Assessment of Sustainable Groundwater Extraction Rate for Quetta City Using MODFLOW

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Abstract

Quetta is the largest population center in Baluchistan province. Its population entirely depends upon the groundwater. The increasing population of the city and unplanned use have depleted water table in the recent decades. USGS groundwater flow model MODFLOW (MODFLOW Pro) was applied for the Quetta city to simulate the behavior of aquifer under stresses. The model solves partial differential groundwater flow governing equation by finite difference method. The data regarding groundwater levels, tube wells, pumping rates and aquifer parameters etc. were collected from Water and Power Development Authority (WAPDA). The data showed that the abstraction rate for the city has increased from 32.25 MGPD to 57.76 MGPD over 20 years. The model was calibrated and validated for the available data. Data from year 1995 to 1999 was used for calibration and from 2000 to 2005 for validation. The water balance showed that 20% of the total precipitation was ultimately going to the groundwater as recharge. It was observed from the model results that the water table under Quetta city has declined at the average rate of 0.91 m/year since 1995 to 2014. The Vermont Storm Water Management (VSWM) method of volume recharge was used to calculate the fraction of recharge that is retained by the imperviousness caused by the urbanization of the city. This fraction comes out to be 0.6 MGPD to 2.9 MGPD per year, depending upon the amount of precipitation and the amount of imperviousness for the same year. The water budget calculated by the model showed that the average recharge per year in the study period was 37.04 MGD and the average abstraction from the aquifer was 84.20 MGD, so there was annual deficit of 47.11MGD. The inflow through the boundaries was increasing with the passage of time due to fall of head inside the model area, whereas the outflow through the boundaries was almost zero during the study period because of higher heads outside the model boundary. The model was then used to predict different future scenarios by giving the same average recharge rates and varying abstraction rates, in order to predict the future behavior of the aquifer.

Key Words: Quetta City, MODFLOW, Sustainable Extraction Rate, Urbanization

1. Introduction

Quetta is the biggest population center and capital of Baluchistan province. It is situated between 30° 17 - 30° 45 Latitude North and 66° 53 - 67° 03 Longitude East, comprising area of 480 Square Km, depends mainly on groundwater beneath its aquifer. Due to scarcity of water, Baluchistan province has lowest population density among the other provinces of Pakistan. Many factors including the only source of water, the unplanned use and the migration to urban area has declined the groundwater levels in Quetta in the last few decades. This situation has serious socio economic impacts on the city resident's life.

Increase of average temperature and decrease of average precipitation in recent years also have impacts on water table decline. But the most serious problem is the rapid urban population growth of Quetta. Being the capital city and the largest business and educational center in Baluchistan, the migration to the city is increasing day by day. The Quetta district population has increased from 0.26 million in 1975 to 1.452 million in 2014 at a growth rate of 3 percent and increase in urbanization rate is 4.2%.

Urbanization impact on groundwater is one of the key factors need to be studied in Quetta city. Impact of urbanization on groundwater is whether it will increase or decrease the recharge to groundwater due to precipitation and also how much will increase the extraction with the increase of population.

These situations need an in-depth study of Quetta aquifer in terms of recharge, extraction and urbanization to evaluate the behavior of aquifer to future stresses and also to find a future strategy for operating the system.

2. Literature Review and Related Works

Groundwater is the main source of water in the province general and in Quetta special for domestic, agricultural and industrial use. Extensive groundwater use has caused water shortages and land subsidence in the valley. Water supply is mainly derived from alluvial aquifer beneath. Groundwater decline was first observed by WAPDA in 1989 as 0.25 m/year. A decline of 0.23 m/year to 1.09 m/year was noticed by the same agency during 1990's [1].

According to Baluchistan Irrigation and Power Department in 2010, the total annual recharge to the valley groundwater was 61.15 Mm^3 and discharge 97.65 million cubic meters with an annual deficit of 36.5 Mm^3 [2]. Alam K. [3] employed Visual Modflow model for Quetta valley to assess the aquifer. He concluded that the fraction of precipitation which reaches to the groundwater is about 13%. The groundwater abstraction has increased from 0.877 Mm^3 in 1964 to 3.25 Mm^3 in 2007 and calculated that likely will increase to 6.54 Mm^3 in 2030. He calculated average decline of 1.0 m/year during 1990's and 1.1 m/year in 2007. Afzal. M. [4] used MODFLOW for Lahore city and evaluated the result for the next 20 years and found that the water table will decline at rate of 1.27 m/year for those future years. MODFLOW has been successfully used for Umm-er-Radhuma region in Iraq to find out the behavior of groundwater flow in unconfined aquifer [5].

Sarzeh Rezvan Plain has an area of 7600 hectors in the Hormozgan province of Iran. Purjenaie. A. in 2012 designed and calibrated MODFLOW model for this area and found that if pumping is decreased 20% the drawdown may decrease up to 6.3 m (60%) [6]. Berehanu et al [7] studied over extraction of ground water in Upper Awash River Basin Ethiopia, using MODFLOW. Gumuła-Kaw˛ecka et al [8] did Numerical simulation of infiltration and groundwater recharge using the Modflow .

A numerical model is simply representation of a system or process. It is the hypothesis that how a system or process operate [9]. Groundwater models use the mathematical equations to describe the groundwater flow and transport processes based on simplified assumptions. Current groundwater models use application of water balance [10].

William M. Alley et al. [11] describe that groundwater system is considered to be safe if the groundwater abstraction does not exceed the groundwater natural recharge. The sustainability of groundwater is as development and use of groundwater in a manner that can be maintained for an infinite time without causing unacceptable environmental, economic, or social consequences.

2.1 Description of MODFLOW

MODFLOW was originally developed by McDonald and Harbaugh in 1984. It is computer program that simulates three-dimensional ground-water flow through a porous medium by using a finite difference method. It simulates flows in steady as well as in transient state both in confined and unconfined aquifers [12]. Because of its ability to simulate a wide variety of systems, its extensive publicly available documentation, MODFLOW became worldwide mostly used groundwater flow model [13].

MODFLOW- 2000 attempts to incorporate the solution of multiple related equations into a single code. To achieve the goal; the code is divided into entities called processes. Each process deals with a specific equation [14]. Processing MODFLOW for Windows (PMWIN) was developed at Germany. It brings various codes of MODFLOW into a single simulation system. Different codes of MODFLOW are given below [15].

i. Particle tracking model PMPATH for Windows (Chiang, 1994) or MODPATH (Pollock, 1988, 1989, 1994)

ii. MODFLOW-88, MODFLOW-98, MODFLOW-2000 and MODFLOW 2005

iii. The solute transport model MT3D (Zheng, 1990)

iv. The parameter estimation program PEST (Doherty et al., 1994)

Description of MODFLOW packages and governing equations is given below;

(a) Packages

Different packages are used by MODFLOW to model different features including.

i. Well Package (WEL)

It features well, including both types i.e. abstraction and recharging wells, during a given stress period. The governing equation of this package is

$$Q_i = (L_i K_{xi}) / \sum (LK_x)_i \quad (1)$$

Where Qi is the discharge from layer i to a particular well in a given stress period, Q_T is the well discharge in that stress period, L_i is the screen length, K_x is the hydraulic conductivity in the x-direction in layer i.

ii. Recharge Package (RCH)

It simulate the aerially distributed recharge to an aquifer

$$Q_{RCHi,j} = I_{i,j}\ x\ DEL_j\ x\ DELC_i \qquad (2)$$

Where $Q_{RCHi,j}$ is the fluid volume per unit time recharge at horizontal cell location (*i*,), I*i,j* is the recharge flux (in units of length per unit time) and *DELR j*, *DELCi* is area of the cell.

iii. General Head Boundary Package (GHB)

This package models the boundaries that permit the flow of water into or out of boundaries. It requires the hydraulic conductance Cb and the head on the external source Hb. Hydraulic Conductance is

$$Cb = K/L \qquad (3)$$

Where L is the length of the general-head boundary within a cell and K is hydraulic conductivity. And flow through the boundary is

$$Q_b = Cd(hb - h) \qquad (4)$$

Where h is the hydraulic head in the aquifer. Besides these, other packages include River Package (RIV), Drain Package (DRN) and many more, which are not part of this study.

(b) Governing Equation

MODFLOW uses a 3D finite difference scheme and the governing water balance equation for an anisotropic aquifer, allowing for 3D flow for an unconfined aquifer [13].

$$\frac{\partial y}{\partial x}\left[Kxh\frac{\partial y}{\partial x}\right] + \frac{\partial y}{\partial x}\left[Kyh\frac{\partial y}{\partial x}\right] = -Sy\frac{\partial y}{\partial x} - R \qquad (5)$$

Where

Kx, Ky = are directional components of hydraulic Conductivity

Sy = specific yield

R = general sink/source term

t = time

3. Study Area

The study area is the Quetta city which is bounded at the north by Baleli gap and at the south by Hazaganji. It is located at about latitude 30°17' - 30° 45' North and longitude 66° 53' - 67° 03' East. The average elevation of the study area is 1680 m varying from 1478 m to 2012 m above mean sea level. Quetta valley is part of Quetta sub basin, which is one of the sub basins of Pishin Lora basin. The city is situated within the valley. The city (study area) is bound by Chiltan Range located west of the city and Takatu Range in the North. The general height of the mountains ranges from 2440 m to 3050 m, however the Zarghoon Mountain ranges up to about 6660 m. The study area stretches over an area of 480 km^2 with maximum length and width of about 30 km and 16 km, respectively. It is located at the north of Baluchistan province. Location of the study area is shown in Fig. 1.The Quetta sub basin encloses two drainage basins, at the south a small closed basin known as Dasht and at the north is the main valley.

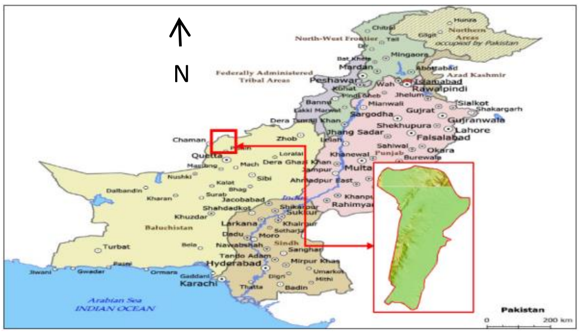

Fig. 1: Location map of study area

Quetta valley has a complex geology. It is a synclinal valley filled with alluvial deposits mainly clay, silt, sand, and gravel. The Sariab river and Baleli river are making the main drainage system of the study area. These rivers flow in the valley through Baleli gap in the northern side of the study area. These are seasonal rivers having steep slopes and flows are very fast resulting in less seepage to groundwater. The population of the valley is increasing enormously due to migration from rural areas, other cities and also from Afghanistan. Approximately 70% of the population of Quetta District is living in the city [16]. The study area has arid climate. The temperature ranges from 30 to 35 C in summer and -4 to 6 C in winters and also sometimes lower than that. The precipitation ranges from 50 mm to 350 mm including small amount of ice falling at the mountains.

4. Data Collection

Different types of data required for the model were collected from the various departments, from the period 1995 up to 2014. Detail is provided in table 1.

Table 1: Type and details of data collected.

Sr. No	Data	Details	Source
1	Precipitation	1995-2014	PMD
2	Population	1995-2014	Statistics Deptt. GoB
3	Tube wells record	1995-2011	WASA Quetta
4	Groundwater levels	1995-2007	BIPD
5	Urbanization	1995-2014	QDA Quetta

5. Methodology

In order to set up the model and achieve the objectives, following methodology were adopted

1. Development of GIS data base using Arc GIS and digitizing of study area boundaries, positions of tube wells as point data and other physical features.
2. Development of study area model using Pro MODFLOW 2000. East, West and North East boundaries were treated as “no flow” Boundaries. South and North West as General Head Boundaries (GHB).
3. Hydraulic parameters i.e. Hydraulic Conductivity and Specific Yield were taken initially from Alam. K. [3] Evaluation of Aquifer System in Quetta Valley through Geophysical Methods and Groundwater Flow Modeling for calibration purpose. The final values come out to be 0.0846 cm/day and 0.20 respectively.
4. Aquifer Recharge was calculated by Indirect Method (Trial and Error), which comes out to be 20%.
5. Total study period (1995-2014) was divided in 40 stress periods each of six months to study the effects of pre and post moon soon and one stress period was taken as one-time step to avoid the overload on system and save the time in calculations.

6. Results and Discussions

6.1 Data Analysis

6.1.1 Current Water Table Profile

Pro MODFLOW 2000, model was set up for the study area. The model was calibrated for the period 1995-1999 i.e. five years and validated for the period up to data available. For the calibration and validation period the perfect match line should fall within 95% confidential interval. The model generated water table profiles, calculated water budget and gave heads for each cell, each for every stress period.

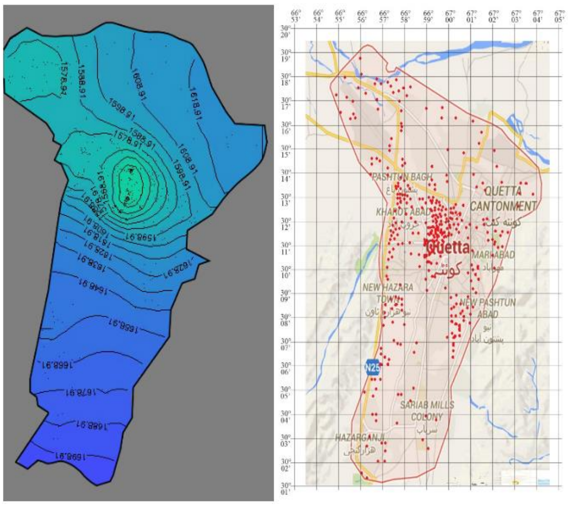

Fig.2: Water Table Profile (m) in the year of 2014

The water level is ranging from 1575 at the city area (El. 1695 m) where greater numbers of wells are dug at the Sariab road side, where the population density is very small. A drop of 35 meter (1605m to 1575m) was observed during last 20 years at the city area, where almost constant level was observed at the suburbs during this study period.

6.1.2 Water Table Decline Rate

Isohyets method was used to assess the depletion rate of water table from the profiles generated by the model. Area weighted elevation for each year was calculated for each stress period and the difference between two consecutive stress periods were found to assess the decline rate. Fig.: 3 & 4 show the water table decline rate for the study period and cumulative decline respectively.

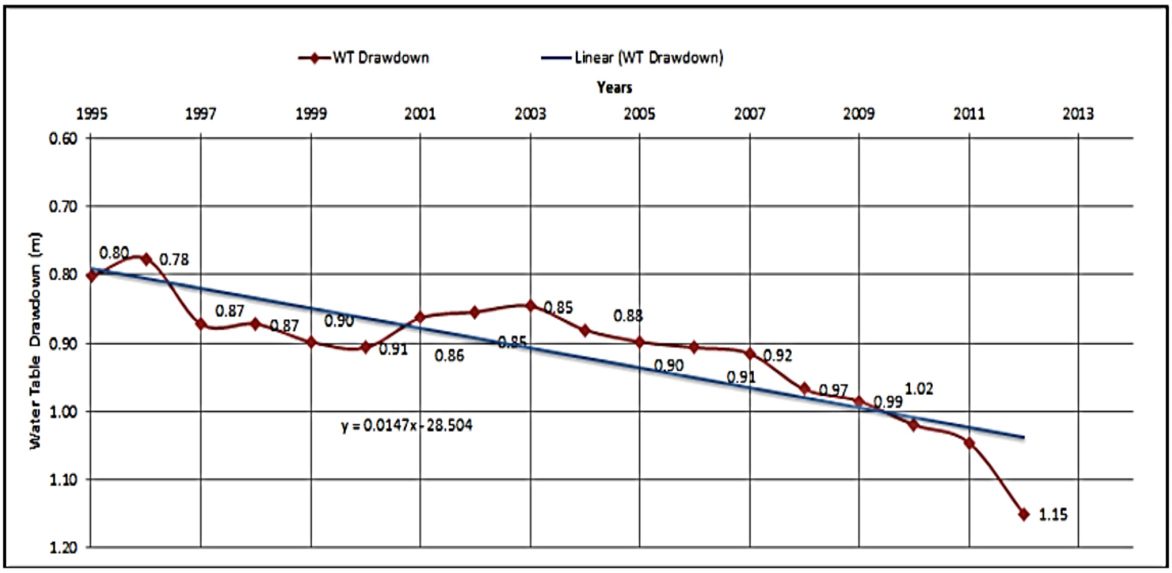

Fig. 3: Water table drawdown

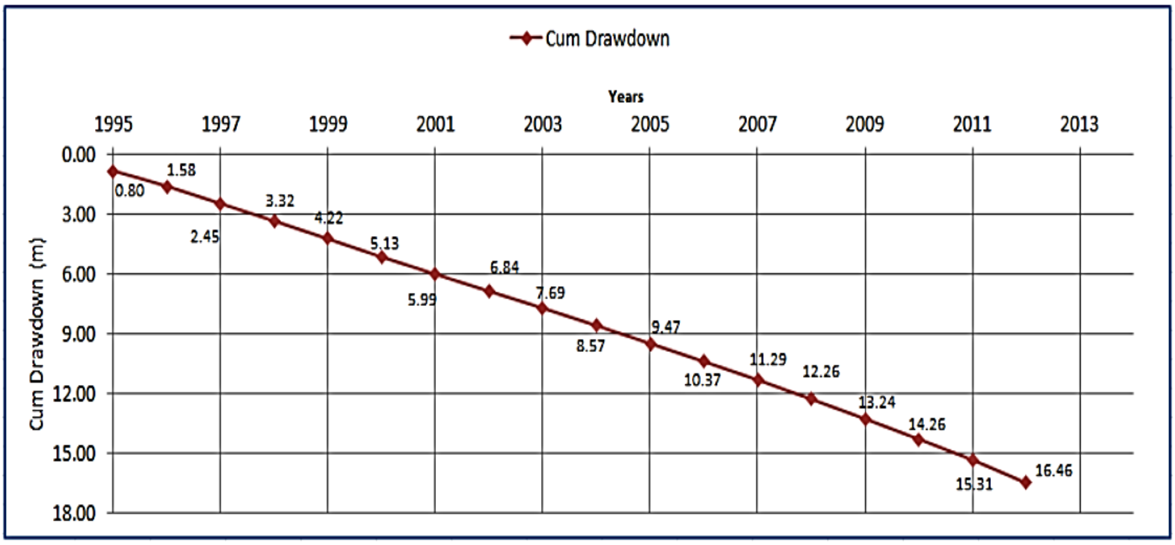

Fig. 4: Cumulative water table drawdown

The average decline for the Quetta aquifer comes out to be 0.91 m/year for this period. The maximum and minimum declines were 1.15 m/year and 0.78 m/year for the years 2013 and 1996 respectively. For the years 1997 to 2000, the decline increases up to 0.90 m/year, but it comes below 0.90 for the next nine years i.e. up to year 2009. After 2009, the water table decline start at faster rate and reaches up to 1.15 m/year for the year 2014.

6.1.3 Past and Present Extraction Rate

The water supply of Quetta city totally depends upon the groundwater. The only source of recharge to the ground water is rainfall and some amount of snowfall at mountains in the winter seasons. The Fig. 5 shows history of tube wells in the study area. It shows that the number of tube wells increase enormously in the study period (last 20 years) from 880 in 1995 to 1630 in 2014. The total extraction for the city was 32.25 MGPD for the population of 0.498 million in the year 1995. This extraction rate increased up to 57.76 MGPD for the population of 1.075 million in the year 2014 as shown in Fig. 6. These include small extractions for irrigation and industries too, as the separate data for these are not available.

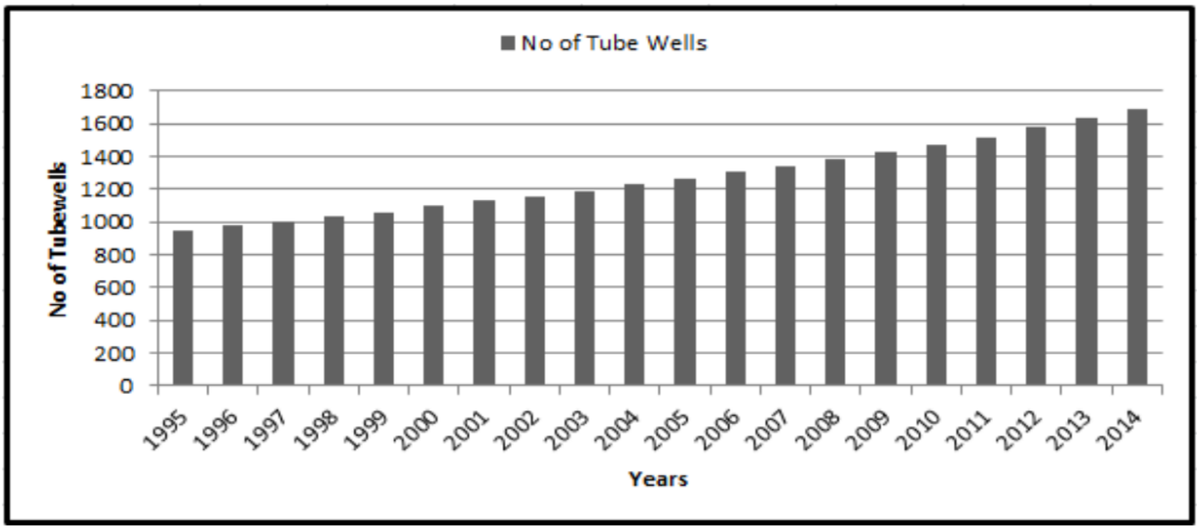

Fig. 5: Number of Tube wells Quetta city

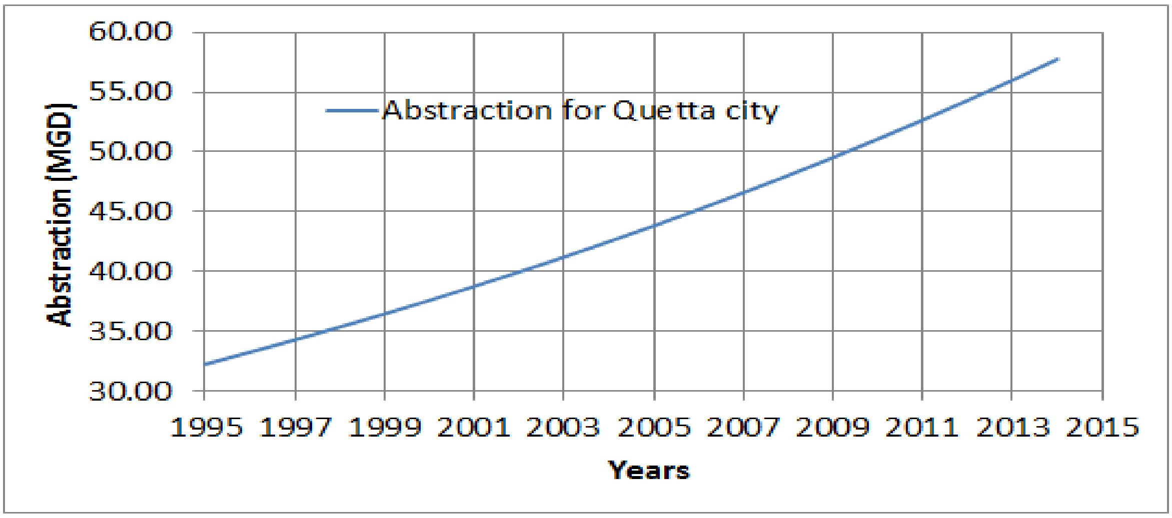

Fig. 6: Abstraction (imperviousness) rates for Quetta city

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6.1.4 Urbanization Effects

The development of cities inevitably increases paved surfaces and roofs (termed impervious cover) and storm drains (John M. Sharp 2010). Groundwater inflow decreases with urbanization, with direct runoff increasing. (Douglas, 1983). The effect of urbanization is, to decrease the recharge to the groundwater by increasing imperviousness. Table 2 shows the percentage of imperviousness offered by different land use types generally.

Table 2: Percent imperviousness offered by different types of surfaces [17]

Sr. No	Land Use Type	Percentage Imperviousness
1	Residential	**70**
2	Commercial	**90**
3	Educational	**50**
4	Industrial	**85**
5	Institutional	**50**
6	Open spaces & parks	**10**
7	Graveyards	**10**
8	Arterial circulation	**90**

Table 3: Shows percentages and areas (10 ha) of land use types of the Quetta city for the year 2014 (sources: Land utilization statistics of Balochistan by district 2015-16).

Sr.No	Use	%age	Total Area	Percentage Imperviousness
1	Residential	45.2	11998	70
2	Commercial	3	796	90
3	Educational	3.3	876	50
4	Industrial	4.5	1194	85
5	Institutional	4	1062	50
6	Open spaces & parks	10	2654	10
7	Graveyards	3.5	929	10
8	Arterial Circulations	22	5840	90
9	Miscellaneous use	4.5	1194	45
Total		100	26544	

Vermont Storm Water Management method of Volume Recharge was used to calculate the recharge deficit caused by imperviousness [18].

Fig.6 shows the deficit caused in groundwater recharge by the imperviousness. This depends upon the hydrologic soil types, amount of annual rainfall and percent of imperviousness. The hydrologic soil types are used to calculate the factor F for the study area. The less amount of annual rainfall for any area, the more will be deficit in recharge for the same year. The maximum amount of deficit comes out to be 2.95 MGD for the year 2012 with annual rainfall of 3.67 (93.3 mm) inches and minimum comes to be 0.586 MGD for the year 2011 with annual rainfall of 18.03 inches (458 mm) for our study period.

6.2 MODFLOW Results

6.2.1 Water Budget

The water budget calculated by the model is shown in the Fig. 7. The difference in recharge and abstraction is increasing with the passage of time upon our study period. At the start of our simulation, recharge is almost 70% of the abstraction which reduce up to 44% at the end of simulation period i.e. 2014.The average recharge rate during these years is 37.04 Mm^3 and the average abstraction is 84.20 MCM. So the annual deficit is 47.11 Mm^3 per year for study period.

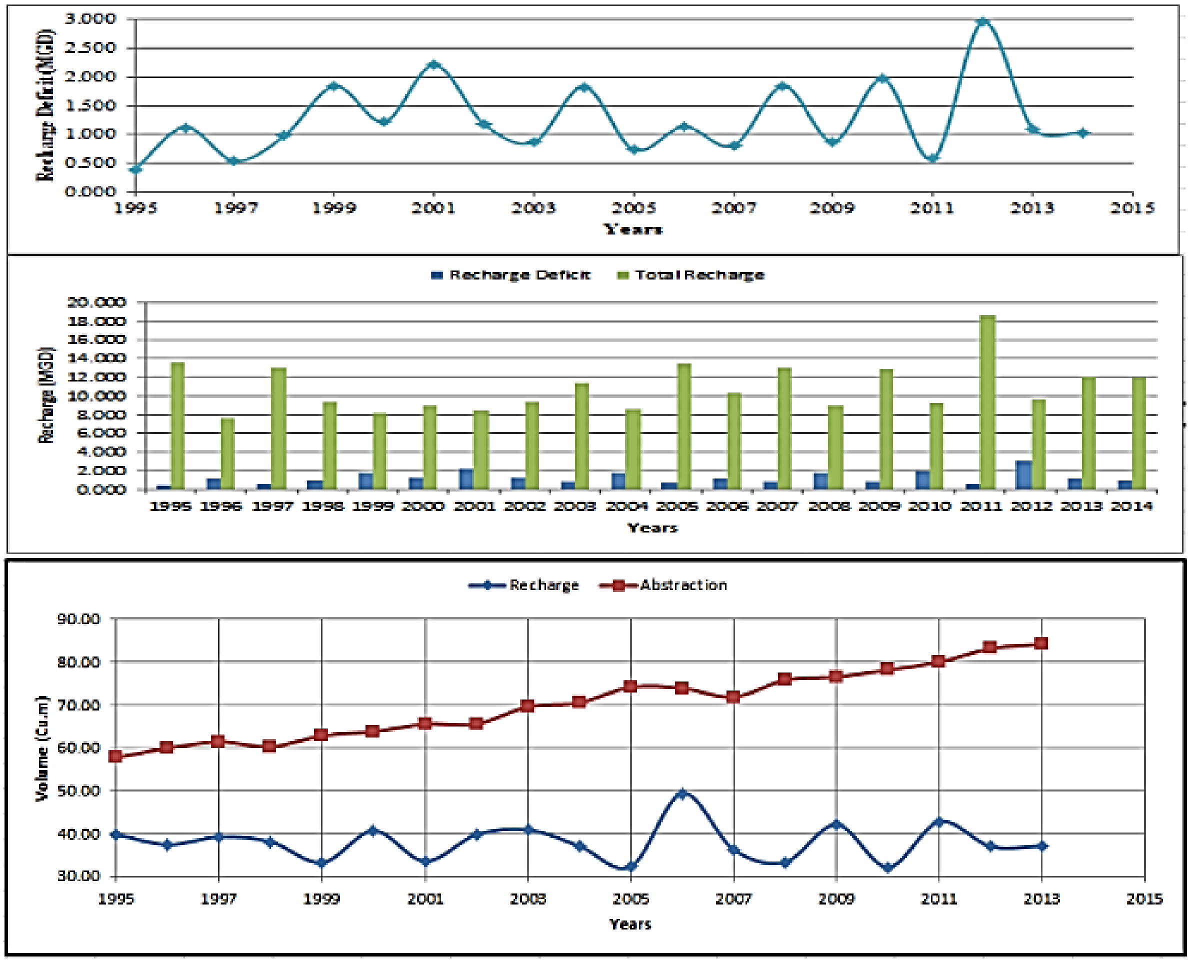

Fig. 7: Water Budget calculated by the Model

Table 4: Water budget components contribution

Flow term	IN	OUT	IN-OUT
Storage	2038072	336891	1701180
Wels	0	3206911	-3206911
Recharge	1495128	0	1495128
Head dep bounds	10338	0	10338

6.2.2 Calibration of the Model

After setting and running of the model, it was first calibrated for steady and then for transient state for the next two years i.e. 1996 and 1997. The calibrated parameters were hydraulic conductivity and specific yield. The calibration process was carried out until the simulated heads comes closer with observed heads within ± 2 m range, in every cell.

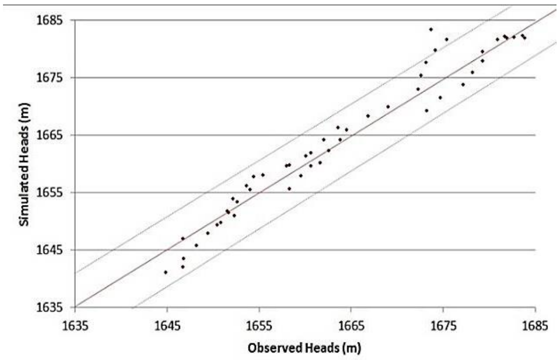

Fig. 8: Calibration results of the Model

6.2.3 Validation of the Model

After calibration the model was validated for the next five years i.e. 2000 to 2005 against the observed groundwater data to establish more confidence in accuracy. The model calibration was carried out until the line of perfect match comes within 95% confidence level.

6.2.4 Application of the Model

Two scenarios were modeled to make future forecast for the study area

- Scenario-I assumes that if government impose ban on groundwater and arrange alternate source for the city then what will be the situation of the aquifer in 2040.
- Scenario-II assumes that the groundwater demand will increase in future as the population of the city increases so to how extent groundwater level will drop in 2040.

7. Scenarios Modeling

7.1 Scenario 1

This scenario assumes that the increase in groundwater abstraction will stop at the level of the year 2014. These are the situation if government takes strict actions on groundwater use and provide another source of water for the city. The abstraction rate for the year 2014 was used for the next 26 years, up to the 2040. The recharge to the groundwater was the 20% of average of rainfall over the last 20 years. The recharge rates used for these two scenarios are shown in Fig. 9.

7.2 Scenario 2

This scenario assumes that the groundwater abstraction will increase as the demand increases for the growing population of the city. Abstraction was increased at the rate of 1.24 MGPD per year, which was the difference between the abstractions of the years 2013and 2014. The recharge was the average over the last 20 years of our study period. The table show the comparisons between the abstractions made to the aquifer for both scenarios.

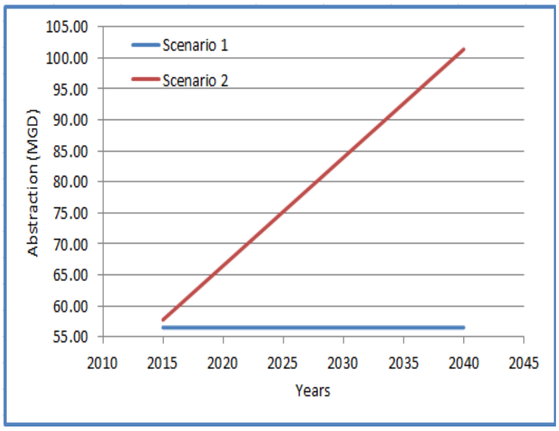

Fig. 9: Abstraction values used for both scenarios

7.3 Drawdown in Water Table

The Fig.: 10 show the predicted drawdowns in the water table under different scenarios for the period 2015-2040. The decline in water table is smaller in scenario I as compared to scenario II. The decline rate for the Scenario I come out to be 1.18, 1.24 and 1.33 m for the years 2020, 2030 and 2040 respectively. Whereas it comes to be 1.23, 1.40 and 1.72 m for the years 2020, 2030 and 2040 respectively for the Scenario II. The average decline was 1.23 m and 1.37 m for the Scenario I and II respectively. The difference in this average is 0.14 m. The decline increased 0.01 m/year for scenario I and 0.022 m/year for the Scenario II. The cumulative decline was 30.81 m over these 26 years. Cumulatively the water table declines 30.81meters in scenario I and 34.6 meters in scenario II. So this relied that water table will decline 34.6 meter more in next 26 years if excessive use of groundwater is not controlled.

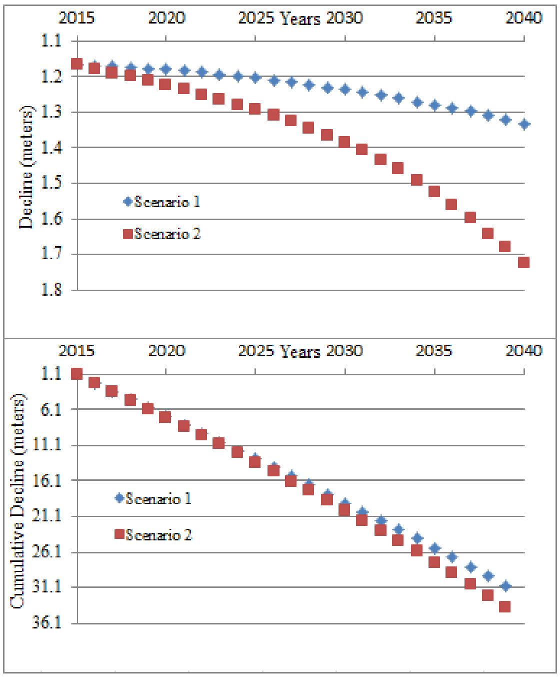

Fig. 10: Water Budget calculated by the Model for both scenarios

7.4 Sustainability

Sustainable yield is the allowable net draft at steady state for a selected equilibrium [19]. Groundwater sustainability is development and use of ground water in a manner that can be maintained for an indefinite time. According to this definition the groundwater extraction should be less or equal to the natural recharge made to the groundwater. In our study period the average recharge was 37.04 Mm^3 to the groundwater, which is 20% of the total precipitation. Whereas the extraction was 84.20 Mm^3, so there is annual deficit of 47.11 Mm^3 per year. So for the groundwater of Quetta city to be sustained for an infinite time, the safe extraction rate is 0.1028 Mm^3 per day or 27.1 MGPD.

8. Conclusions

MODFLOW Pro 2000 was applied for Quetta city to investigate the groundwater sustainability. The model was calibrated to the available groundwater data and validated the results up to the year 2007. The calibrated results were brought to 95% confidence level. After calibration and validation, the model was used for further analysis. These results showed that groundwater table of Quetta city is declining at very fast rate. The average decline rate came 0.91 m/year. The maximum decline was for the year 2013 with 1.15 m. An irregular cone of depression was being created at the center of the city, which was becoming deeper and deeper with the passage of time. The water level dropped from average 1635 m in 1995 to 1605 m in 2014 in the city area with a drop of 30 m in 20 years. The abstraction rate for the city was 24.82 MGPD in 1995 which increased up to 44.09 MGPD in 2014 i.e. 56% increased. The number of tube wells increased from 950 to 1680 with average of 36.5 tube well per year. These are excluding the illegal borings drawn at homes and gardens. The net effect of urbanization was to decrease the recharge rate by increasing impervious area. Vermont Storm Water Management method was used to assist the recharge deficit caused by increasing imperviousness. The maximum amount of deficit comes out to be 2.95 MGPD for the year 2012 and minimum comes to be 0.586 MGPD for the year 2011.

9. Recommendations

- All wells data should be recorded at fixed intervals.
- All possible measures should be taken to reduce the rate of abstraction.
- As the only source of groundwater recharge is precipitation so delay actions dams should be constructed to increase the recharge
- Care should be taken in urban planning to design depressions for rain water to infiltrate
- Agricultural use of groundwater should be reduced in the valley
- Provision of infiltration galleries
- Studies should be conducted to see opportunities of importing water from external source outside the valley i.e. Ziarat, Zarghoon Mountains or Bolan etc.

10. Acknowledgement

The authors are thankful to Irrigation and Power Department of Baluchistan for sharing groundwater data and WAPDA for sharing their reports on Quetta groundwater. We are also thankful to all Government Departments of Baluchistan including WASA, Statistics, PHE and QDA for their cooperation in this study.

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