

Article

Groundwater Level Dynamics in Bengaluru City, India

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Abstract: Groundwater accounts for half of Indian urban water use. However, little is known about its sustainability, because of inadequate monitoring and evaluation. We deployed a dense monitoring network in 154 locations in Bengaluru, India between 2015 and 2017. Groundwater levels collected at these locations were analyzed to understand the behavior of the city's groundwater system. At a local scale, groundwater behavior is non-classical, with valleys showing deeper groundwater than ridge-tops. We hypothesize that this is due to relatively less pumping compared to artificial recharge from leaking pipes and wastewater in the higher, city core areas, than in the rapidly growing, lower peripheral areas, where the converse is true. In the drought year of 2016, groundwater depletion was estimated at 27 mm, or 19 Mm³ over the study area. The data show that rainfall has the potential to replenish the aquifer. High rainfall during August–September 2017 led to a mean recharge of 67 mm, or 47 Mm³ for the study area. A rainfall recharge factor of 13.5% was estimated from the data for 2016. Sustainable groundwater management in Bengaluru must account for substantial spatial socio-hydrological heterogeneity. Continuous monitoring at high spatial density will be needed to inform evidence-based policy.

Keywords: groundwater dynamics; Bengaluru; monitoring; groundwater balance; India

1. Introduction

Groundwater is an important, decentralized source of drinking water for millions of people in India. It meets nearly 85% of rural domestic water needs and 50% of urban water needs [1]. Dependence on groundwater for water-supply in urban towns and cities is increasing due to accelerated growth, increasing per capita water use and poor reliability of imported surface water from distant sources [2,3]. In a review of urban recharge, Lerner [4] describes how urbanization affects the groundwater cycle by way of changes to both the total water budget, and to pathways recharge. The total imported water supply of many temperate European cities is comparable to the annual rainfall endowment, while, in many dense cities in arid areas, water supply imports are greater than annual rainfall. Leakage through water supply pipes then becomes a major source of recharge. In cities with inadequate sewerage systems, leakage through septic tanks and soakpits, and untreated wastewater released into drainage channels, are also major components of recharge quality. While these anthropogenic flows increase groundwater recharge, natural recharge rainfall can decrease in dense built-up areas of towns and cities, where a significant proportion of land surface is altered through soil compaction, roofing and paving, all of which reduce normal infiltration. The net effect on the groundwater budget also

depends on the level of pumping from the aquifer. Spatio-temporal variation in the anthropogenic components and spatial variation hydrogeological properties such as specific yield and transmissivity add to the complexity of urban groundwater systems. Thus, reflecting the diversity of development pathways, geographies and geohydrology, urbanization induced changes to the groundwater system may include sharp changes of groundwater levels [5–7]; reduced well yields and deterioration in quality of groundwater [5,8–10]; poor quality base flow [1]; and migration of polluted urban groundwater into surrounding areas [11,12].

In rapidly growing Indian cities, both imported surface water and groundwater pumping have been increasing apace [13]. At the same time, sewer line connections, and wastewater treatment in Indian cities are severely lacking, with the Government of India acknowledging that some 70% of wastewater is estimated to be released without treatment into drainage features [14]. Increased recharge from anthropogenic sources (leaking water supply and wastewater systems), and increased pumping from the aquifer are likely to be occurring simultaneously. One of the goals of groundwater management plans in such circumstances is to safeguard groundwater levels in urban aquifers by influencing the magnitude and use of groundwater pumping. This requires a scientific understanding of urban groundwater systems based on a comprehensive database of groundwater levels, availability and use at appropriate spatial scale. Depending upon the groundwater monitoring network, spatial variations of recharge and of hydrogeological properties such as specific yield can also be estimated (e.g., [15]). Such monitoring is essential to help inform hydrogeological models that could be used for support towards sustainable urban groundwater management.

However, the majority of studies utilizing simple to complex groundwater models have been in large agricultural catchments (e.g., [4,16]). Investigations of urban groundwater systems, especially in developing countries, are limited [10,17–21]. In India, only two comprehensive urban groundwater studies have combined monitoring with models. Sekhar and Kumar [22] monitored 472 wells to study and model the groundwater dynamics of a central, 27 km² portion of Bengaluru, to assess the possible groundwater impacts related to the underground section of the city's metro rail system. A second study comprehensively evaluated groundwater for the small city of Mulbagal, 95 km from Bengaluru [21]. Groundwater levels in 272 wells covering 50 km² were monitored for three years. A distributed groundwater model was built based on this dataset, and applied to investigate climate and demographic scenarios for the city. These investigations highlight the fact that models can be built only if there is an adequate spatial representation of the groundwater monitoring network. In India, the nationwide long-term groundwater level monitoring by the Central Groundwater Monitoring Board (CGWB) is on average at a density of one station for approximately every 100 km². This density is very coarse if one wants to model urban systems, which usually cover areas of a few tens to few hundreds of square kilometers. Heterogeneous characteristics (e.g., hydraulic conductivity, transmissivity, and specific yield) of the aquifer in hard rock areas that underlie much of peninsular India add another good reason for a dense network of wells for small scale urban systems.

In this paper, we focus on understanding the groundwater patterns and dynamics in Bengaluru (earlier known as Bangalore), India. Bengaluru is one of the fastest growing cities in Asia, where population has grown from 180,366 in 1891 [23] to 8.5 million in 2011 [24]. The area of city limits, as by the municipal boundaries, has also grown substantially—ten times from a mere 75 km² in 1901 [25]. Water supply from the utility, Bengaluru Water Supply and Sewerage Board (BWSSB) has grown, but not managed to keep up with the rapid growth in demand. The inability of utility water supply growth to keep up with the city's growth is well documented (e.g., [24,26]). As a result, similar to all Indian cities, groundwater is heavily used to make up the deficit. Although based on a sparse monitoring network, the CGWB has estimated that groundwater is more than 100% developed in Bengaluru, which means that abstraction (pumping) is more than recharge to the aquifer [25]. In this paper, we report on the establishment of an innovative, dense monitoring network across the city, with the objectives of: (i) collecting a time series of groundwater table depths and using the data to study the spatial patterns in groundwater levels; (ii) estimating net groundwater storage changes

during drought year 2016 and during extreme rainfall periods; and (iii) estimating the rainfall recharge factor net groundwater flux. Our intention in this paper is to describe the patterns observed and to estimate the net groundwater storage change and aggregate flows, based on the water table method. In the Conclusions Section, we describe a more elaborate modeling framework that will be used in a forthcoming paper to estimate separate components of the groundwater budget.

2. Materials and Methods

2.1. Study Area

Bengaluru city is situated within $12^{\circ}45'N$ – $13^{\circ}10'N$ and $77^{\circ}25'E$ – $77^{\circ}45'E$, and covers an area of 720 km^2 (Figure 1). The city core is at 900 to 930 m amsl (above mean sea level), on a divide with a roughly North–South axis, with the Arkavathi River drainage Westward to the River Cauvery, and the South Pennar drainage to the East (Figure 2) [24]. The climate is semiarid with normal rainfall of 820 mm, September being the peak rainfall month. Close to 60% of the rainfall on average occurs during the southwest monsoon from June to September [27]. The retreating, northeast monsoon also brings rain from October to December. The dry period extends from January to May, although convectional thunderstorms occur from March through May. Typically, January and February receive almost no rain.

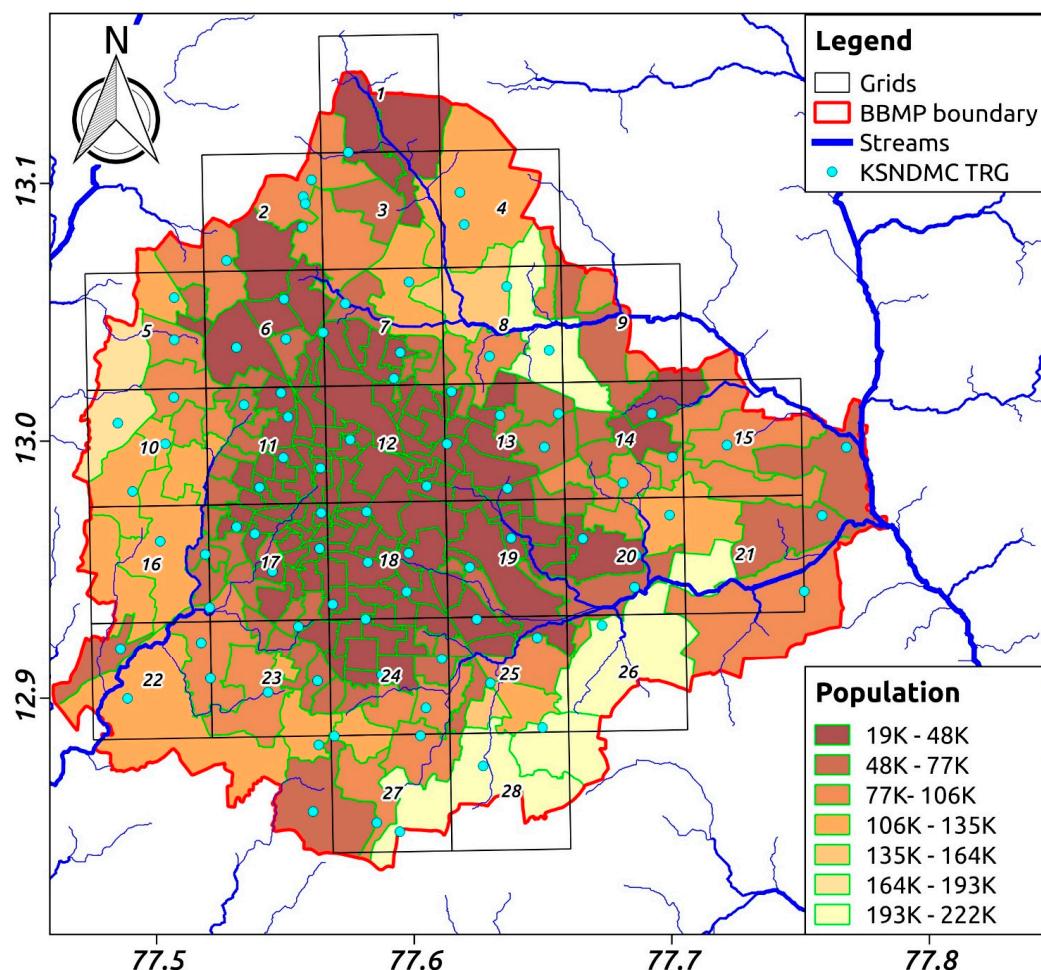


Figure 1. Spatial distribution (ward-wise) of the population in Bengaluru city. The streams, $5 \text{ km} \times 5 \text{ km}$ grid and Telemetric Rainfall Gauge (TRG) of KSNDMC are also shown. Numbers represent the grid-IDs.

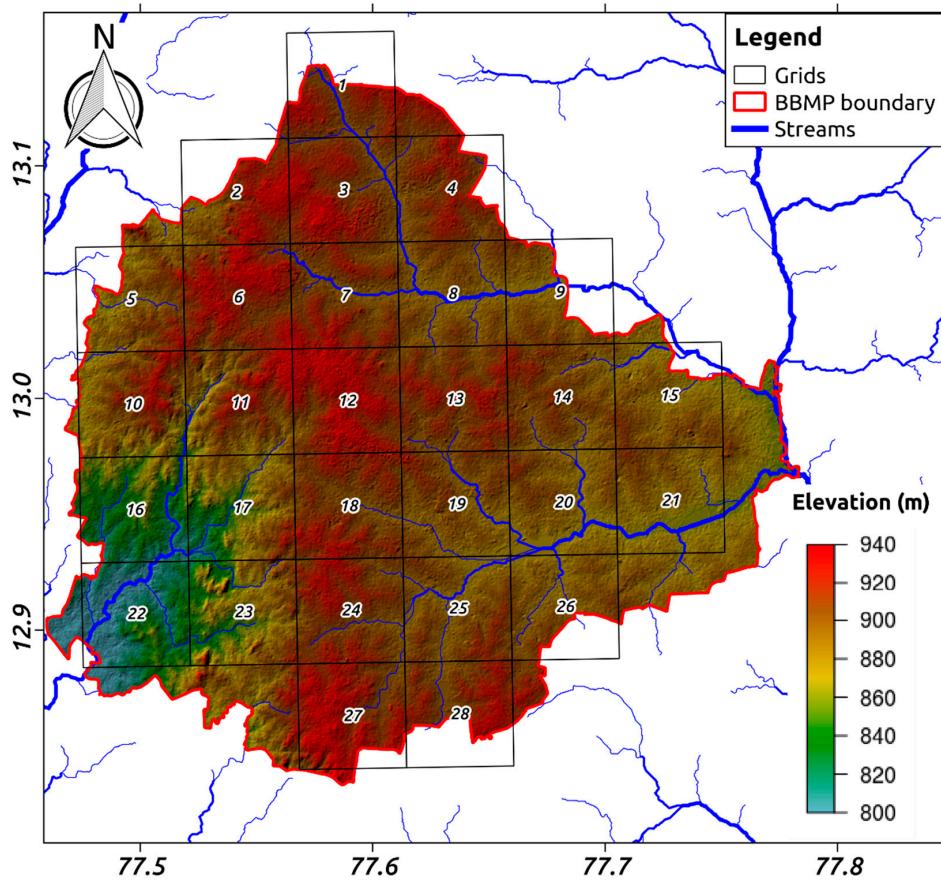
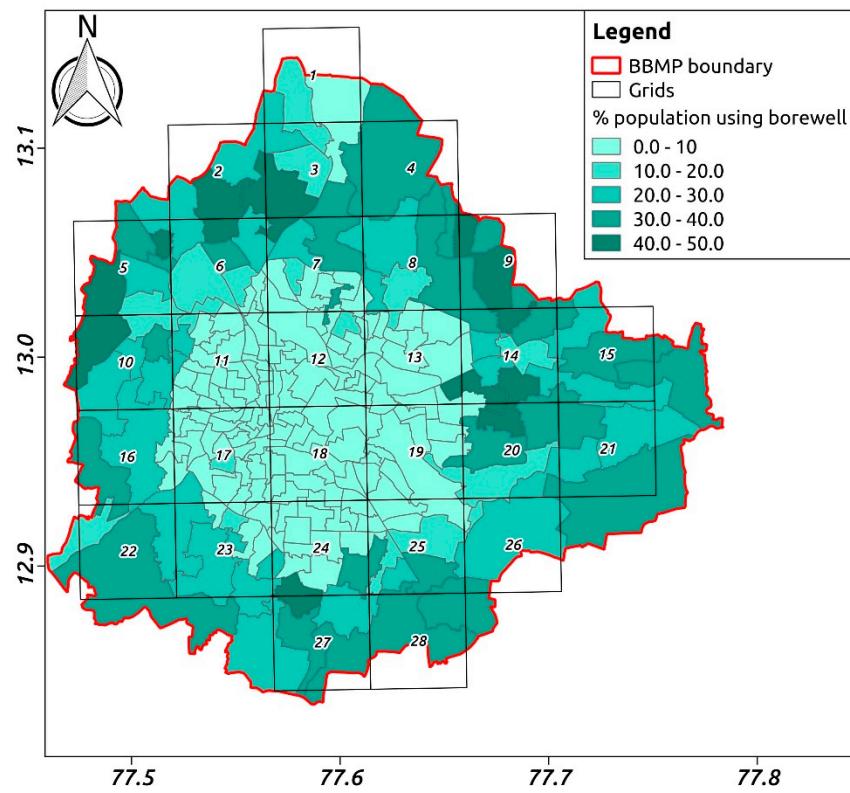
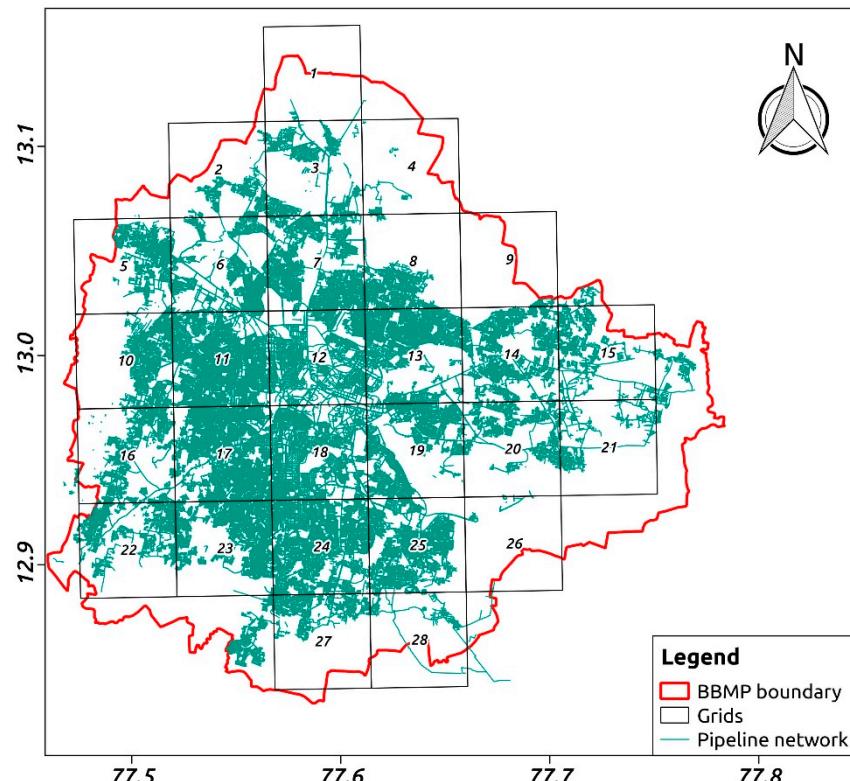


Figure 2. Digital Elevation Model (DEM) of Bengaluru city. Numbers represent the grid IDs.

Except for a few central areas in the old city core, the population growth between 2001 and 2011 has been positive with some outer areas reaching a growth of more than 300% [26]. The water needs of the city are mainly met by surface water supply from Cauvery River, and from groundwater. Surface water imported from the Cauvery River, currently at close to 1400 million liters per day (MLD), is approximately 75% of the average rainfall over the city, signaling the substantial anthropogenic influence on the urban water budget [26]. Non-revenue water, made up largely of leakage losses, was almost 50% in 2011 [24]. Although surface water supply has increased over time, it has been unable to catch up with the rapid growth and expansion of the city [26]. As a result, groundwater provides a large proportion of the current water consumption, and is likely to continue to do so in several wards of the municipality, which is called Bruhat Bengaluru Mahanagara Palike (BBMP) (see Figure 3). There is no effective regulation of the use of groundwater in these wards for domestic, commercial, industrial or government agency purposes. Free and unrestricted use is made of this resource by households, businesses, institutions and government agencies, including the Bengaluru Water Supply and Sewerage board (BWSSB). Consequently, there is practically no reliable data on the rate and distribution of groundwater withdrawals. Monitoring of the aquifers from which groundwater is withdrawn is conducted by the Department of Mines and Geology (DMG) and the Central Ground Water Board (CGWB). Both these organizations conduct regional exploration and investigation programs. Although many wells are used for pumping groundwater in the city, the density of the existing monitoring networks is very low [27]. Furthermore, the temporal frequency of monitoring by CGWB is once every few months. Hence, even though this dataset might reveal some larger, regional scale groundwater behavior over many years, it is not useful for assessing the state of the urban groundwater system; its resilience to important stressors such as anthropogenic forcings and drought conditions; and its response to extreme rain events.



(a) Percentage of people using groundwater



(b) Water pipeline network

Figure 3. Percentage of people using groundwater in 2011 (a); and water pipeline network in Bengaluru from 2015 (b).

2.2. Groundwater Monitoring

The first step was to create a comprehensive database for the city. Groundwater table mapping was carried out between December 2015 and September 2017. Groundwater levels (GWL) were measured using a monitoring network of 158 wells in an area of 700 km^2 . Out of these 158 wells, 154 wells had an unbroken record through the study period and were selected for the analysis reported here. The monitoring network was established using a novel approach in which the existing wells (predominantly municipal bore wells) were used as piezometers where groundwater levels were measured. To achieve a uniform spatial distribution, the study area was divided into grids of $5 \text{ km} \times 5 \text{ km}$, resulting in 28 grids for the city. Monitoring wells should be free from pumping to be used as piezometers. Those municipal wells that were not in use were carefully selected in each grid. In each grid, 5–6 monitoring wells were established. Groundwater levels were measured each month using a manual water level sensor (Heron Instruments Inc.). Figure 4 shows the location of the 154 groundwater monitoring locations, along with land-cover. The inner part of the city has relatively higher built-up area. Several secondary datasets, assembled at the grid scale, are presented in Table 1.

Maps were interpolated from the depth to GWL measurements using ordinary kriging. Kriging has been found to perform better than inverse distance weighting [28,29], and has been used in other studies in hard-rock aquifers in southern India [15,21,22,30]. Kriging was performed using the *geoR* library of *R* (<https://cran.r-project.org/package=geoR>). Variograms for each month were fitted using numerical optimization. Exponential variograms were found to fit the data well, and used to create interpolated maps of depth to groundwater (DGW) at a spatial grid of 100 m.

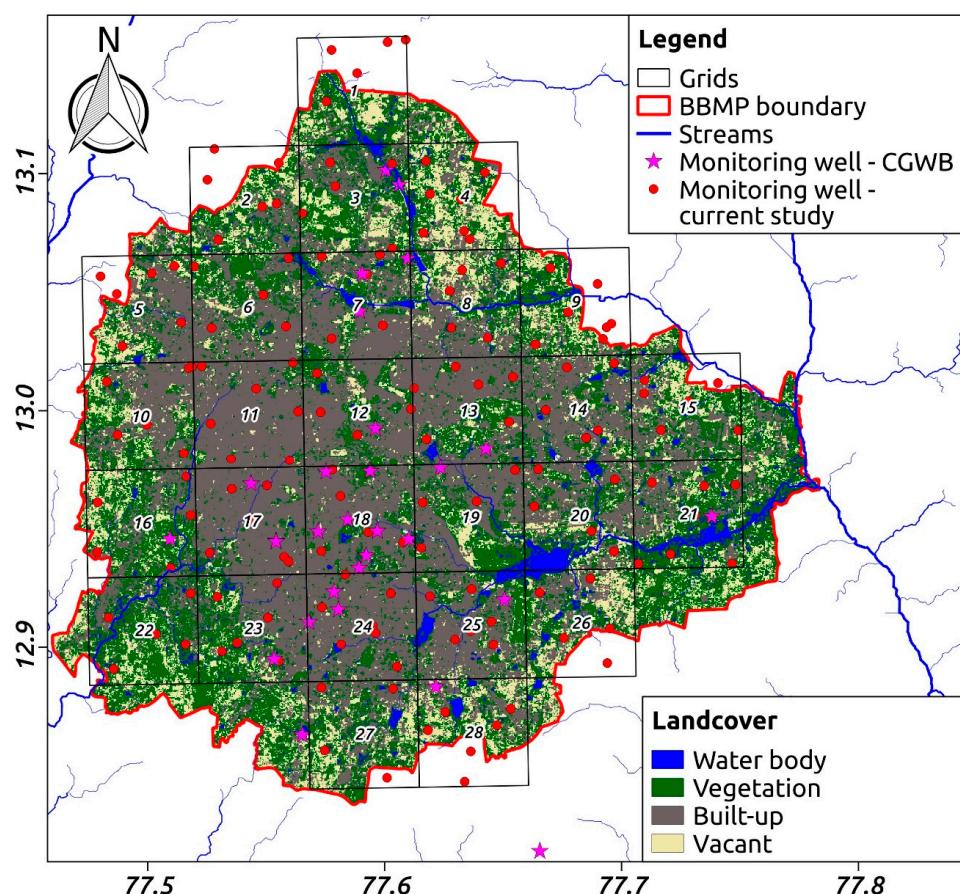


Figure 4. Spatial distribution of the land cover and monitoring network. Numbers represent the 5 km grid IDs. Landcover data are from 2011 [31].

Table 1. Different variables for each 5 km grid (Relative density of water supply pipeline is computed using *heatmap* plugin of QGIS; 1 means highest density and 0 means lowest density).

Grid ID	Grid Name	Population	Percentage of Built-Up Area	Elevation (m)	Percentage of People Using Groundwater	Relative Density of Water Supply Pipeline
1	Ganganahalli	76,442	15	901	15	0.000
2	Vidyaranyapura	143,937	28	907	28	0.063
3	Yelahanka New Town	222,281	35	905	35	0.088
4	Agrahara	117,935	28	919	28	0.016
5	Peenya	382,500	53	875	53	0.130
6	Jalahalli	363,359	67	914	67	0.892
7	Hebbal	506,535	71	892	71	0.565
8	Hennur	406,705	52	884	52	0.323
9	Channasandra	131,351	26	877	26	0.015
10	Herohalli	553,028	63	900	63	0.065
11	Rajajinagar	984,649	94	934	94	1.000
12	Bangalore Palace	525,245	89	937	89	0.643
13	Cooke Town	572,268	81	920	81	0.318
14	Krishnarajapuram	377,085	70	902	70	0.087
15	Kodigehalli	192,238	43	875	43	0.043
16	Bangalore University	332,918	38	851	38	0.008
17	Chamarajpet	1,048,839	92	849	92	0.608
18	Shantinagar	529,064	92	895	92	0.675
19	Domlur	395,813	69	905	69	0.488
20	HAL Airport	284,738	50	893	50	0.178
21	Whitefield	158,578	35	879	35	0.075
22	Kengeri	152,050	28	824	28	0.033
23	Chikkasandra	514,428	66	864	66	0.205
24	JP Nagar	691,729	87	906	87	0.146
25	HSR Layout	579,786	74	887	74	0.126
26	Doddakannelli	161,190	40	886	40	0.002
27	Kothnur	301,144	35	912	35	0.047
28	Begur	229,851	38	911	38	0.003

2.3. Rainfall Data

Annual rainfall for more than 100 years (1901–2012) is shown in Figure 5. During this period, the maximum, minimum and average annual rainfall were 1527, 393 and 880 mm, respectively. Daily rainfall data covering the study period were collected from about 150 stations maintained by the Karnataka State Natural Disaster Monitoring Cell (KSNDMC) for the period January 2015–October 2017. The spatial distribution of these KSNDMC rainfall gauges is shown in Figure 1. A plot of monthly rainfall averaged over these stations is shown in Figure 6. Total rainfall (January–December) for the years 2015, 2016 and 2017 (up to October 2017) was 1153, 716 and 1435 mm. The intra-year rainfall distribution during these three years has strong variability, and each year was quite different. In all three years, the southwest monsoon rainfall was much lower than normal. However, during 2015 and 2017, there were extreme rainfall events, while 2016 was a drought year. In 2015, the months of September–November produced about 50% of the annual rainfall. In 2016, the months of May–July produced about 70% of the annual rainfall. In 2017, the months of August–October produced about 75% of the annual rainfall. The 2017 rainfall was close to the highest received rainfall in more than 100 years. These patterns of drought conditions and extreme rain events over the study period provided a natural opportunity to study the response and resilience of Bengaluru's groundwater system.

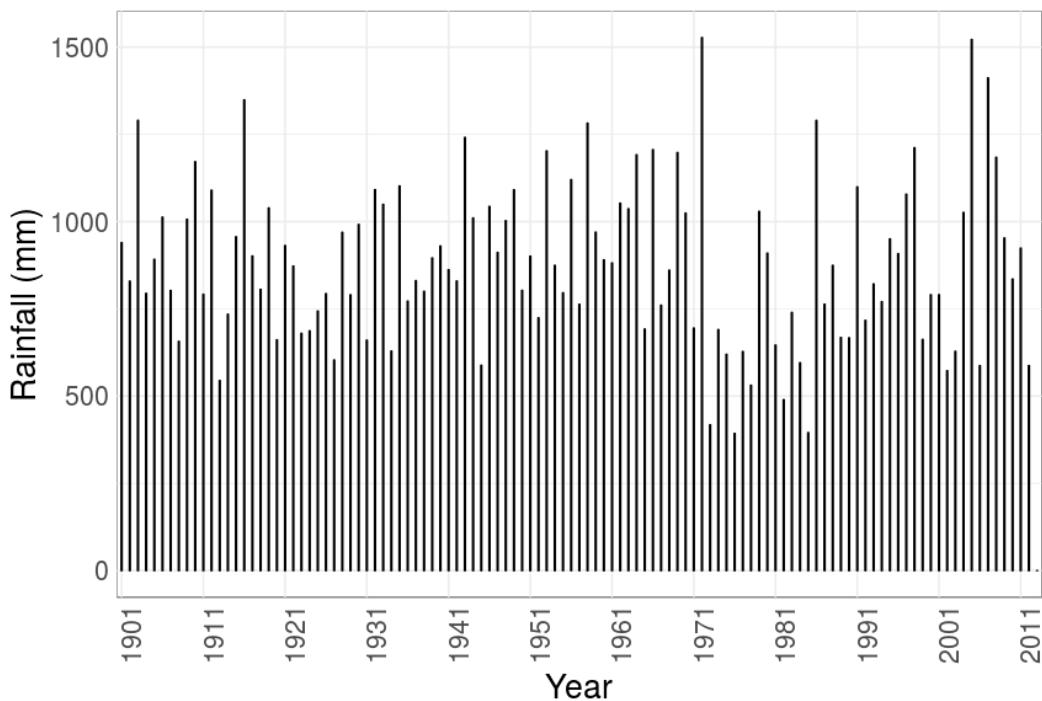


Figure 5. Annual rainfall in Bengaluru during 1901–2012.

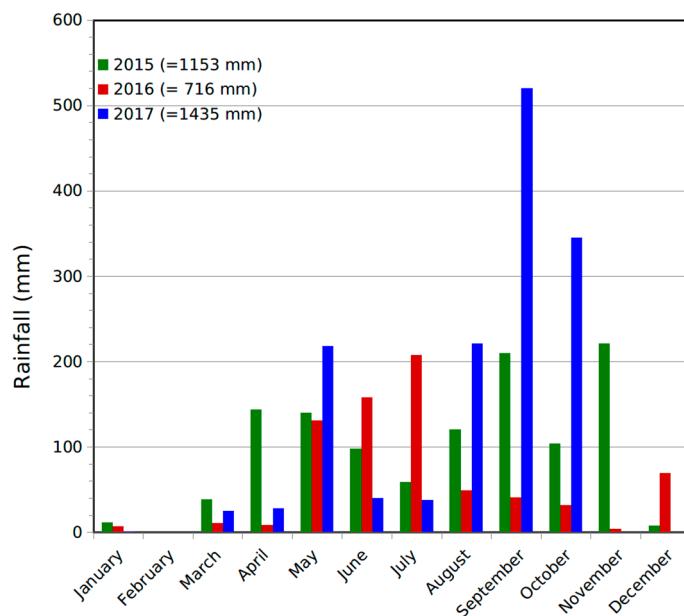


Figure 6. Monthly rainfall patterns in Bengaluru city during January 2015–October 2017.

2.4. Cluster Analysis

In order to aid the interpretation of observed groundwater patterns, a clustering analysis was performed using the secondary data in Table 1. Hierarchical cluster analysis was applied to explore the number of distinct clusters emerging from the secondary data. Ward's linkage algorithm is used for hierarchical clustering by minimizing the increase in total within-cluster sum of squared error [32]. The optimal number of clusters were identified by visual inspection of the resulting dendrogram.

2.5. Groundwater Analysis

The Water Table Fluctuation (WTF) method was used to estimate the storage change, natural recharge and net outflow for distinct periods of observation. The advantage of the WTF method, described comprehensively in Healy and Cook [33], is that it is a simple method that relies on dense groundwater level measurements, has only one parameter (the specific yield), and no assumptions are made on the mechanisms by which water recharges the aquifer. The WTF method is used in India for operational annual groundwater recharge assessment by government agencies [34]. Nationally, it is performed by delineating the land area into watersheds or catchments with an area of about 600–1000 km². This scale is tied to the density of long term observation network which is approximately one observation well per 100 km². Recharge assessment for a year is performed for each of these catchments, treating them as one unit or cell. Several researchers have used variations of the WTF method in southern Indian hard-rock aquifers [15,21,22,35]. We use WTF in two ways in this paper, described below.

2.5.1. Natural Recharge and Net Outflow

First, we use the “double water table fluctuation method” [15], which involves splitting the groundwater budget into two distinct periods—dry and wet. These authors used the double WTF method in combination with water balance models and detailed information on several water balance components in a 50 km², unconfined hard rock aquifer research site in southern India, to estimate both recharge and the effective specific yield [15].

In this paper, we apply the double WTF method to estimate rainfall recharge and total net outflow in the same manner as Sekhar et al. [21] did for the town of Mulbagal (mentioned in the Introduction). Because many components of the budget are not known quantitatively for Bengaluru (pumping, and water and wastewater leakage), we use the double WTF to estimate only the rainfall recharge factor (from the wet period), and the net outflow (from the dry period). For the same reason, we cannot independently estimate specific yield as Maréchal et al. [15] did. Instead, we specify specific yield based on the literature and recent experience, and also show the sensitivity of some of our results to this parameter.

The double WTF method is expressed as follows:

$$S_y \frac{\Delta h}{\Delta t} = R - Q_{net} \quad (1)$$

where S_y is the specific yield (-), h is the groundwater level (L), t is time (T), R is recharge due to rainfall (LT^{-1}), and Q_{net} is the net outflow,

$$Q_{net} = Q_{out} - Q_{in} \quad (2)$$

where Q_{out} is the total outflow including baseflow, lateral flow and draft. Q_{in} is the recharge to groundwater from anthropogenic flows, i.e., leaking water supply and wastewater systems (LT^{-1}).

Given the value of S_y and measurements of Δh , Equation (1) has two unknowns. The equation was written for dry (no or insignificant rainfall) and wet (significant rainfall) periods separately, with the assumption that there was no rainfall recharge during the dry period. After solving both equations, net outflow and rainfall recharge can be computed as,

$$Q_{net} = \frac{-h_y \Delta h_{dry}}{\Delta t_{dry}} \quad (3)$$

and

$$R = \frac{S_y \Delta h_{wet} + Q_{net} \Delta t_{wet}}{\Delta t_{wet}} \quad (4)$$

Equation (3) is solved first to estimate the Q_{net} by applying it over the dry period where Δt_{dry} is the length of dry period (T). Then, Equation (4) is solved over the wet period where Δt_{wet} is the length of wet period, to estimate R .

2.5.2. Changes in Groundwater Storage

For the net change in groundwater storage in 2016, and from the extreme rainfall months in 2017, the simple form of the WTF is used.

$$\Delta V = S_y \Delta h \quad (5)$$

where ΔV is the net storage change (L) and Δh is the change in groundwater level (L) over a specified period (Δt) (T).

3. Results and Discussion

3.1. Clustering Results

Five variables, as presented in Table 1, were used for the cluster analysis. To account for the location, the distance of each grid from the central grid (#12) was also used in the cluster analysis. Details of the clusters formed are presented in Figure 7 and Table 2. Figure 7a shows the dendrogram obtained from the six variables, which could organize the city into four clusters quite sensibly. The spatial distribution of these four clusters is shown in Figure 7b. Cluster 1 is characterized by the outer periphery, which has significant open space, less water supply from BWSSB and significant groundwater usage. Detailed water supply analysis in [26,36] illustrate that the fast-growing outer areas receive much less water supply than the core areas. Cluster 2 is the inner periphery characterized by moderate groundwater usage, moderate supply of water from BWSSB and moderate open space. Cluster 3 contains grids lying in the central, older parts of the city, which has better water supply from the BWSSB and is densely built-up. Cluster 4 is similar to Cluster 3, except that it has high population density and hence water demand is high and not met by the water supply from BWSSB.

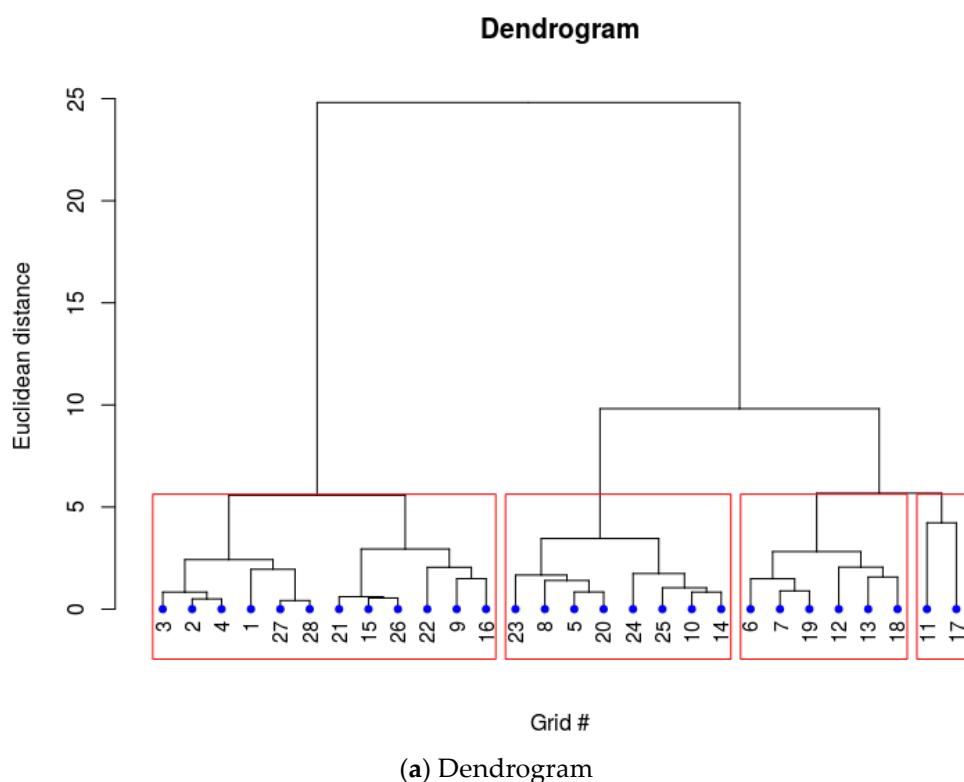
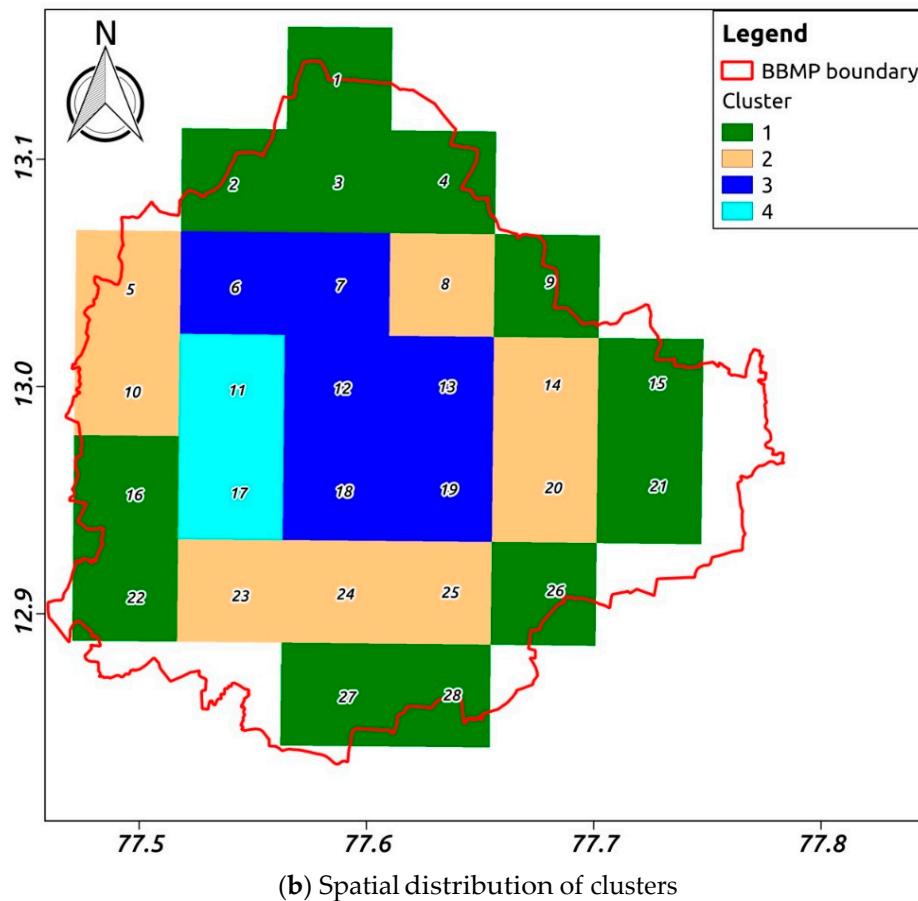


Figure 7. Cont.



(b) Spatial distribution of clusters

Figure 7. Dendrogram and spatial distribution of the clusters obtained from Ward's Linkage algorithm.

Table 2. Details of the clusters formed.

Cluster ID	Grids	Description
1	1, 2, 3, 4, 9, 15, 16, 21, 22, 26, 27 and 28	Outer periphery, lower population density, significant open space, less water supply from BWSSB
2	5, 8, 10, 14, 20, 23, 24 and 25	Inner periphery, moderate population density, moderate open space, moderate water supply from BWSSB
3	6, 7, 12, 13, 18 and 19	Older city core, moderate population density, lower open space, better water supply from BWSSB
4	11 and 17	Highest population density, lower open space, better water supply from BWSSB

3.2. Groundwater Levels and Dynamics

All groundwater level data collected in various monitoring wells during the period of the study are publicly available (see Supplementary Materials). For the 154 wells over 22 months (December 2015–September 2017), DGW varied from 1 to 72 m, with a mean of 25.74 m and standard deviation of 13.98 m. Figure 8 shows the box and whisker plot of all 154 wells over time. The start in the rise in groundwater level matches with the onset of monsoon season and the shallowest groundwater levels were observed in the peak rainfall month. In 2016, shallowest groundwater is observed in August, while, in 2017, it is observed in September. The groundwater table is deepest in peak summer, in the month of April 2016. It is also deep in April 2017, but the lateness of the 2017 monsoon extended the dry period, resulting in the groundwater table in July 2017 being slightly deeper than that in April 2017. Extremely high rainfall occurred immediately after the dry spell, in August (221 mm) and September

(520 mm) 2017. The boxplot shows the groundwater table recovering quite dramatically in response to this extreme rainfall. This extreme rainfall response is investigated further in Section 3.4.

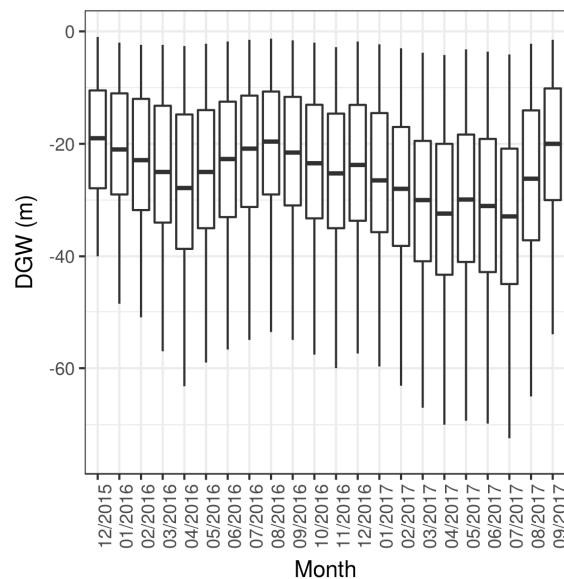


Figure 8. Box and whisker plot of the DGW of all 154 wells during December 2015–September 2017. The horizontal line within the box indicates the median and boundaries of the box indicate the 25th and 75th percentile. The upper whisker extends from the hinge to the largest value and the lower whisker extends from the hinge to the smallest value.

Figure 9 shows the box and whisker plot for 154 wells grouped into the four clusters. Groundwater levels showed substantial spatial and temporal variability in all clusters. A relatively lower variability was observed in Cluster 4 due to less number of grid and data points in this cluster. Mean depths to groundwater table of 29.27 m, 26.22 m, 17.30 m and 23.14 m were observed in Clusters 1–4, respectively. All clusters showed similar temporal variation, as described above. Cluster 3 shows the shallowest groundwater level, which lies in the inner part of the city. This could be due to relatively higher leakage from the sewerage and water supply lines. Cluster 4 showed relatively deeper groundwater level compared to Cluster 3, due to higher water demand (higher population). Cluster 1 showed the deepest groundwater level due to less water supply from BWSSB and high groundwater draft.

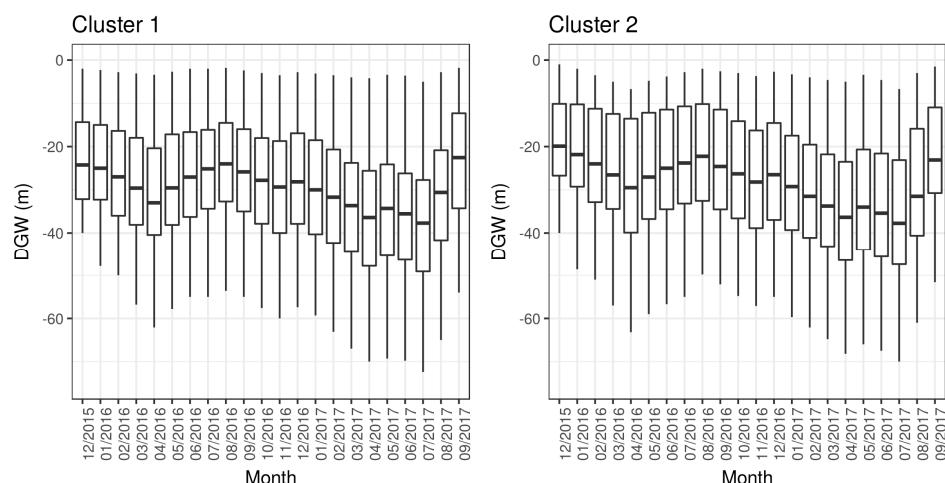


Figure 9. Cont.

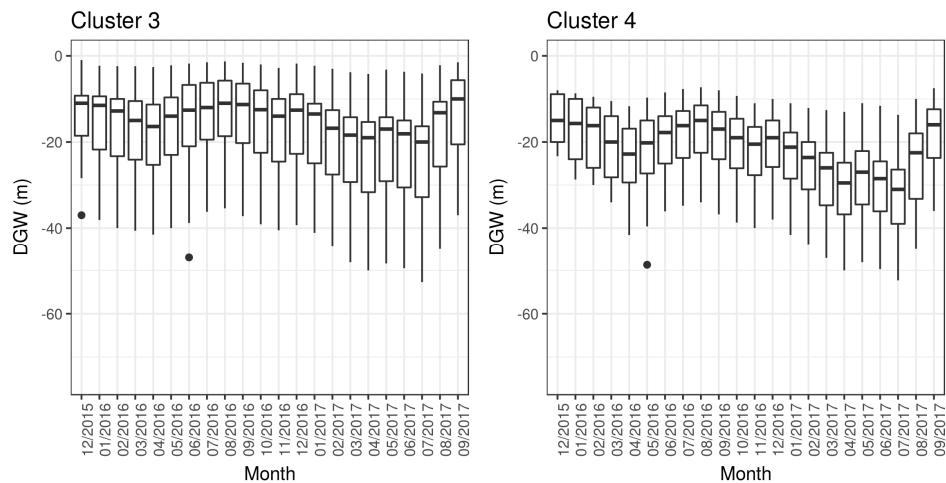


Figure 9. Box and whisker plots of the depth to groundwater (DGW) of all 154 wells during December 2015–September 2017. The horizontal line within the box indicates the median and boundaries of the box indicate the 25th and 75th percentile. The upper whisker extends from the hinge to the largest value no further than $1.5 \times IQR$ (Inter-Quartile Range) from the hinge. The lower whisker extends from the hinge to the smallest value at most $1.5 \times IQR$ of the hinge. Data beyond the end of the whiskers are called “outlying” points and are plotted individually by filled circle.

Kriged maps of the groundwater table were produced for each month from December 2015 to September 2017. For the monthly variograms used in creating the interpolated maps, the nugget varied from 31.7 m to 127.9 m, partial sill varied from 63.2 m^2 to 132.0 m^2 and range varied from 1.65 km to 5.44 km. As an example, Figure 10 shows the variograms for two months of 2016. The nugget quantifies the small scale variability present in the data at lag below the average minimum distance among observations. The presence of nugget indicates that a higher small scale spatial variability is present in groundwater level compared to the monitoring network. Studies performed in similar lithology, climate context and scale showed the presence of nugget in an urban catchment (in Mulbagal) [21] and an absence of nugget in agricultural catchments [37]. As suggested by Sekhar et al. [21], the possible reason for the higher small scale variability could be the influence of anthropogenic effects in urban catchments. These variograms suggest that a denser monitoring could be tested in the future, to investigate if, at least in some areas of the city where the nugget is particularly high, an even denser monitoring network is needed. The sill in the variogram indicates the variance in the data. These variograms shows a higher sill when deeper groundwater levels are observed (see Figure 10a) and lower sill when shallowest groundwater levels are observed (see Figure 10b).

Maps of the groundwater table for a few months are presented in Figure 11. The color legend shown for groundwater level is same across the maps to facilitate comparison. Significant spatial variability in the water levels drawdown and rises are observed in different dry and wet months. Typically, groundwater levels are deeper in April (see DGW for April 2016 in Figure 11) following recession from the previous October (i.e., post-monsoon period). However, in 2017, the deepest groundwater levels in any part of the city were recorded as late as July 2017, because 2016 was a drought year and the monsoon, which typically begins in June, was delayed in 2017.

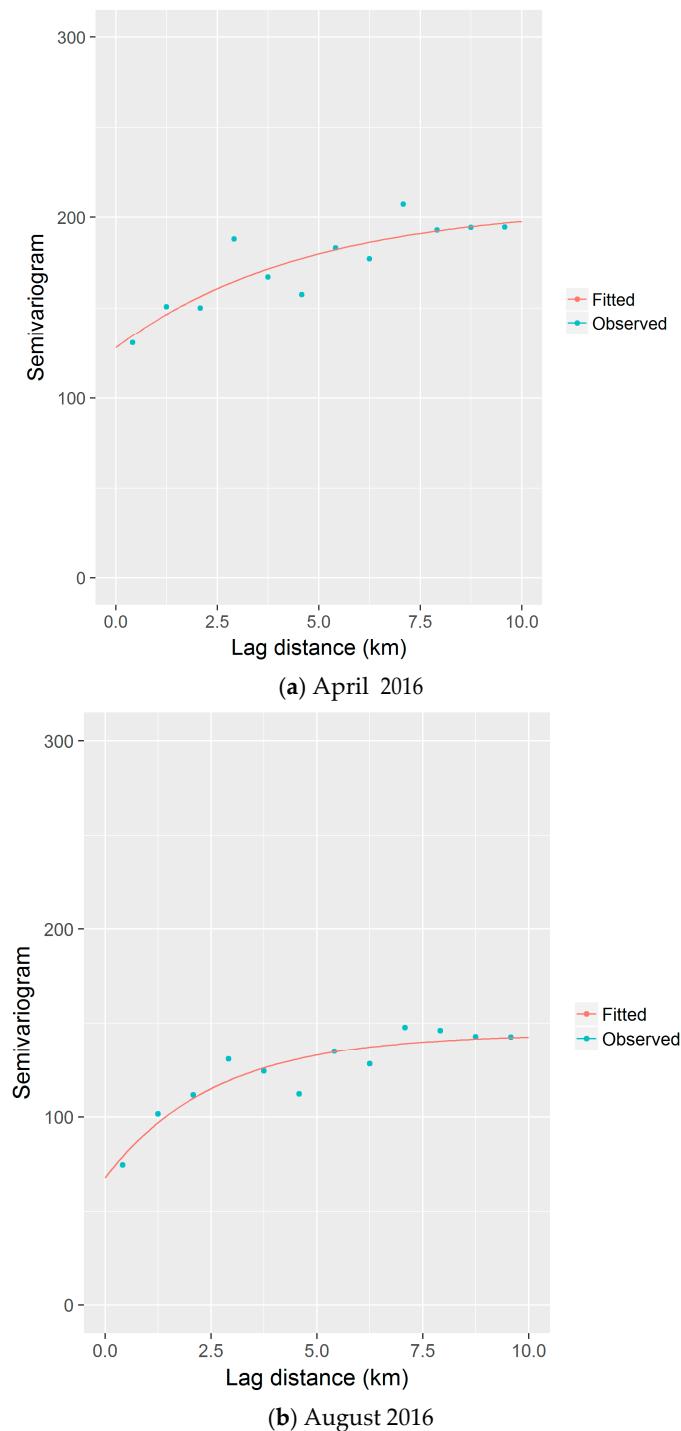


Figure 10. Experimental and fitted exponential variogram for April and August in year 2016.

Most of the grids of Cluster 1 showed relatively deeper groundwater levels, while most of the grids of Cluster 3 showed a relatively shallow groundwater level. The shallow levels in these grids are unaffected even by drought year of 2016 (see April 2016 and July 2016 maps in Figure 11). Shallow groundwater levels in these older, core areas of the city were also observed in a 2009 sampling of 472 wells in central Bengaluru [22]. The secondary data-informed clustering supports the narrative that the shallow groundwater levels in the inner part of the city (Cluster 3) are due to lower groundwater use combined with greater recharge leakage from water and waste water systems in the city. On the

contrary, the reason for deeper groundwater levels in the outer areas of the city is due to higher groundwater extraction in the absence of water supply from the water utility agency, the BWSSB. The topography of the city is such that the city center sits at higher elevation, while the newly growing peripheries are at lower elevation. Figure 11 therefore suggests that the lower-lying peripheries have deeper groundwater table than the higher-lying, older city core. This suggests that at a local scale the groundwater behavior is non-classical, i.e., the groundwater is relatively deeper in the valleys than the higher topographic relief. This non-classical behavior of groundwater levels in the valleys points to a deepening of the hydraulic gradient, which could result in greater lateral flows from the city center to periphery areas.

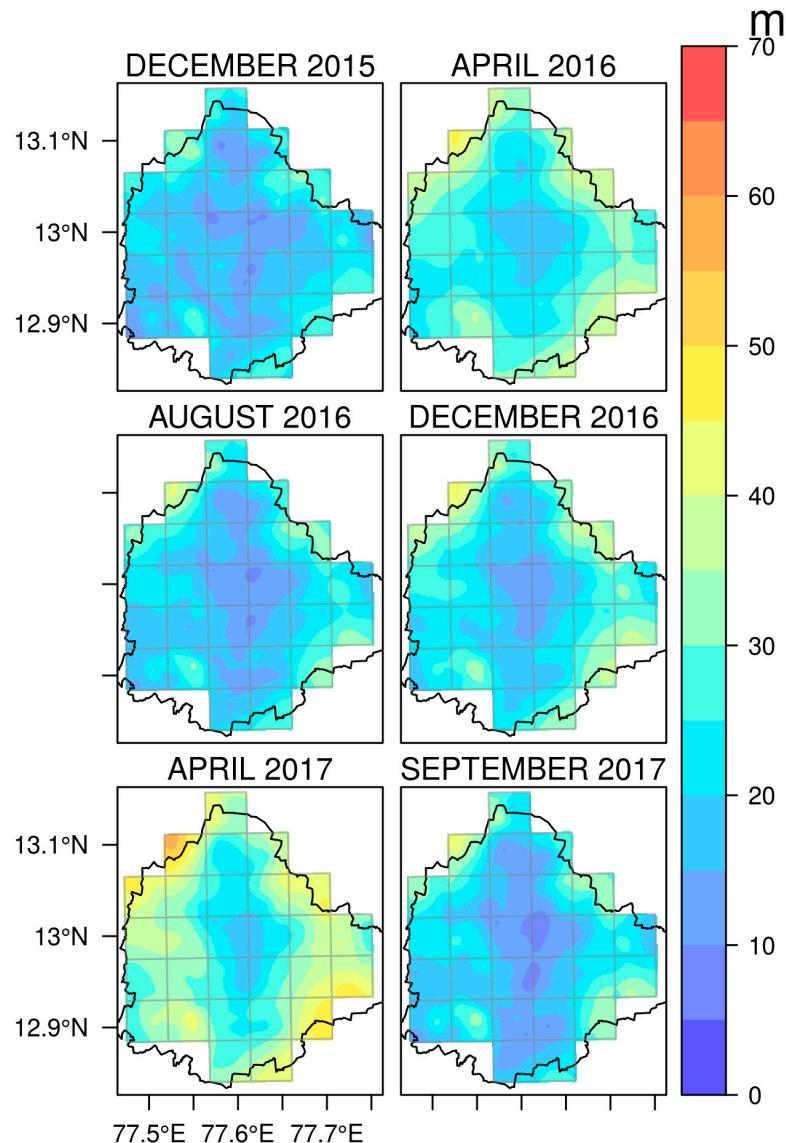


Figure 11. Interpolated depth to ground water table for selected months during December 2015–September 2017.

3.3. Rainfall Recharge and Net Outflow

Groundwater balance was estimated using Equations (3) and (4) over 154 monitoring wells. There was insignificant rainfall during January–February (see Figure 6) and it was assumed as dry period. The remaining 10 months (March–December) of 2016 were taken as the wet period. A sensitivity analysis of specific yield to rainfall recharge was performed by varying specific yield from 0.001 to 0.1. The range

of specific yield was taken based on the experiments in similar hard rocks (e.g., [21,30]). The natural rainfall recharge factor (annual recharge/annual rainfall) was computed using Equations (3) and (4) for each value of specific yield and is plotted in Figure 12 along with the spatial variability over 154 monitoring wells. The spatial variability in the rainfall recharge factor (RF) increases with the increase in Sy, as expected (refer Equations (4) and (5)). At a Sy of 0.005, the RF is 13.5%, which is close to the range observed in the literature in hard rock, e.g., 15.6% by Maréchal et al. [30], 13–19% by Maréchal et al. [15] and 8.6% by Sekhar et al. [21]. The RF value used by the CGWB for hard rock aquifers is 12% [15]. The RF values used and estimated by these researchers provide a reasonable constraint to the very wide range illustrated in Figure 12. A value of 0.005 was taken as a reasonable assumption of effective specific yield for further analysis.

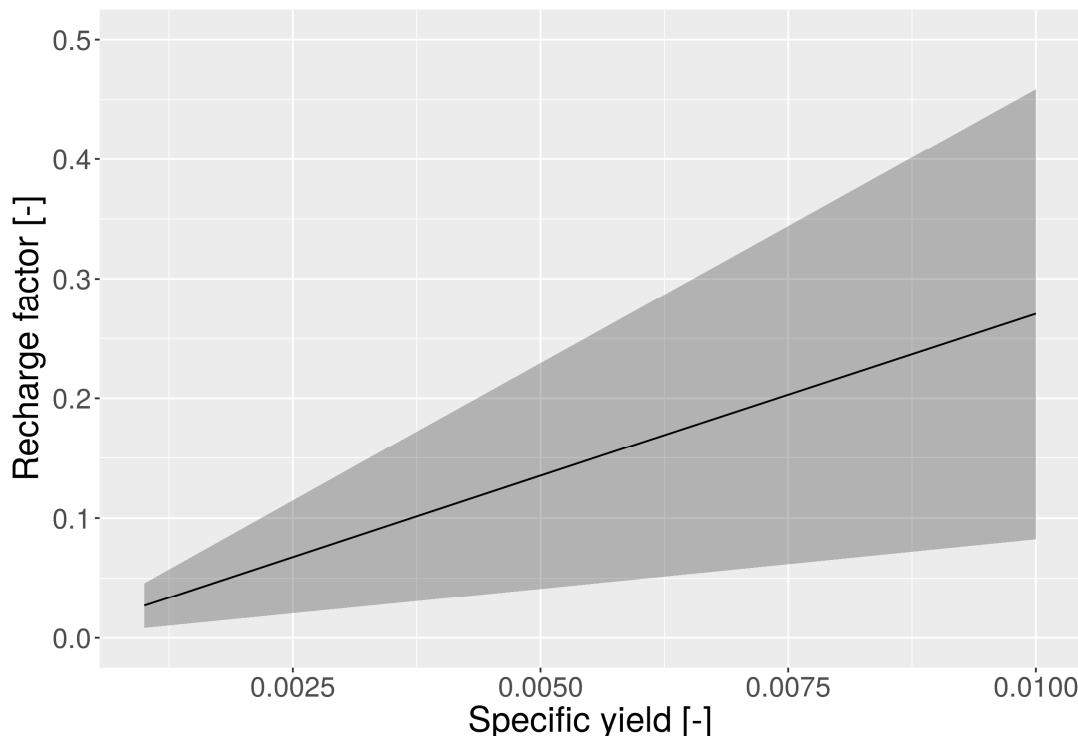


Figure 12. Sensitivity analysis of rainfall recharge factor (RF) to specific yield. Shaded region shows the spatial variability over 154 monitoring wells.

Using Equation (3), Q_{net} was estimated to be 123.8 mm with a standard deviation of 82.6 mm and, using Equation (4), R was estimated to be 96.9 mm with a standard deviation of 67.4 mm. The standard deviation was computed over 154 monitoring wells. Table 3 shows the mean and standard deviation of computed Q_{net} and R over 154 wells for different clusters. Clusters 1 and 2 shows the highest mean values of Q_{net} and R , and a similar mean value of net storage change. These are periphery areas, with relatively higher open space conducive to more infiltration and rainfall recharge. Cluster 3, covering the core central areas, shows the lowest mean values of Q_{net} and R . These areas are densely built-up, explaining the low R . One hypothesis for the contrasting behavior of Q_{net} in central versus periphery areas, as articulated in [25,36] and also suggested by the clustering, is the differential forcings of anthropogenic recharge from leaking water and wastewater versus pumping. In periphery Clusters 1 and 2, Q_{net} is likely high because of more groundwater use compared to the central Cluster 3, which is better connected to surface water supply.

The difference between the net outflow and recharge listed in Table 3 gives the net change in groundwater storage. As can be seen, in 2016, using the 154 well observations, the net change in groundwater storage is negative in all clusters, i.e., groundwater depletion occurred, as is also apparent

in the boxplots presented in Figures 8 and 9. The net storage change is most negative in Cluster 4, indicating more groundwater usage and outflow compared to the recharge, as this cluster has lowest open space and highest water demand (highest population density). Cluster 4 shows the lowest spatial variability due to fewer grids falling in this cluster.

Annual groundwater storage change was computed using the 154 well data and interpolated GWD maps for January 2016 and January 2017 in Equation (5). The change in the groundwater level over this period is shown in Figure 13. Since 2016 was a drought year for Bengaluru city, a significant depletion in the groundwater was observed in entire area except some parts of central Bengaluru (close to grid 12) where a rise of up to 2 m was observed. This area is also highlighted in Mehta et al. [26] who used data from a relatively long-term CGWB monitoring in this area to show the steady rise in GWL over time, and attributed it to the dominance of anthropogenic recharge over pumping. In all other areas, the figure indicates that, due to poor rainfall in 2016, the groundwater level declined by about approximately 12 m in some of the grids, mostly in the outer parts of the city. Estimated mean water storage depleted in the 700 km^2 area of the city for 2016 was about 26.9 mm (18.8 million cubic meters) based on the data of 154 wells and 26.2 mm (18.3 million cubic meters) based on the interpolated data. The standard deviation over space was found to be about 18 mm based on the data of 154 wells and 11 mm based on the interpolated data. The lower estimate of standard deviation from kriged data could be due to the presence of nugget in the variogram, which smoothens the data.

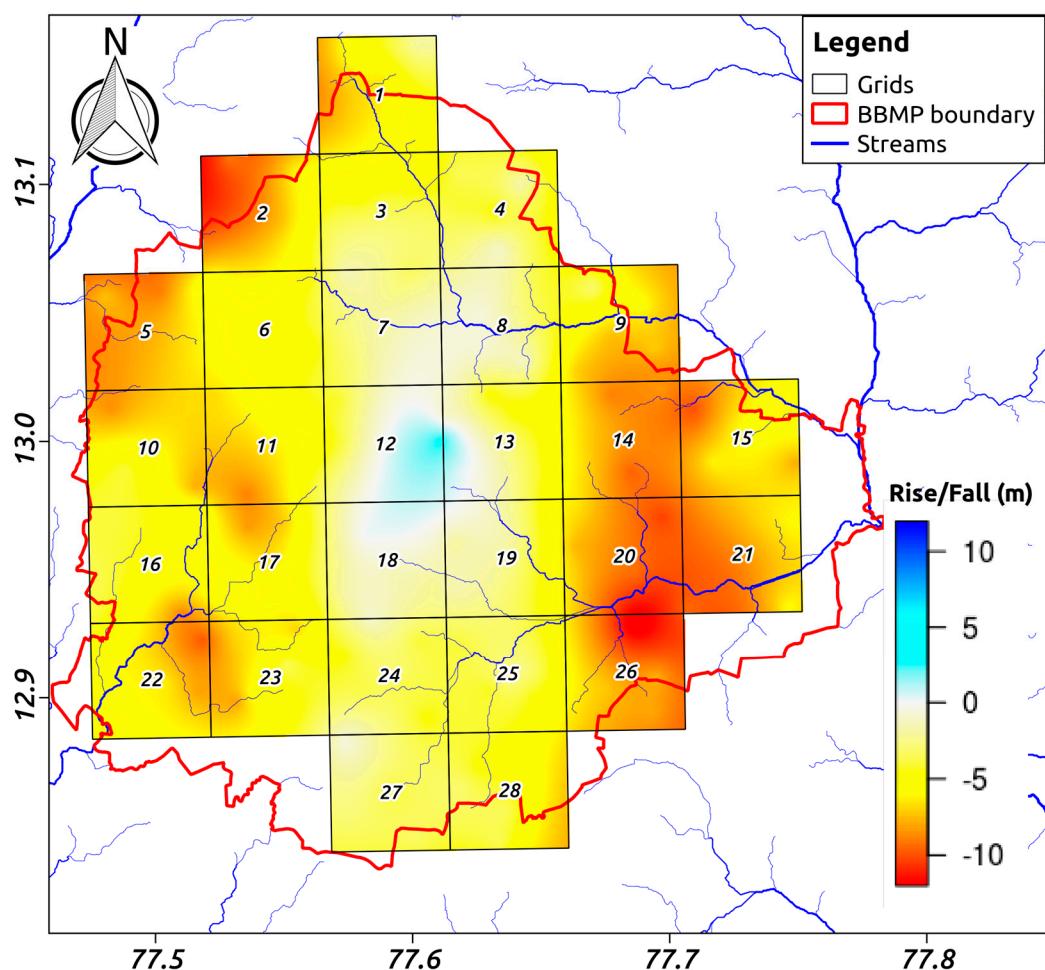


Figure 13. Difference in the groundwater level between January 2017 and January 2016. Positive numbers indicate rise, and negative numbers indicate fall.

Table 3. Mean and standard deviation of the R , Q_{net} and net storage change ($R - Q_{net}$) over 154 wells for all the clusters. Numbers in brackets represent the standard deviation.

Cluster ID	Q_{net} (mm)	R (mm)	$R - Q_{net}$ R (mm)
1	128.89 (84.26)	100.79 (69.22)	-28.10
2	138.33 (89.12)	108.79 (73.05)	-29.54
3	86.00 (69.08)	72.69 (59.89)	-13.31
4	118.85 (46.31)	84.46 (34.78)	-34.39

3.4. Extreme Rainfall Response

A total of 740.7 mm rainfall was received during August–September, 2017. The recharge from these extreme rainfall events over these two months was estimated using Equation (5). Figure 14 shows the differenced groundwater level map between July 2017 and September 2017. Interestingly, the highest rise is observed in outer grids (Cluster 1) and lowest rise is observed in inner grids (Cluster 3). These outer clusters are in low-lying areas, whereas the central areas are at higher elevation and more densely built-up. A higher fraction of extreme rainfall likely runs off towards the outer areas, where relatively more recharge from the extreme rainfall occurs.

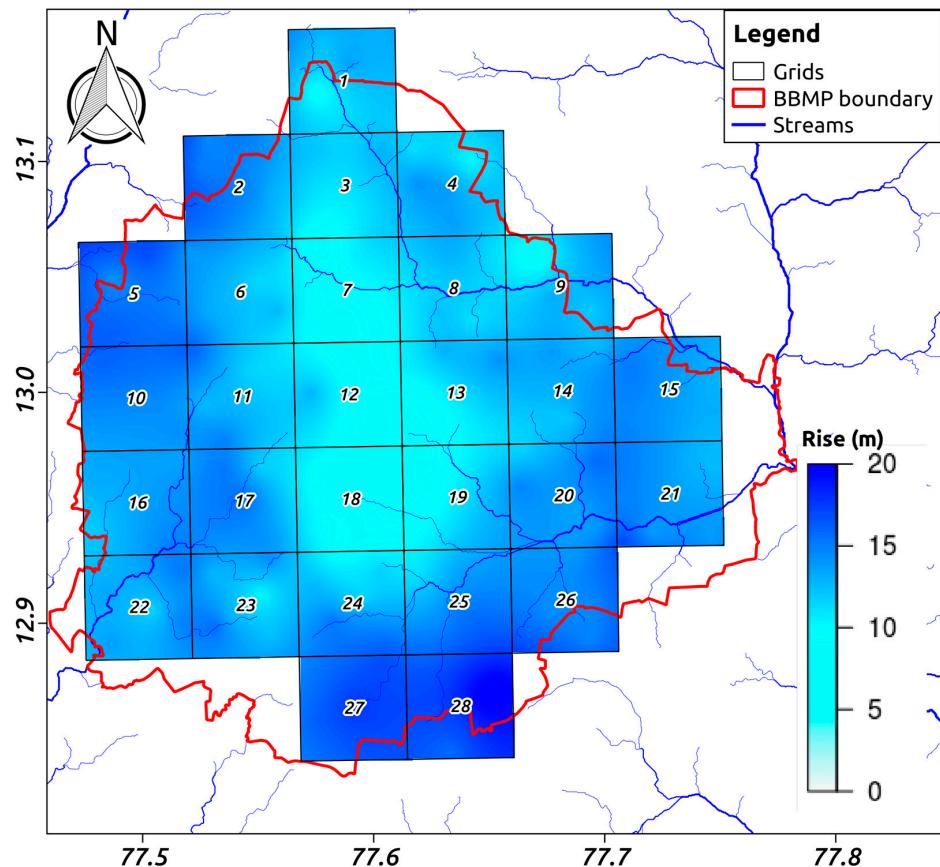


Figure 14. Rise in the groundwater level from July 2017 to September 2017.

The boxplots (Figure 8) show that GWLs were falling in 2017 through June and July, when monsoon rains were less than normal. Interestingly, the data also show that the extremely high rainfall that immediately followed, during August–September 2017 (see Figure 6), resulted in a quick recharge of groundwater levels in all the stations spread over the city. Average rise in GWL in September 2017 from that of July 2017 was 13.3 m across 154 monitoring wells, while the lowest recorded was 2.6 m

(in grid 19) and highest recorded was 24.2 m (in grid 28). The mean rise of 13.3 m due to the rainfall during August–September 2017 had a relatively low standard deviation (over space) of about 4.0 m. During this period, a mean recharge of 66.5 mm for the entire city and a peak recharge of 121 mm (in Grid 28) in some areas were observed. The mean recharge estimate based on the kriged map data also showed nearly the same mean estimate (65.4 mm). However, there was significant difference in the standard deviation over space, 20 mm over 154 wells versus 8.29 mm from interpolated data, owing to the presence of nugget in the data. These two months resulted in a net recharge (increase in net groundwater storage) of about 46.6 million m³ (or 46.6 billion liters) in the 700 km² of the city.

The recharge generated by these extreme events (rainfall of August–September 2017) is similar to the annual recharge in some agricultural areas in semiarid tropical conditions [15,30]. This suggests that groundwater recharge from extreme rainfall is quite significant in Bengaluru, despite being predominantly built-up. In the literature, significant recharge events from extreme precipitation have been reported [38–40] in agricultural regions. In urban areas, however, the conventional narrative is that groundwater recharge is impeded by the dominance of built-up, impervious areas (e.g., [27]). Our observations suggest that, also in urban regions, extreme events can play a major role in groundwater recharge. We hypothesize that these recharge conditions are significantly different from those in agricultural areas, where the recharge is often as a non-point source recharge, i.e., recharge distributed across large areas, such as fields. In urban areas, such non-point source recharge is not feasible due to altered land surfaces in the form of paved surfaces and buildings. However, increased runoff from these altered land use conditions caused localized flooding conditions, during extreme rainfall events. Compounded by the poor storm water drainage conditions in urban cities, the flood waters have higher residence times, which result in recharge through pathways such as construction pits, ponds, storm water drains, and rainwater harvesting structures—the “indirect recharge pathways” that Lerner [4] alludes to as one of the impacts of urbanization. Hence, the recharge would be substantial, and quick, as observed here.

4. Conclusions and Future Improvements

In this paper, we have described the monitoring network and groundwater dynamics across a city, highlighting some of the key findings. First, estimates of groundwater storage changes were made using a simplified, vertical balance. The monitoring will be continued until December 2017. This will provide an opportunity to make groundwater level observations for two monsoon and two non-monsoon seasons during the study period.

One limitation of this study is that only a vertical and simplified estimate of net outflow was made. This net outflow term aggregates both natural and anthropogenic components. To understand the urban groundwater budget more completely, a more elaborate modeling framework would need to include the magnitude of lateral flow and baseflow, for example, as well as the socioeconomic and infrastructural variables that inform the anthropogenic forcings of recharge from leaking pipes and return flows, and draft from pumping. We are working on such a framework, which is briefly described below.

Park and Parker [41] developed a physically based lumped model to simulate groundwater fluctuations in response to precipitation. This model is applicable to estimate groundwater recharge from the observed groundwater level fluctuations as well as groundwater discharge or underflow. One of the limitations of the Park and Parker model is that no external sources or sinks other than uniformly distributed precipitation was considered. Hence, if groundwater pumping exists, then the model needs a suitable adaptation. To use this model for regions with groundwater pumping conditions, Kumar [42] improved the model by taking groundwater pumping into account, which was tested for various conditions by Subash et al. [16]. This improved model (ambhasGW) is available in R (<https://cran.rproject.org/package=ambhasGW>) for ease of use and to estimate parameters of recharge, discharge, and specific yield from the time series of groundwater level observations. The model provides balance terms of recharge, underflow (or groundwater discharge) and pumping as

output. We are currently working on applying this model, and collecting additional socioeconomic and infrastructure data to inform it. To account for the considerable uncertainty in the anthropogenic forcings, we will be applying a formal uncertainty framework, the Generalized Likelihood Uncertainty Framework (GLUE), with the model [43].

More work will be needed to establish the evidence base for these future model outputs. For example, the source of the recharge to groundwater in urban areas could be identified through water chemistry and solute mass balance methods [44,45].

Sustainable groundwater management in Bengaluru must account for substantial spatial socio-hydrological heterogeneity. Continuous monitoring at high spatial density will be needed to inform evidence-based policy. Variables in addition to groundwater levels will need to be monitored for identifying sources and flow paths, and linked to their possible anthropogenic drivers.

Supplementary Materials: The data used in the analysis is available at <http://bangalore.urbanmetabolism.asia/geoportal/>.

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Author Contributions: M. Sekhar and Vishal K. Mehta conceived and designed the experiments; M. Sekhar led the groundwater measurements campaign; M. Sekhar, Sat Kumar Tomer and Vishal K. Mehta analyzed the data and wrote the paper; S. Thiyaku and Sanjeeva Murthy performed the GIS processing and mapping; P. Giriraj and Sanjeeva Murthy measured the groundwater levels; and Vishal K. Mehta was the principal investigator of the research project.

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