767371	341	251	-356	298	180361	3766523	344	254	-540
249	185277	3767300	342	252	-497	299	180303	3766408	347	257	-498
250	185366	3767636	346	256	-865	300	180371	3766344	318	228	-259

S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day	S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day
301	179268	3765576	325	235	-330	351	179325	3765029	332	242	-631
302	185226	3765269	345	255	-325	352	169207	3768131	330	240	-574
303	179793	3765717	355	265	-468	353	169402	3768723	327	237	-384
304	180064	3765739	356	266	-534	354	169955	3768121	328	238	-436
305	180358	3765418	358	268	-600	355	173040	3772406	365	275	-453
306	180701	3765133	360	270	-720	356	173668	3768143	360	270	-940
307	180911	3765094	362	272	-672	357	179625	3767873	362	272	-460
308	180662	3764582	364	274	-324	358	173919	3768444	358	268	-951
309	180410	3764539	366	276	-392	359	174087	3768483	356	266	-516
310	181507	3765863	365	275	-420	360	174696	3769245	355	265	-574
311	181483	3765594	368	278	-540	361	175103	3769177	351	261	-574
312	182201	3766331	350	260	-720	362	176431	3768297	350	260	-574
313	179639	3765979	328	238	-780	363	176350	3768184	348	258	-562
314	179581	3765901	330	240	-732	364	176219	3768174	346	256	-499
315	179508	3765042	332	242	-540	365	176371	3768180	345	255	-459
316	179370	3764916	334	244	-253	366	176295	3768086	343	253	-402
317	179674	3764790	336	246	-617	367	176250	3767954	340	250	-373
318	179868	3765240	347	257	-480	368	176059	3768044	338	248	-287
319	180886	3765578	354	264	-432	369	176071	3768450	336	246	-258
320	181111	3765599	352	262	-325	370	176266	3768652	334	244	-516
321	180991	3765936	350	260	-540	371	176465	3768535	332	242	-689
322	180561	3765743	348	258	-612	372	176489	3769031	330	240	-643
323	179092	3765277	344	254	-735	373	176886	3768598	328	238	-765
324	178906	3764664	343	253	-780	374	176949	3768991	326	236	-201
325	178398	3764740	344	254	-792	375	175689	3772075	335	245	-546
326	178338	3764572	340	250	-420	376	176462	3770743	343	253	-499
327	178546	3765072	339	249	-450	377	175952	3770805	348	258	-984
328	178756	3765208	338	248	-459	378	176565	3771496	350	260	-516
329	178270	3764919	336	246	-720	379	175467	3770459	352	262	-503
330	177768	3764771	334	244	-792	380	175541	3770550	354	264	-446
331	177823	3766072	332	242	-720	381	175921	3772345	355	265	-515
332	177137	3766033	330	240	-456	382	176607	3769701	362	272	-482
333	176787	3766236	328	238	-617	383	176869	3769364	360	270	-488
334	177171	3766535	326	236	-559	384	177021	3769363	367	277	-486
335	177143	3767992	324	234	-504	385	176594	3769300	358	268	-493
336	177689	3767471	322	232	-463	386	176089	3770226	350	260	-494
337	177296	3768004	320	230	-471	387	177572	3770444	349	259	-498
338	176561	3765754	319	229	-358	388	177826	3771123	339	249	-504
339	176512	3765596	318	228	-402	389	177337	3769169	327	237	-521
340	177218	3765376	341	251	-430	390	177256	3769057	322	232	-579
341	176238	3765972	344	254	-437	391	178997	3769356	320	230	-579
342	174659	3767002	345	255	-389	392	178365	3768833	337	247	-579
343	174820	3767274	346	256	-689	393	177871	3768904	349	259	-695
344	174634	3767110	349	259	-574	394	178467	3768610	350	260	-712
345	174528	3767237	351	261	-562	395	178425	3768642	365	275	-405
346	173693	3767300	354	264	-559	396	179152	3769808	370	280	-440
347	178807	3765673	361	271	-732	397	179680	3769499	372	282	-324
348	177464	3765220	362	272	-373	398	179252	3768956	371	281	-951
349	181036	3764971	366	276	-430	399	176500	3769196	373	283	-459
350	182299	3765037	336	246	-689	400	173847	3768651	375	285	-1071

S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day	S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day
401	176166	3768525	377	287	-402	451	185015	3769508	360	270	-643
402	176194	3769357	367	277	-459	452	186121	3770658	345	255	-631
403	176655	3768852	366	276	-631	453	186708	3770715	340	250	-402
404	173446	3769153	362	272	-689	454	185903	3770001	342	252	-430
405	187289	3769757	360	270	-643	455	183268	3770552	336	246	-590
406	186988	3769897	346	256	-551	456	182814	3770681	334	244	-689
407	186666	3769344	344	254	-316	457	183904	3770657	331	241	-951
408	187058	3769475	346	256	-310	458	183306	3771346	328	238	-448
409	186961	3770220	349	259	-396	459	183168	3769985	347	257	-516
410	186535	3769731	342	252	-505	460	172379	3778940	356	266	-689
411	186058	3770699	336	246	-516	461	183068	3772532	359	269	-706
412	181589	3775292	338	248	-574	462	183052	3770688	332	242	-746
413	184960	3771019	340	250	-287	463	183076	3769984	330	240	-853
414	185289	3771316	326	236	-344	464	183394	3770351	328	238	-951
415	184233	3771426	324	234	-689	465	183162	3770250	338	248	-375
416	185985	3768480	355	265	-574	466	182831	3770349	340	250	-689
417	185164	3771617	345	255	-689	467	182533	3770372	342	252	-551
418	185055	3772078	348	258	-746	468	183877	3769206	346	256	-516
419	184632	3771104	355	265	-574	469	183553	3769147	350	260	-546
420	184588	3770970	357	267	-743	470	183419	3769195	332	242	-433
421	185260	3770925	360	270	-765	471	185071	3769163	329	239	-402
422	184559	3770697	362	272	-384	472	183245	3769857	347	257	-344
423	184977	3770267	355	265	-459	473	182989	3770340	316	226	-373
424	183934	3770328	334	244	-499	474	184154	3769695	337	247	-689
425	185452	3770532	332	242	-516	475	183159	3769729	348	258	-574
426	185160	3770221	328	238	-545	476	182794	3771252	366	276	-831
427	184276	3770599	346	256	-721	477	183977	3769964	362	272	-689
428	184174	3770724	360	270	-689	478	183753	3769875	358	268	-557
429	184700	3770229	342	252	-643	479	184510	3769698	332	242	-459
430	185119	3770561	338	248	-746	480	184645	3769567	328	238	-453
431	184294	3770480	336	246	-402	481	184759	3770002	349	259	-874
432	184924	3770714	330	240	-601	482	184530	3770052	344	254	-387
433	183977	3771246	326	236	-951	483	184978	3769912	354	264	-402
434	184126	3770188	360	270	-874	484	184275	3769491	376	286	-534
435	185737	3770103	362	272	-499	485	184980	3770059	372	282	-574
436	186640	3770563	364	274	-984	486	184154	3769695	339	249	-574
437	186180	3770062	356	266	-689	487	184048	3769766	348	258	-574
438	185147	3769539	366	276	-746	488	184895	3769101	346	256	-459
439	185113	3769592	368	278	-574	489	184923	3769088	335	245	-384
440	185713	3769804	370	280	-453	490	186877	3776703	305	215	-402
441	186244	3770393	368	278	-853	491	187639	3776672	302	212	-402
442	185555	3770289	366	276	-459	492	188274	3776735	307	217	-459
443	185682	3769736	355	265	-984	493	188813	3776640	301	211	-574
444	186107	3771174	346	256	-516	494	188655	3776322	301	211	-384
445	185367	3770303	334	244	-574	495	189131	3776322	298	208	-273
446	185823	3770631	332	242	-700	496	189448	3776386	300	210	-546
447	185581	3770721	330	240	-631	497	186051	3776132	307	217	-372
448	186309	3770265	326	236	-874	498	185321	3775306	308	218	-350
449	186545	3770300	328	238	-732	499	184686	3775433	309	219	-437
450	186211	3769731	364	274	-689	500	184051	3775751	310	220	-415

S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day	S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day
501	184178	3775370	308	218	-831	576	174431	3761305	434	344	-437
502	184051	3774862	308	218	-623	577	174812	3761146	432	342	-437
503	184432	3774925	306	216	-350	578	174748	3761463	424	334	-470
504	184813	3774925	307	217	-361	579	174462	3760987	437	347	-492
505	185289	3774640	308	218	-372	580	188083	3764353	330	240	-350
506	185702	3775497	306	216	-426	581	187766	3764257	333	243	-230
507	184972	3775719	308	218	-470	582	187702	3764607	332	242	-197
508	184527	3775973	311	221	-656	583	187416	3764353	331	241	-208
509	183829	3776354	311	221	-328	584	187037	3764210	335	245	-328
510	183543	3775846	310	220	-175	585	187323	3763861	333	243	-853
511	183606	3775370	307	217	-765	586	187546	3763924	333	243	-350
512	182844	3777021	310	220	-656	587	187736	3763829	333	243	-350
513	182590	3776672	309	219	-579	588	188054	3763924	334	244	-372
514	183035	3776481	310	220	-699	589	188911	3763956	319	229	-383
515	182178	3777021	312	222	-984	590	188657	3763702	322	232	-492
516	182051	3776545	313	223	-557	591	188403	3763448	324	234	-383
517	182432	3776195	313	223	-568	592	188022	3763321	334	244	-546
518	182908	3775941	311	221	-634	593	187609	3763130	337	247	-710
519	183543	3776608	316	226	-645	594	188244	3762241	325	235	-678
520	183257	3776767	311	221	-732	595	188466	3762559	334	244	-689
521	183289	3777021	311	221	-492	596	186752	3763988	335	245	-350
522	184178	3776354	308	218	-109	597	186815	3763670	339	249	-339
523	184114	3776100	309	219	-240	598	187006	3763607	338	248	-393
524	183511	3776164	309	219	-219	599	186752	3764559	332	242	-383
525	183352	3776322	308	218	-350	600	186434	3764432	330	240	-374
526	185511	3775687	309	219	-372	601	186307	3764020	336	246	-262
527	185734	3775878	308	218	-437	602	186307	3763607	340	250	-339
528	182908	3774132	310	220	-437	603	186498	3763321	342	252	-470
529	182559	3773909	314	224	-590	604	186815	3763257	339	249	-568
530	182273	3773814	312	222	-525	605	187101	3763257	338	248	-557
531	182114	3774100	312	222	-536	606	187482	3763480	340	250	-612
532	182495	3774195	309	219	-612	607	185672	3763480	332	242	-481
533	182749	3774417	308	218	-732	608	185735	3763924	335	245	-350
534	182527	3774513	310	220	-546	609	186021	3764337	333	243	-339
535	182273	3774481	312	222	-546	610	185989	3763480	335	245	-164
536	187321	3776862	305	215	-492	611	185989	3762972	348	258	-144
537	186432	3774195	302	212	-579	612	186402	3762972	342	252	-144
538	186750	3774195	303	213	-492	613	183576	3761574	348	258	-230
539	186654	3774544	304	214	-546	614	183131	3761543	356	266	-568
540	168462	3769623	414	324	-339	615	182973	3761257	354	264	-404
541	168335	3770036	414	324	-361	616	183385	3761225	352	262	-656
542	168049	3769750	420	330	-372	617	183195	3762146	353	263	-699
543	168843	3769972	409	319	-393	618	181575	3762908	367	277	-743
544	168684	3770258	409	319	-459	619	181575	3762654	367	277	-699
545	168493	3770417	408	318	-372	620	181512	3762305	367	277	-546
546	169065	3770480	404	314	-503	621	181925	3762432	364	274	-590
547	169478	3770385	397	307	-557	622	182020	3762749	365	275	-656
548	170240	3770449	392	302	-579	623	190150	3766846	314	224	-350
549	171129	3766734	396	306	-546	624	189896	3766465	316	226	-197
550	171510	3766829	394	304	-383	625	190213	3766401	318	228	-203
551	171287	3767115	392	302	-328	626	189800	3766846	315	225	-820
552	170938	3767147	396	306	-230	627	189483	3766528	318	228	-470
553	171033	3767369	392	302	-240	628	185513	3763099	342	252	-590
554	171446	3767559	392	302	-273	629	186752	3762749	338	248	-350
555	171637	3767337	389	299	-295	630	187228	3762749	326	236	-470
556	171764	3767020	388	298	-306	631	186148	3762527	345	255	-940
557	170748	3766766	400	310	-339	632	182338	3761828	359	269	-262
558	170779	3766543	401	311	-372	633	180432	3759478	385	295	-167
559	170970	3766385	402	312	-317	634	180051	3759351	385	295	-350
560	171383	3766448	398	308	-295	635	180400	3759066	383	293	-470
561	170557	3767274	399	309	-251	636	180781	3759161	385	295	-350
562	169668	3765369	423	333	-208	637	180845	3759542	376	286	-230
563	169605	3765146	421	331	-372	638	180083	3759764	385	295	-350
564	169827	3765115	423	333	-481	639	180337	3760050	381	291	-230
565	169478	3764797	427	337	-492	640	180654	3759923	379	289	-230
566	169700	3764702	423	333	-568	641	179575	3759574	389	299	-219
567	173986	3763305	418	328	-656	642	179606	3759859	389	299	-131
568	173700	3763622	408	318	-350	643	179956	3760272	384	294	-350
569	173573	3763972	411	321	-186	644	183862	3765290	343	253	-328
570	173446	3763718	411	321	-262	645	184179	3765417	338	248	-350
571	173383	3763337	417	327	-383	646	184497	3765099	342	252	-328
572	173637	3763114	418	328	-481	647	185037	3765734	334	244	-251
573	173891	3763940	407	317	-546	648	181321	3769609	327	237	-219
574	174145	3763749	407	317	-437	649	181258	3769196	334	244	-175
575	174050	3765464	388	298	-262	650	180813	3769259	340	250	-164

S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day	S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day
651	180940	3768942	342	252	-158	726	171754	3761450	442	362	-33
652	181544	3769386	329	239	-142	727	169849	3763228	426	346	-33
653	181798	3769704	324	234	-546	728	168833	3771229	398	318	-33
654	181004	3769609	330	240	-470	729	177723	3774277	328	248	-33
655	181607	3768942	337	247	-350	730	177786	3776754	321	241	-33
656	181290	3768688	344	254	-350	731	180961	3777516	315	235	-33
657	170492	3771705	380	290	-240	732	181025	3780056	314	234	-33
658	170778	3772022	377	287	-656	733	182739	3779103	310	230	-33
659	170302	3772022	378	288	-350	734	178612	3781008	323	243	-33
660	170143	3771832	381	291	-230	735	176072	3779929	325	245	-33
661	170588	3772498	380	290	-153	736	174611	3778722	328	248	-33
662	171096	3772721	365	275	-175	737	173722	3783167	336	256	-33
663	173859	3761892	425	335	-328	738	186613	3777833	306	226	-33
664	174367	3762114	419	329	-546	739	184581	3777960	308	228	-33
665	174621	3762209	422	332	-350	740	190105	3755481	377	297	-33
666	175319	3762527	408	318	-230	741	195058	3754465	403	323	-33
667	174970	3762495	414	324	-164	742	191502	3749575	457	377	-33
668	175097	3763035	408	318	-153	743	185978	3745384	468	388	-33
669	174780	3762876	417	327	-503	744	180580	3745194	482	402	-33
670	170275	3765043	436	346	-546	745	183120	3752116	415	335	-33
671	177786	3741225	575	495	-33	746	183057	3743797	496	416	-33
672	180644	3741670	553	473	-33	747	171754	3786152	340	260	-33
673	185216	3741289	521	441	-33	748	178929	3785072	325	245	-33
674	191058	3743130	528	448	-33	749	181279	3784437	317	237	-33
675	193026	3746496	514	434	-33	750	186549	3782342	306	226	-33
676	196328	3749861	475	395	-33	751	190994	3779167	301	221	-33
677	197598	3754052	417	337	-33	752	189026	3775738	304	224	-33
678	198424	3757926	375	295	-33	753	196201	3753068	436	356	-33
679	192836	3757291	365	285	-33	754	195947	3757513	367	287	-33
680	191502	3752782	393	313	-33	755	176072	3751671	456	376	-33
681	187756	3749353	423	343	-33	756	176072	3752687	449	369	-33
682	182993	3748210	446	366	-33	757	177977	3752941	436	356	-33
683	178802	3749861	453	373	-33	758	200202	3752370	475	395	-33
684	175564	3754814	445	365	-33	759	169404	3780627	343	263	-33
685	180009	3754179	412	332	-33	760	174802	3785834	332	252	-33
686	185660	3754116	401	321	-33	761	187375	3766911	317	237	-33
687	195312	3761418	328	248	-33	762	193788	3774341	292	212	-33
688	193661	3764657	312	232	-33	763	187362	3755710	387	322	-888
689	194233	3767832	310	230	-33	764	187933	3753551	374	309	-888
690	191439	3767197	311	231	-33	765	186219	3752535	389	324	-888
691	188962	3766816	319	239	-33	766	183107	3755900	400	335	-888
692	181660	3762625	361	281	-33	767	191489	3759012	400	335	-888
693	179310	3761037	387	307	-33	768	192759	3760980	380	315	-888
694	175373	3761228	426	346	-33	769	192188	3762885	360	295	-888
695	173024	3758497	463	383	-33	770	181837	3756980	405	340	-888
696	174548	3765038	392	312	-33	771	183933	3757234	374	309	-888
697	171119	3769038	393	313	-33	772	186282	3759012	402	337	-888
698	173849	3771007	361	281	-33	773	190981	3765044	433	368	-888
699	179437	3772721	314	234	-33	774	189457	3751709	371	306	-888
700	180771	3770562	316	236	-33	775	189521	3747137	407	342	-888
701	186994	3772658	308	228	-33	776	194410	3751074	312	247	-888
702	189216	3771070	309	229	-33	777	185012	3750376	322	257	-888
703	191629	3772340	300	220	-33	778	183869	3780221	329	264	-888
704	199249	3761514	333	253	-33	779	182853	3777363	333	268	-888
705	191566	3776246	297	217	-33	780	179615	3776982	310	245	-888
706	188137	3780056	304	224	-33	781	176376	3778125	334	269	-888
707	183565	3783358	312	232	-33	782	177329	3780792	304	239	-888
708	177088	3786977	327	247	-33	783	178281	3783078	306	241	-888
709	176326	3782278	330	250	-33	784	181012	3781935	400	335	-888
710	178675	3778786	320	240	-33	785	172566	3770886	320	255	-888
711	179374	3775357	318	238	-33	786	172312	3768410	329	264	-888
712	170992	3782850	338	258	-33	787	173519	3762060	335	270	-888
713	170865	3776182	351	271	-33	788	172947	3775522	332	267	-888
714	169468	3773452	374	294	-33	789	176186	3784412	330	265	-888
715	168134	3777770	362	282	-33	790	193902	3749106	331	266	-888
716	175310	3776246	330	250	-33	791	193648	3753297	322	257	-888
717	178231	3758085	410	330	-33	792	192315	3755392	319	254	-888
718	185343	3757640	363	283	-33	793	192632	3766314	321	256	-888
719	186803	3764562	332	252	-33	794	193648	3762695	322	257	-888
720	177278	3763228	395	315	-33	795	192188	3764663	345	280	-888
721	181977	3769324	331	251	-33	796	180758	3759393	345	280	-888
722	187756	3771293	310	230	-33	797	179996	3757551	357	292	-888
723	188645	3769578	312	232	-33	798	173328	3765743	362	297	-888
724	183819	3765324	342	262	-33	799	172566	3766886	367	302	-888
725	175183	3763482	402	322	-33	800	186028	3756789	385	320	-888

S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day	S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day
801	186917	3757551	396	331	-888	876	187430	3773190	307	242	-888
802	188187	3756916	393	328	-888	877	188516	3772104	310	245	-888
803	193394	3759202	358	293	-888	878	189530	3771959	305	240	-888
804	192950	3763838	320	255	-888	879	191195	3772176	300	235	-888
805	179615	3780094	297	232	-888	880	191267	3771090	306	241	-888
806	179361	3781999	304	239	-888	881	190181	3771090	308	243	-888
807	174662	3781046	318	253	-888	882	190181	3772828	304	239	-888
808	175106	3783015	380	315	-888	883	189530	3773552	303	238	-888
809	184758	3755583	382	317	-888	884	189385	3774493	305	240	-888
810	189965	3753868	336	271	-888	885	190688	3774420	296	231	-888
811	190981	3757234	421	356	-888	886	191774	3773696	303	238	-888
812	195045	3759266	434	369	-888	887	191991	3772755	300	235	-888
813	176208	3764502	383	318	-888	888	190978	3773479	302	237	-888
814	174398	3764936	398	333	-888	889	191484	3774927	296	231	-888
815	172588	3765370	396	331	-888	890	194163	3777027	295	230	-888
816	170778	3765660	411	346	-888	891	192715	3777099	297	232	-888
817	168896	3771090	396	331	-888	892	191991	3777606	297	232	-888
818	168968	3773117	381	316	-888	893	191629	3779706	299	234	-888
819	169982	3775651	364	299	-888	894	194235	3774565	293	228	-888
820	170561	3773045	368	303	-888	895	194018	3772828	303	238	-888
821	172516	3771452	370	305	-888	896	192208	3768049	309	244	-888
822	175991	3773479	335	270	-888	897	193729	3768484	309	244	-888
823	170995	3777968	343	278	-888	898	193005	3768990	305	240	-888
824	170923	3780068	336	271	-888	899	192788	3768556	311	246	-888
825	171792	3782384	337	272	-888	900	192498	3768556	310	245	-888
826	172733	3784918	339	274	-888	901	192208	3768918	309	244	-888
827	174905	3788756	340	275	-888	902	191846	3768484	306	241	-888
828	178018	3781588	326	261	-888	903	191919	3769570	307	242	-888
829	179828	3780936	322	257	-888	904	192498	3769425	306	241	-888
830	181348	3781805	318	253	-888	905	193294	3769642	308	243	-888
831	182145	3783760	317	252	-888	906	194091	3770511	302	237	-888
832	181348	3783036	315	250	-888	907	195539	3770511	303	238	-888
833	182000	3782674	313	248	-888	908	192715	3767904	310	245	-888
834	182579	3781950	315	250	-888	909	193150	3768049	312	247	-888
835	174760	3772683	349	284	-888	910	191629	3768990	310	245	-888
836	174181	3771959	352	287	-888	911	191195	3768266	309	244	-888
837	173602	3771452	363	298	-888	912	190833	3767615	313	248	-888
838	173240	3771090	365	300	-888	913	189457	3767542	316	251	-888
839	172443	3772176	365	300	-888	914	188661	3768773	314	249	-888
840	172443	3772900	361	296	-888	915	189602	3769208	314	249	-888
841	174326	3770294	359	294	-888	916	188950	3770149	312	247	-888
842	175194	3769497	361	296	-888	917	188950	3770945	310	245	-888
843	175484	3768339	365	300	-888	918	187720	3771524	309	244	-888
844	175122	3768194	362	297	-888	919	187140	3772104	312	247	-888
845	179104	3771959	326	261	-888	920	187864	3772393	307	242	-888
846	178163	3771959	334	269	-888	921	186561	3772828	311	246	-888
847	178090	3772683	332	267	-888	922	186851	3773696	308	243	-888
848	179394	3773334	313	248	-888	923	186127	3773479	308	243	-888
849	178235	3773986	325	260	-888	924	185258	3774276	307	242	-888
850	178959	3774276	315	250	-888	925	184679	3775651	306	241	-888
851	180045	3774203	318	253	-888	926	184389	3777316	313	248	-888
852	181638	3773624	314	249	-888	927	183665	3777606	314	249	-888
853	183231	3775217	309	244	-888	928	181131	3777896	316	251	-888
854	183231	3776520	313	248	-888	929	179538	3779633	321	256	-888
855	182652	3777823	312	247	-888	930	177439	3780430	326	261	-888
856	182869	3779054	311	246	-888	931	176280	3781371	327	262	-888
857	184172	3778402	308	243	-888	932	175918	3780864	325	260	-888
858	185113	3778837	309	244	-888	933	175991	3767108	369	304	-888
859	184317	3779488	313	248	-888	934	176570	3766963	368	303	-888
860	183593	3780357	313	248	-888	935	177294	3767108	364	299	-888
861	184606	3780574	311	246	-888	936	178525	3767108	367	302	-888
862	185258	3781371	310	245	-888	937	178452	3767760	352	287	-888
863	186706	3780864	307	242	-888	938	178235	3770294	343	278	-1072
864	188371	3781443	306	241	-888	939	180190	3770076	323	258	-1072
865	190036	3782022	302	237	-888	940	181493	3769787	327	262	-1072
866	189964	3780864	304	239	-888	941	180697	3768990	347	282	-1072
867	189385	3780647	301	236	-888	942	181855	3769063	335	270	-1072
868	188733	3780285	301	236	-888	943	181276	3771018	311	246	-1072
869	186851	3777027	302	237	-888	944	180697	3770728	318	253	-1072
870	185982	3777099	304	239	-888	945	181131	3770583	314	249	-1072
871	186199	3776013	306	241	-888	946	180769	3771235	316	251	-1072
872	186272	3774276	305	240	-888	947	181276	3769135	334	269	-1072
873	187068	3774855	305	240	-888	948	181204	3768484	349	284	-1072
874	188226	3775072	300	235	-888	949	180769	3768339	350	285	-1072
875	188009	3773769	304	239	-888	950	180407	3767832	356	291	-1072

S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day	S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day
951	179973	3767542	360	295	-1072	1026	174977	3758927	445	380	-1072
952	179321	3767108	360	295	-1072	1027	173891	3759289	448	383	-1072
953	179032	3768122	345	280	-1072	1028	173529	3759868	449	384	-1072
954	179756	3768773	339	274	-1072	1029	177728	3764067	386	321	-1072
955	180697	3772755	317	252	-1072	1030	174615	3763271	409	344	-1072
956	183303	3774058	308	243	-1072	1031	173312	3762764	424	359	-1072
957	182724	3775724	309	244	-1072	1032	172950	3762185	430	365	-1072
958	173240	3766456	386	321	-1072	1033	172009	3761895	436	371	-1072
959	175267	3765298	387	322	-1072	1034	173167	3764212	411	346	-1072
960	175629	3766746	374	309	-1072	1035	171574	3768773	389	324	-1072
961	176136	3765081	381	316	-1072	1036	171792	3768122	389	324	-1072
962	177004	3764574	381	316	-1072	1037	171719	3767398	390	325	-1072
963	181131	3762836	369	304	-1072	1038	171285	3766601	397	332	-1072
964	180407	3763198	372	307	-1072	1039	169982	3766312	415	350	-1072
965	179828	3763705	371	306	-1072	1040	171719	3765588	400	335	-1072
966	179032	3763416	383	318	-1072	1041	170054	3765226	415	350	-1072
967	177801	3763271	386	321	-1072	1042	169475	3764864	427	362	-1072
968	177149	3763416	395	330	-1072	1043	168968	3764212	436	371	-1072
969	176498	3762909	401	336	-1072	1044	170416	3764067	415	350	-1072
970	175556	3763126	397	332	-1072	1045	170488	3763343	429	364	-1072
971	174543	3762402	418	353	-1072	1046	170488	3762474	438	373	-1072
972	173964	3761823	426	361	-1072	1047	169258	3763343	427	362	-1072
973	173312	3761316	432	367	-1072	1048	171864	3763343	425	360	-1072
974	172443	3760954	442	377	-1072	1049	171719	3763922	419	354	-1072
975	172733	3759651	454	389	-1072	1050	171212	3763054	427	362	-1072
976	174688	3759941	441	376	-1072	1051	170416	3761678	450	385	-1072
977	174977	3760592	433	368	-1072	1052	172660	3765950	395	330	-1072
978	176136	3761388	415	350	-1072	1053	173819	3765443	390	325	-1072
979	175412	3762040	416	351	-1072	1054	175701	3764574	389	324	-1072
980	173602	3763633	414	349	-1072	1055	182507	3763488	358	293	-1072
981	172443	3763126	421	356	-1072	1056	182362	3764067	359	294	-1072
982	171502	3762402	435	370	-1072	1057	183158	3763705	353	288	-1072
983	169764	3763560	423	358	-1072	1058	179249	3764284	375	310	-1072
984	169547	3766022	421	356	-1072	1059	178525	3763922	376	311	-1072
985	169258	3765443	426	361	-1072	1060	178452	3763560	380	315	-1072
986	169040	3766963	424	359	-1072	1061	178090	3763778	380	315	-1072
987	172154	3766384	388	323	-1072	1062	177584	3763778	387	322	-1072
988	178597	3762619	385	320	-1072	1063	177222	3763778	390	325	-1072
989	175918	3759506	426	361	-1072	1064	177366	3764357	382	317	-1038
990	176860	3759868	420	355	-1072	1065	176715	3763850	391	326	-1038
991	176715	3760882	411	346	-1072	1066	178380	3762909	390	325	-1038
992	174036	3760230	440	375	-1072	1067	178163	3762764	390	325	-1038
993	171719	3760375	450	385	-1072	1068	177873	3762764	391	326	-1038
994	171068	3761606	446	381	-1072	1069	177584	3762692	389	324	-1038
995	171212	3764574	408	343	-1072	1070	177439	3762909	391	326	-1038
996	172371	3764429	410	345	-1072	1071	179611	3763416	373	308	-1038
997	170995	3763705	422	357	-1072	1072	179394	3763633	378	313	-1038
998	169982	3764646	422	357	-1072	1073	179683	3763995	374	309	-1038
999	175194	3763922	399	334	-1072	1074	180335	3762185	379	314	-1038
1000	173602	3764864	404	339	-1072	1075	180045	3762112	381	316	-1038
1001	177511	3762330	398	333	-1072	1076	183955	3763488	346	281	-1038
1002	180914	3763343	366	301	-1072	1077	169475	3771452	390	325	-1038
1003	182145	3762981	360	295	-1072	1078	168099	3770366	412	347	-1038
1004	181855	3762764	363	298	-1072	1079	167665	3769642	426	361	-1038
1005	181204	3762402	369	304	-1072	1080	167013	3768990	439	374	-1038
1006	180624	3762330	377	312	-1072	1081	167810	3778185	363	298	-1038
1007	180190	3762619	377	312	-1072	1082	179828	3785063	322	257	-1038
1008	179538	3762836	382	317	-1072	1083	168606	3767687	425	360	-1038
1009	179466	3762040	387	322	-1072	1084	183665	3764791	352	287	-1038
1010	178742	3761895	396	331	-1072	1085	185620	3764284	332	267	-1038
1011	179176	3761316	390	325	-1072	1086	183882	3765515	340	275	-1038
1012	179973	3761388	384	319	-1072	1087	193656	3765732	310	245	-1038
1013	178670	3760520	399	334	-1072	1088	192715	3765515	311	246	-1038
1014	177873	3760013	410	345	-1072	1089	192208	3765153	315	250	-1038
1015	176498	3760230	413	348	-1072	1090	191629	3764791	320	255	-1038
1016	176063	3760158	421	356	-1072	1091	191050	3764284	319	254	-1038
1017	175774	3760882	423	358	-1072	1092	190471	3763633	325	260	-1038
1018	175194	3761244	429	364	-1072	1093	191774	3761316	345	280	-1038
1019	174398	3761244	437	372	-1072	1094	190543	3759217	348	283	-1038
1020	173964	3760809	437	372	-1072	1095	189168	3758348	356	291	-1038
1021	173384	3760592	441	376	-1072	1096	188661	3757986	358	293	-1038
1022	172733	3760375	446	381	-1072	1097	187937	3758203	367	302	-1038
1023	172298	3759144	464	399	-1072	1098	187358	3757551	368	303	-1038
1024	173312	3758782	456	391	-1072	1099	186561	3757189	376	311	-1038
1025	174108	3758927	446	381	-1072	1100	185113	3757262	372	307	-1038

S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day	S.No	X	Y	Elev	Well bottom elevation	Pumping rate in m3/day
1101	183738	3758710	366	301	-1038	1153	176642	3755379	430	365	-1038
1102	185692	3761171	348	283	-1038	1154	177077	3755307	424	359	-1038
1103	186851	3762547	336	271	-1038	1155	178597	3759144	399	334	-1038
1104	186054	3762474	347	282	-1038	1156	179466	3760013	388	323	-1038
1105	184244	3761678	347	282	-1038	1157	182290	3758565	375	310	-1038
1106	184027	3760954	352	287	-1038	1158	182290	3755886	384	319	-1038
1107	182869	3760230	358	293	-1038	1159	185113	3759506	356	291	-1038
1108	180624	3758999	381	316	-1038	1160	188588	3759651	363	298	-1038
1109	179321	3757841	393	328	-1038	1161	187864	3761606	342	277	-1038
1110	178090	3756393	409	344	-1038	1162	190543	3762040	329	264	-1038
1111	177439	3755886	422	357	-1038	1163	189530	3765805	320	255	-1038
1112	176860	3755886	425	360	-1038	1164	187502	3766674	321	256	-1038
1113	176280	3755741	433	368	-1038	1165	187213	3764646	331	266	-1038
1114	175846	3755741	435	370	-1038	1166	181348	3760013	375	310	-1038
1115	175412	3755524	445	380	-1038	1167	180480	3754511	406	341	-1038
1116	175194	3754004	451	386	-1038	1168	180407	3753931	411	346	-1038
1117	175701	3753497	450	385	-1038	1169	180624	3753280	409	344	-1038
1118	178814	3753497	418	353	-1038	1170	182652	3752918	407	342	-1038
1119	178742	3750963	437	372	-1038	1171	182652	3753569	403	338	-1038
1120	176136	3751687	456	391	-1038	1172	182290	3754800	393	328	-1038
1121	173022	3752483	489	424	-1038	1173	174326	3757696	452	387	-1038
1122	172226	3754800	491	426	-1038	1174	171502	3759506	463	398	-1038
1123	173384	3756538	465	400	-1038	1175	174470	3763778	403	338	-1038
1124	178814	3755017	409	344	-1038	1176	174108	3764357	400	335	-1038
1125	177366	3754511	423	358	-1038	1177	188154	3756248	374	309	-1038
1126	181204	3748936	450	385	-1038	1178	187285	3756248	380	315	-1038
1127	179900	3749877	442	377	-1038	1179	187575	3759144	373	308	-1038
1128	177004	3749298	468	403	-1038	1180	191267	3766384	313	248	-1038
1129	183882	3746619	454	389	-1038	1181	195177	3767108	307	242	-1038
1130	183158	3747922	450	385	-1038	1182	193874	3767108	309	244	-1038
1131	188806	3747126	454	389	-1038	1183	195104	3768773	306	241	-1038
1132	188516	3749443	430	365	-1038	1184	194308	3771597	300	235	-1038
1133	181783	3745823	465	400	-1038	1185	193005	3774131	294	229	-1038
1134	178887	3746909	480	415	-1038	1186	195032	3773190	299	234	-1038
1135	193150	3756321	376	311	-1038	1187	192064	3762257	329	264	-1038
1136	198507	3759651	355	290	-1038	1188	190543	3760303	338	273	-1038
1137	195032	3759796	341	276	-1038	1189	189530	3759072	349	284	-1038
1138	189312	3760882	352	287	-1038	1190	184244	3756248	371	306	-1038
1139	187068	3760447	355	290	-1038	1191	187679	3751392	397	357	-1981
1140	188733	3762981	325	260	-1038	1192	183615	3753741	393	353	-1981
1141	188588	3764429	327	262	-1038	1193	181456	3755075	370	330	-1981
1142	194959	3765226	314	249	-1038	1194	179234	3759266	333	293	-1981
1143	193801	3764646	315	250	-1038	1195	181012	3761234	313	273	-1981
1144	192715	3764284	322	257	-1038	1196	190346	3767140	306	266	-1981
1145	193512	3763126	319	254	-1038	1197	180821	3778760	317	277	-1981
1146	193294	3761823	329	264	-1038	1198	182155	3780221	329	289	-1981
1147	191340	3760303	347	282	-1038	1199	173709	3777808	354	314	-1981
1148	177946	3758058	414	349	-1038	1200	173709	3773934	350	310	-1981
1149	176787	3758203	426	361	-1038	1201	179107	3755773	310	270	-1981
1150	175556	3757986	439	374	-1038	1202	197268	3761552	423	383	-1981
1151	172805	3757696	473	408	-1038	1203	189965	3777427	383	343	-1981
1152	176208	3754873	432	367	-1038	1204	184377	3781745	304	264	-1981
						1205	186155	3747264	312	272	-1981

Appendix C

Observation head data

S.No	Description	X	Y	Ground Elevation	Water tabe depth	Water Table Elevation
1	Afghan Colony Chowk	71.581	34.027	321	3	318
2	Shaheed Abad No.1	71.517	33.970	382	47	335
3	Audit colony kohat road	71.560	33.990	351	27	324
4	District council Nothia	71.547	33.997	347	21	326
5	Sheikh Abad	71.436	34.061	357	17	340
6	Hayatabad D4 supper market	71.435	33.978	410	68	342
7	Hayatabad PHASE 3 k4 Park	71.459	33.981	389	52	337
8	Zargar Abad	71.581	33.998	344	23	321
9	Land Arbab	71.548	33.982	362	31	331
10	Achini Payeen	71.475	33.961	409	69	340
11	Pishtikhara	71.511	33.968	385	49	336
12	Kakshal	71.567	33.998	344	23	321
13	Dheri Baghban	71.557	33.994	354	29	325
14	Mushtarzai	71.495	33.908	435	75	360
15	Forest Land	71.486	34.017	356	22	334
16	Nursery Area	71.488	34.020	353	21	332
17	Football Ground	71.487	34.021	358	25	333
18	Works Directorate	71.479	34.022	359	25	334
19	Professor Colony	71.470	34.019	360	24	336
20	Biotechnology Land	71.471	34.023	360	24	336
21	Malakhandir Farm	71.463	34.021	368	33	335
22	Military Farm	71.459	34.021	373	35	338
23	Veterinary Hospital	71.459	34.015	378	40	338
24	Kacha Garhi near A	71.460	34.007	375	38	337
25	Kacha Garhi near B	71.456	34.001	378	42	336
26	Phase 4 Drain	71.452	33.990	380	41	339
27	Phase 3 Civil Quarters	71.458	33.982	385	45	340
28	Phase3 Police Post	71.452	33.988	387	47	340
29	Phase 3 Ring Road	71.454	33.972	406	65	341
30	Phase 3 Drain	71.452	33.970	411	71	340
31	Phase 7 F-7	71.429	33.956	429	86	343
32	Phase 7 IM Sciences	71.417	33.961	437	87	350
33	Phase 7 Haji Camp	71.417	33.968	434	94	340
34	Phase 7 Behram Market	71.424	33.967	427	84	343