GIS-Based Modeling for the Monitoring of Groundwater Scarcity Fluctuation

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Abstract

More stress on freshwater resources make Lahore a water-scarce city. To accommodate this scarce condition a management system is required which give detailed information about which part of the city is facing more water-scarce condition and also in which season more scarcity prevails in the city to resolve this problem and to provide better management of the reserve, an easy and coast effective GIS-based modeling for groundwater scarcity measurement. In this study different Geo-statistical techniques were used along with limited groundwater depth measurements, from 2014 to 2017, from already installed production wells within the residential area. As the depression zone formation occurred due to overexploitation of groundwater resulting in the depletion of the underlying aquifer. Aquifer response had been assessed using Groundwater Scarcity Footprint (GSF). This GSF fluctuates both in response to the variation in recharge and withdrawal condition of groundwater. The acceleration in scarcity level from 2014 to 2017 for the study area is -1.9, 16.21 and19.69 km^2/year in July, April, and October respectively. The fluctuation in the center of the depression zone/ Groundwater scarcity center (GSC) gives better identification of which part of the city is in more water stress condition. And these regions are the eastern and southern parts of the city where a newly constructed housing scheme and metro train create a great influence on recharge and abstraction rates of groundwater. The depth at GSC (D-GSC) is found to help cross-check the trends of the groundwater budget that was initially concluded from GSF.

Keywords: Groundwater Scarcity Footprint, Scarcity Center, Depression cones, Geographic Information System

Introduction

Freshwater is an essential factor for the existence of all the creatures living in this universe. Earth is merely the planet wherever the water exists to beat the regular needs of human beings. 71% of the earth's surface is covered with water (USGS, 1984). From the whole of 71% water, 97% is seawater and the remaining 2.5% is freshwater from which hardly 0.01% is accessible for human intake; the remaining water is confined in snowcaps and glaciers (Ahmed et al. 2014). Groundwater systems are often outlined as a dynamic systems characterized by nonstationary input (recharge), output (baseflow), and response (groundwater levels). Any phenomenon which produces pressure change within the aquifer results in a change of groundwater level which is called groundwater level fluctuation (Shamsa et al., 2015). The recharging method is stricken by numerous hydrologic processes (i.e. precipitation, evaporation, transpiration, runoff, infiltration, and soil moisture that successively rely on part temperature and pressure, radiation, wind speed, topography, land use, land cover, etc.) and by the hydraulic properties of soils and aquifers.

But Groundwater resources are being stressed by fast socioeconomic development and global climate change combined with population growth and industrial developments. Due

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to enlarging the number of people worldwide, the increase in per capita water and food demands, and the rise in living standards (Veldkamp, et al., 2017). Fluctuation in the amount of water can be seen all around the world due to the unequal spread of this precious resource. As the study area is concerned, Lahore is considered a water-scarce city of Pakistan. The demography of Lahore is rapidly growing on transformation and the census reaches 11 million which is double of 1998 census which was 5 million people (Survey of Pakistan2017-2018). Climate change strongly affected the length and severity of the season of the study area. Any change in annual rainfall, warm, and winter season received, hence the correspondence change in recharge rates of groundwater Aquifer underlying Lahore metropolis is facing deteriorating conditions due to the over-abstraction of groundwater to fulfill the demand of city inhabitants. A higher rate of removal of water and a very low recharge rate which is the result of the presence of a wide impermeable surface or small surface available for seepage leads to lowering of the water table. Thus, the depth to water level increases, creating a depression cone which represents lowering the quantity of groundwater. This depression cone may expand or contract due to different recharge conditions. These conditions may be of seasonal variations or infrastructural changes that happen in Lahore due to which the groundwater scarcity fluctuates. Hence, the mismanagement and over-exploitation of water lead to a water scarcity problem.

In past, most studies have been conducted to monitor and estimate this precious resource. Mehmood et al., (2013) conducted a study to calculate the groundwater depression zone using the GIS technique. A recession zone in the groundwater levels below 38m has been detected. This depression goes on growing after 2004 continually with an average rate of about 24.5 km^2 per year. Jaber A, Fawazia A-R (2006) researched cyclic activities of groundwater fluctuations in residential areas to observe the relationship with monthly-averaged temperature and total rainfall, monthly water level measurements are used. A time series model is developed for water level data that stimulates the influence of the detected periodicities.

Aim of the study

The major aims of the study are (1) to assess the ground scarcity conditions prevailing in the urban areas of Lahore Metropolis (2) To study how the season has impacts on groundwater levels (3) To monitor the seasonal scarcity fluctuations of groundwater depth (4) To monitors the Spatial-temporal scarcity fluctuations of groundwater (5) To study the Spatial and temporal variations of water table depth for the years of 2014-2017 (6) To assess the movement of depression cone which were developed due to heavier abstraction.

Materials and Methods

Profile of Study Area:

Lahore is the center of Punjab Territory and 2nd Major-town of Pakistan. Lahore is located between 31° 15´31° 45´N and 74° 1´74° 39´E and is located 217 meters above MSL (Mahmood et al., 2011). Geographically, it is connected with India which is on the eastern border of Sheikhupura district is located northwest and south of Kasur. It is an entire city dependent on groundwater (Mehmood et al., 2013) due to the uneven distribution of surface water. Lahore Aquifer is an unconfined aquifer with a depth of about 400 m (1,300 ft.) (Gabriel and Khan, 2006, Akram and Gabriel, 2007). This region is under unconsolidated Quaternary age alluvial landfills (Basharat and Rizvi, 2011). Hydrogeological, Lahore aquifer is the part of Bari Doab, between the Ravi and Sutlej rivers. It is also a small part of Great Rachana Dob (Muhammad et al., [2014). The extension of the Lahore district takes place across the Ravi River due to rapid urbanization. The aquifer now also includes part of Rachna Doab (Khan S. et al., 2003).

The Bari Doab and the Rachna Doab are themselves part of the vast sedimentary plain obstructed by the current of the Indus and its branches. The main sources of groundwater aquifer recharge are rainwater and the Ravi River

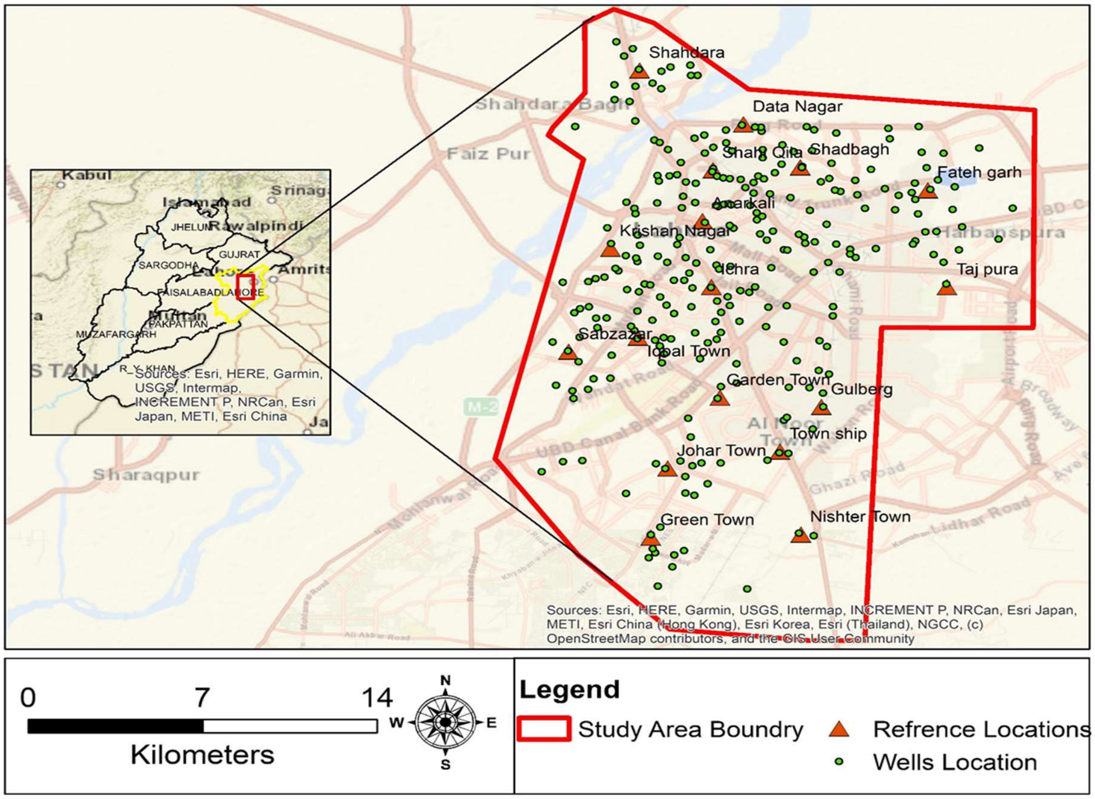

Figure 1: Map of Study Area

Lahore has a semi-arid climate with rainy, and extremely hot summers, dry and hot winters, and dust storms. During the monsoon season, the humidity level is very high and most of the rainfall occurs in this season, which makes the environment stickier. It persists from July to September when the depression moves west towards Pakistan. Groundwater is recharged by about 40% per year due to rainfall during the monsoon season. Since India built a thin reservoir in 2000, now this recharge resource has dried up and contributes little to recharge the underground waters. This situation makes the aquifer completely dependent on the rainfall and its related fluctuations which is insufficient to hold the heavy abstraction in the area (Mahmood et al., 2013Rapid land cover change, increased human growth and low groundwater recharge puts a burden on aquifer capacity. A higher rate of removal of water and a very low recharge rate which is the result of the presence of a wide impermeable surface or small surface available for seepage leads to lowering of the water table. Thus, the depth to water level increases, creating a depression cone which represents lowering the quantity of groundwater as cited by studies (Gabriel & Khan, 2010; Mahmood et al., 2013).

Dataset

In metropolis WASA and other private companies are responsible for providing water facilities to all inhabitants to fulfill the domestic, industrial, and agricultural needs of the region (Basharat and Rizvi 2011). Static Water Level (SWL values) for April, July, October from 2014, 2015, 2016, 2017 had been obtained from WASA. This enterprise periodically measures the depth of every of its tube wells mounted inside the Lahore district. A ground survey was turned into prepared to gain the coordinate records for 273 tube wells via way of means of the usage of a German GPS receiver (GPSmap-76CSx) with a precision of 3 meters. Groundwater depth records for every April, July, and October for the years of 2014, 2015, 2016, and 2017 had been assembled in keeping with their vicinity places. Georeferencing is done in a GIS software program named ArcMap 10.5.0. These developments and changes place pressure on our freshwater resources regionally, thus increasing water scarcity (Wada et al., 2014, Veldkamp, et al., 2017).

Formation of spatially distributed data:

Geographical Information System had been used to prepare basic data. Values of static water levels have been taken from Water and Sanitation Agency (WASA), Lahore. These values with the accuracy of ±3m were exhibited. The placement of these installed wells is not even. However, Different statistical methods named interpolation techniques applied on point data to create a continuous and regular spatial distribution. Interpolation techniques which were used named as Inverse Distance Weighted (IDW), Spline, and Kriging with its different methods were employed to point data set for the generation of groundwater depth surfaces. All the observations were then compared based on the least root mean square (RMS) and mean values for the optimal selection of interpolation method for better assessment of underground water conditions in Pre Monsoon. Monsoon, and Post Monsoon seasons in preceding years 2014 to 2017. The detail of the optimal interpolation selected method is given in table 1.

Seasonally Annual Data	Apr-14		Jul-14		Oct-14		Apr-15		Jul-15		Oct-15		Apr-16		Jul-16		Oct-16		Apr-17		Jul-17		Oct-17	
Optimal interpolation methods	**ME**	**RMSE**	**ME**	**RMSE**	**ME**	**RMSE**	**ME**	**RMSE**	**ME**	**RMSE**	**ME**	**RMSE**	**ME**	**RMSE**	**ME**	**RMSE**	**ME**	**RMSE**	**ME**	**RMSE**	**ME**	**RMSE**	**ME**	**RMSE**
Inverse distance method (IDW)	0.3	2.71	0.3	2.99	0.4	3.06	0.3	2.8	0.3	2.69	0.29	2.87	0.31	2.89	0.33	2.96	0.34	2.56	0.4	3.24	0.4	3	0.38	3.44
Global polynomial (GP)	0	2.78	0	2.95	0.1	2.9	0	2.67	0	2.5	-0	3.08	0	3.05	-0	3.2	-0	3.01	0	3.28	0	2.71	0.01	3.11
Radial basis function (RBF)	0.2	2.54	0.2	2.86	0.3	2.89	0.18	2.67	0.2	2.53	0.18	2.73	0.21	2.74	0.22	2.82	0.21	2.41	0.2	3.09	0.2	2.88	0.28	3.32
Local polynomial (LP)	0.1	2.37	0.1	2.64	-0.4	2.61	0.07	2.51	0.1	2.38	-0.3	2.66	-0.5	2.7	-0.5	2.67	-0.1	2.18	-0.6	2.85	0	2.53	0.02	3
Ordinary kriging (OK)	**0**	**2.32**	**0**	**2.62**	-0	2.58	0.05	2.51	**0**	**2.29**	**0.06**	**2.5**	-0.1	2.56	-0.1	2.55	0.02	2.27	0	2.8	0	2.6	0.06	3.19
Simple kriging (SK)	0.1	2.47	0.1	2.68	0	2.61	0.09	2.56	0.2	2.5	0.09	2.55	0.22	2.8	0.06	2.63	0.14	2.35	0.1	2.96	0.1	2.78	0.07	3.16
Universal kriging (UK)	-0.2	2.34	-0	2.65	**-0.2**	**2.5**	**-0.11**	**2.46**	-0.1	2.3	-0.1	2.7	**-0.2**	**2.48**	**-0.2**	**2.54**	**-0.1**	**2.13**	**-0.2**	**2.7**	**-0.1**	**2.51**	**-0.13**	**2.95**

Table 1: Optimal selection of interpolation method

Raster was calculated for every three observations of the selected month for each year. A continuous surface of each raster was generated and then selecting the best surface was based on the least RMSE Values and visual observation. On these selected appropriate surfaces further, analysis was done.

Contour Analysis:

Water table contour lines are kind of like topographical lines on a map. These contour lines are drawn to hitch areas of equal heads, and these lines are referred to as equipotential lines. If we draw a contour of the same height on the raster surface for the different seasons then the area under that contour could be varied. These lines also give information about, in which direction groundwater will flow. So the Monitoring of groundwater scarcity fluctuations can be done by respective contours of each type of interpolation. Variations in these contours can often give a good indication of fluctuation, which is the direct effect of overexploitation and recharge of groundwater happening in respective seasons and years in the city. The contour of 40m on raster for April, July, and October of 2014 to 2017 are drawn for the monitoring of scarcity fluctuations. The area under the contours was calculated by the formation of polygons underneath the contour lines. The area was calculated in square kilometers for each month polygons for each year which are given in table 2 below

Years	April (sq. km)	July (sq. km)	October (sq. km)
2014	70.95	123.66	58.45
2015	60.66	150.33	130.83
2016	87.50	106.91	106.88
2017	116.03	131.71	132

Table 1: Contour Area (sq. km)

By using GSF, two other kinds of variations were picked, seasonal variation in a year and yearly variation of seasons. To understand this variability for the study area, a graphical relationship with time was developed. The spatial distribution of these contours are represented in fig.2

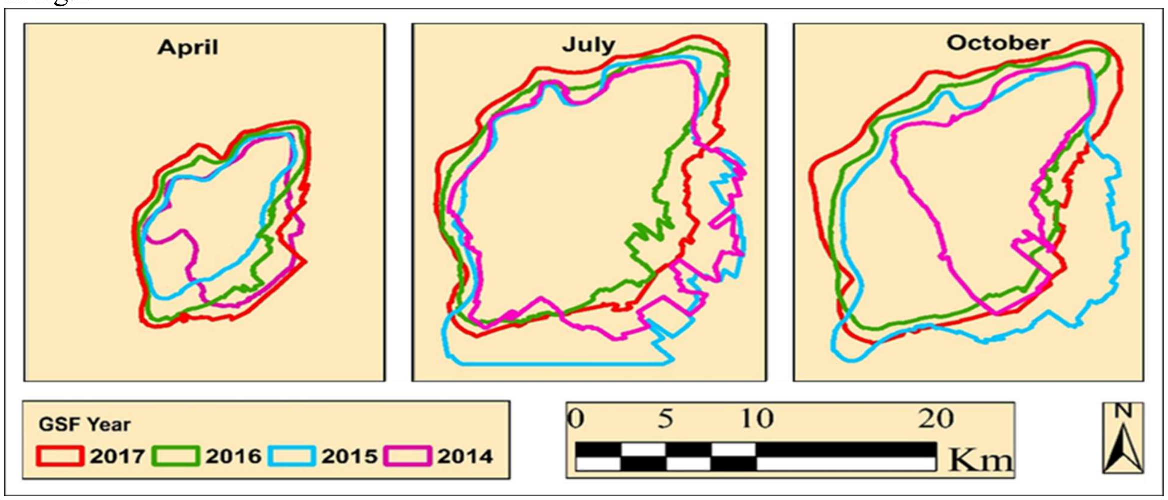

Figure 2: Annual distribution of seasonal GSF

Monitoring of Seasonal Movement of Groundwater Scarcity Center (GSC):

Groundwater Scarcity Center (GSC) is another variable presenting the center of the varying depression zone which is the centroid of the mapped GSF polygons. The GSC must be shifted in response to the spatial variations of water abstraction and recharge in the study area. The seasonal movement of GSC is mapped to assess the dimensional changes in the seasonal GSF polygons. Furthermore, to get an overall perspective, all three seasonal locations of GSC in each year are averaged to a single point using the triangle's center determine technique, shown in figure 3, to trace out an annual shift in the GSC from 2014 to 2017. The depth at GSC (D-GSC) would also change under the influence of the scarcity level in the region or with improving regime water level at GSC would rise and vice versa, the time-based trend of these variations has been represented graphically in Figure 3.

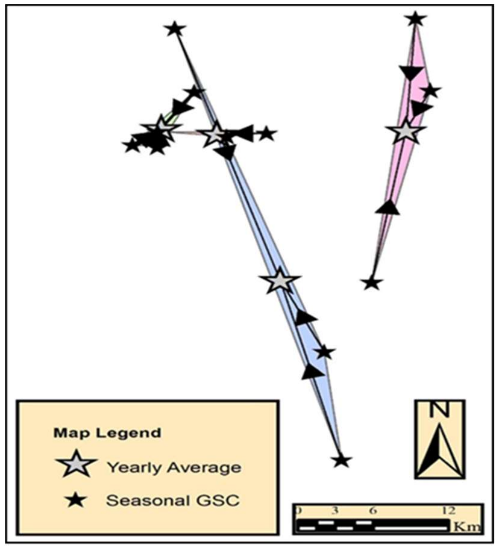

Figure 3: Averaging the Position for each Year

Results and Discussions

Groundwater Scarcity Footprint (GSF):

Overexploitation and less recharge of groundwater make Lahore a water-scarce city. This water scarcity condition has a strong relationship with the seasons faced by the city, demography, and the land cover of the city. Lahore is laying in a semi-arid climate with having four seasons pre-monsoon, monsoon, post-monsoon, and dry season. These seasons and other factors generate a strong impact on groundwater levels, and hence scarcity fluctuated. For the monitoring of this scarcity fluctuation, a groundwater scarcity footprint /depression zone with a depth of 40m was used as GSF of three seasons for 2014-2017 years that is found to be increasing or contracting with time because of seasonal and topological changes that occurred within the city. GSF gives not only annually variation trend of seasoned GSF but also it provides seasonal trend of annual GSF.

Annual Trend of Seasonal GSF:

Every hand-picked season has shown an increase or decrease in the extent of the Great Depression zone. However, this growth or contraction isn't uniform as shown in figure 4. Monsoon season (July) shows a very reduced rate, -1.93 Km^2 per year, of increase in water deficiency zone. By analyzing the graph, the depression zone was expanding in the preceding 2 years 2014 and 2015 relying upon two factors, a terrible low recharge rate and a higher rate of abstraction. Because hot weather conditions prevail within the study space in July, so, recharge to groundwater for this month is nearly zero, and the rate of abstraction is high due to raised water consumption during this season that ends up in the conclusion that the behavior of GSF in this month is management by abstraction rates.

But a decreasing trend for the years 2016 and 2017 is found. This is the result of topological changes, like the construction of the Lahore Orange Line Metro Train Project, which takes place in the city. The OL Metro Train begins in the east of Lahore from Dera Gujran, along GT Road to the Main Railway Station, across the city center to Chauburji before heading southwest and terminus at Ali Town. The total length of OL is about 26.23 km in whole, which includes 1.15 km of the underground section, 0.70 km of transition section, and 24.38 km of elevated sections. In October 2015, the construction of Metro Train was started. For the elevated section, deep holes were bored for the installation of pillars in the roundabout of the city. But heavy rainfall commences in the winter season which leads to these holes as deep wells which started to recharge the underlying aquifer. As the seepage of rainwater is a slow process and this water has completely reached its destination, resulting in the lowering of the GSF area for both succeeding years like 2016 and 2017 but this is a temporary change which is occurred in the monsoon season.

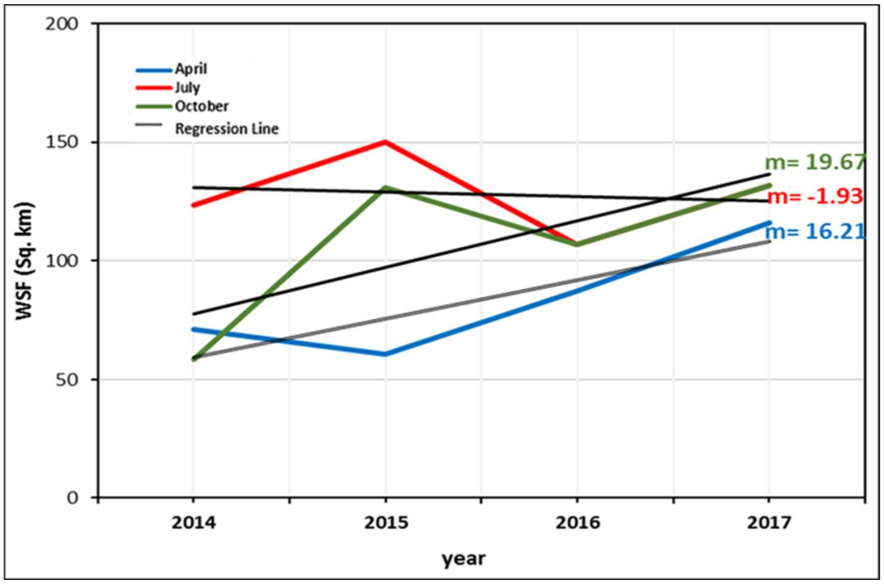

Figure 4: Annual Increasing Trend of Seasonal GSF

As compared to July, the month of April with an increase of 16.21 Km^2 per year, has high rates of depression zone expansion, for this month the rate of GSF depends mainly on two factors, comparatively low abstraction of groundwater in winters and slow infiltration of monsoon rainfall which is now fully reached to the aquifer. From the figure, it is clear that the most vigorous behavior is found in the post-monsoon season (October) with an annual increment of 19.67 Km^2 in the groundwater scarcity zone. These readings were just taken after the monsoon rainfall but the slowly seeping rainwater has not fully reached the aquifer. The high abstraction rates in the summer season also contribute to post-monsoon scarcity. These effects could be seen for the year 2014 and 2015 readings but in the years 2016 and 2017 GSF tends to be reduced due to the recharge that takes place during the formation of Metro Train. The rising trend in GSF is an overall increase in abstraction rates which directly link to the consumer population of the city.

Seasonal Trend of Annual GSF:

To locate the yearly scarcity fluctuations, we draw a multiline line graph between seasons for the years 2014-2017 and spread the area of contour in square km.

For the year 2014, seasons show normal behavior of the rate of recharge and discharge. In April area spread is slightly higher than in October because the infiltration of water is taken place due to monsoon rainfall and recharging the groundwater resources. Hence, the spread area of the contour is small. But in July rate of abstraction of groundwater is high due to the warm summer season. so. The area spread of contour is bigger than for the remaining two seasons. The overall effect of 2014 shows the recharge trend of the aquifers.

For the year 2015, seasons also show normal behavior of the rate of recharge anddischarge. In April area spread is slightly less than the preceding year due to the recharge of groundwater on October 14. In July, the area spread is quite high than the remaining lines which show high water scarcity condition prevails in the city. In October, smaller recharge of groundwater resources is taken place which can be seen in the graph. The abstraction rate of groundwater was higher than the amount of rainfall, so a smaller recharge occurs this month.

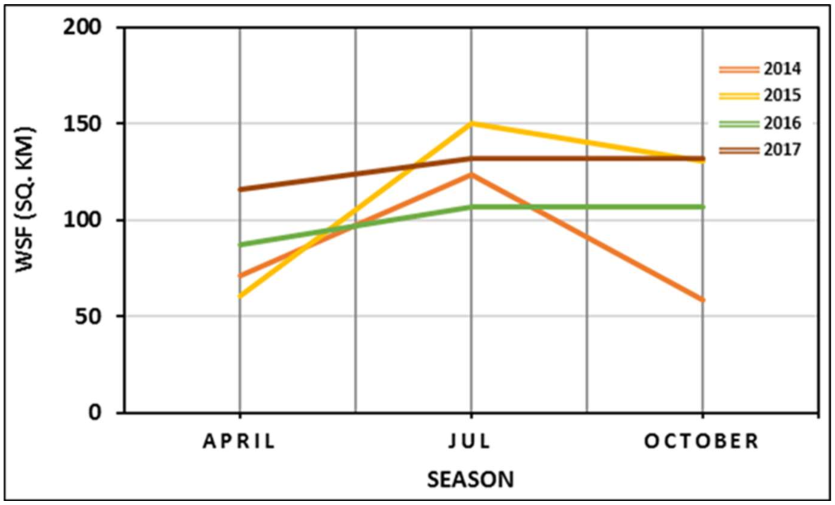

Figure 5: Seasonal trend of Annul GSF

The graph shows some unusual behavior for the years 2016 and 2017, for April,it shows linear behavior of increasing trend of groundwater exploitation as the number of inhabitants increases in the city. For July, it shows the declining trend for bothyears. This trend of decline is due to the infrastructural changes in the land cover. Construction of the orange line train started in October 2015 and the formation of smaller well-like holes was formed all around the stud area. Here winter rainfall plays an important role in the recharge of groundwater. As the movement of surface water into the ground is very slow so this effect is seen in July. As more monsoon rainfall was taken place hence more recharge is occurred in October. From the graph we can conclude here 2015 is the most water scarcity year.

Groundwater Scarcity Center (GSC):

Groundwater moves under the influence of gravitational force and corresponding to the slop of the land and this movement slows down as the slope of water come close to zero. If the rate of groundwater abstraction increases from a certain part of the city increases the depression zone expands in this direction. As a result, GSC started moving to the side with increased stress to groundwater was experienced. On the other hand, if recharge from a certain part of the city increases, it causes an increase in the flow of water from side to depression zone. As a result, GSC will move away from the providing side to the recharge. This movement of GSC gives a better version of understanding of the directional history of the variation in recharge rates and stress of the aquifer. Figure 6 shows a general trend of GSC movement in the southward direction at the beginning followed by the west to the eastward direction.

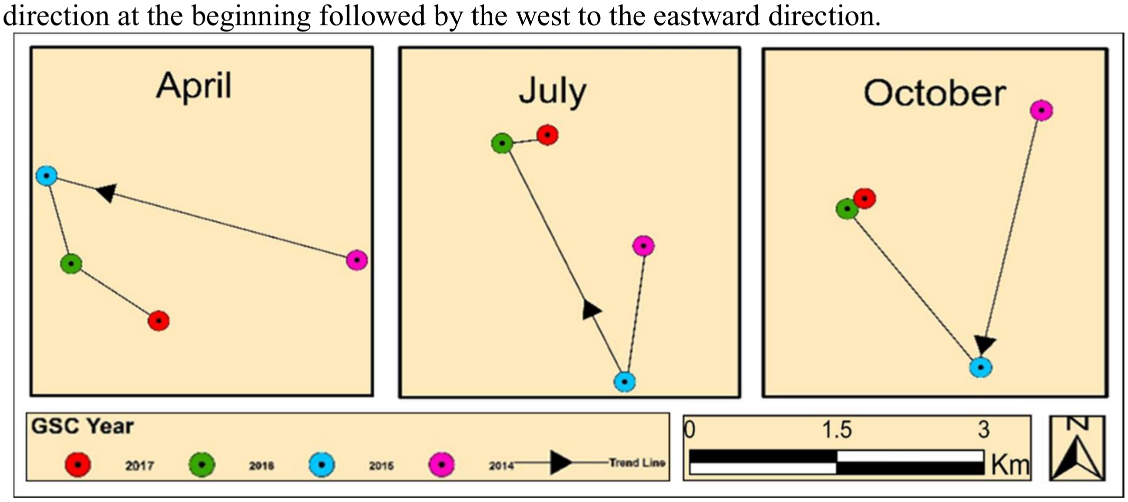

Figure 6: Seasonal Movement of GSC

This shift in GSC is the result of the land cover change that takes place in the form of the construction of a new housing scheme in the southern part of the city. Furthermore, GSC shifted to the eastward direction which is a combined result of the formation of new housing societies and also recharge from river Ravi were take place. This trend predicts that if heavy recharge from the river could take place, then GSC will sharply move towards the eastern side of the city. The stress of growing water demand and decreases in previous surfaces is keenly picked by the movement of GSC.

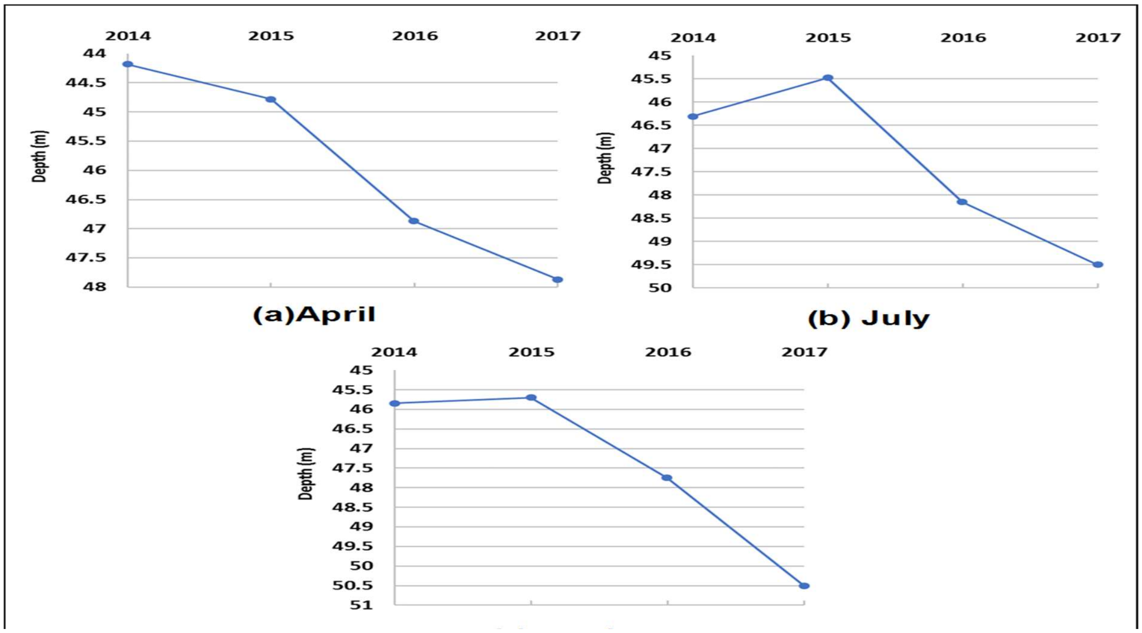

Figure 7: Variation in the Seasonal depth of Groundwater Scarcity Center (D-GSC)

The trend of increase in depth at GSC is shown in figure 7, which strongly correlates to the results concluded from the GSF measure. The fluctuation in depth is found in April and July which are showing their dependence on the varying rates of rainfall recharge and topological changes in the city. On the other hand, the controlling factor in October is an abstraction that is continuously increasing with almost no fluctuation.

Conclusion:

The regime estimation of the underlying unconfined aquifer was measured by Groundwater Scarcity Footprint (GSF) which is an area of the depression zone for a selected depth and measured by comparing with some selected depth. Variations in the area of GSF were observed which is not uniform for each season. These variations would be the result of recharge and abstraction rates. These conditions are directly linked to the severity of the season, land cover and topological changes, and rapid population growth rate. Another term that was also introduced in this study is Groundwater Scarcity Center (GSC) which finely picked the spatial distribution of water stress conditions to prevail in the city. The rate of abstraction and recharge also influence the placement of the Groundwater Scarcity Center. The acceleration in scarcity level from 2014 to 2017 for the study area is -1.9, 16.21 and19.69 km^2/year in July, April, and October respectively. The highest fluctuations were observed in October with a rate of 19.69 km^2 per year. This increment is a result of higher abstraction rates and low recharge and the lowest rate was found in July with -1.9 km^2 per year. Although, in this month abstraction was found to be very high. Construction of Metro Train highly influences recharge rates which lower the GSF. The fluctuation in the Groundwater scarcity center (GSC), gives better identification of which part of the city is in more water stress condition. The general trend of the GSC movement is in the southward direction at the beginning followed by the west to the eastward direction. And these changes had been occurred due to the newly constructed housing scheme and metro train which highly influence recharge and abstraction rates of groundwater. The depth at GSC (D-GSC) is found to be helpful for correlation to the results concluded from the GSF measure. The fluctuation in depth is found in April and July which are showing their dependence on the varying rates of rainfall recharge and topological changes in the city. On the other hand, the controlling factor in October is an abstraction that is continuously increasing with almost no fluctuation.

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