Chapter 3
Estimating Present-Day Groundwater Recharge Rates in India

Abhijit Mukherjee and Soumendra Nath Bhanja

Abstract Large number of people in the globe depends on groundwater as a major source of freshwater. Here, we provide present-day regional-scale groundwater recharge rates in a major part of the Indian subcontinent. We have used a combination of ground-based observed water level data obtained from an intense network of observational wells, along with satellite and global land-surface model-based outputs to calculate our estimates. Large variations were observed in the spatial groundwater recharge rates over the region based on geology and climate. High groundwater recharge rates (>300 mm/year) are observed over the highly fertile alluvial plains of Indus–Ganges–Brahmaputra (IGB) system. Comparatively higher rate of precipitation, high porosity and permeability of the unconsolidated fluvial deposits and rapid groundwater withdrawal (>90% of groundwater withdrawal are associated with irrigation) synergistically influence high recharge rates. Most of the regions on the central and southern study areas exhibit lower recharge rates (<200 mm/year). Magnitude of estimated recharge rates was quite similar from different approaches of groundwater recharge calculation; however, inconsistency in the output of different approaches over some of the regions is discussed herein.

Keywords Groundwater recharge · Indian subcontinent · Water table fluctuation Water budget

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3.1 Introduction

Groundwater is the largest source of freshwater available in the globe. Large number of people solely depends on groundwater to fulfill their requirement of potable water (Bates et al. 2008). The number will increase further as the population continues to increase. However, the balance between global groundwater depletion rates with natural renewal rate is still unclear (Gleeson et al. 2012). Therefore, groundwater resource quantification is a solemn issue in the densely populated regions of the globe, where it is a challenging task to provide adequate amount of water to every citizen of present and future. Thus, as a component of groundwater resource quantification, groundwater recharge estimation became important in recent times. The downward movement of water reaching water table can be termed as groundwater recharge, which ultimately increases the amount of groundwater storage (Healy 2010).

Intense agricultural activities in parts of the densely populated Indian subcontinent are highest in the world in terms of percentage of irrigated land (Siebert et al. 2013). More than 50% of the irrigational water demand has been fulfilled by abstracting groundwater (CGWB 2009). World Bank (1998) and Ministry of Water Resources, Government of India, estimated approximately 9% of India's GDP has come from groundwater. However, so far, only few studies (Goel et al. 1975; Bhandari et al. 1982; Athavale et al. 1992; Rangarajan et al. 1995, 1997, 1998; Athavale et al. 1998; Rangarajan and Athavale 2000; Scanlon et al. 2010) have reported groundwater recharge rates in some sporadic locations (Fig. 3.1). Highest groundwater stress has been indicated on upper Ganges aquifer of India and Pakistan among all the global aquifers (Gleeson et al. 2012). Although, groundwater is an annually renewable resource but the rate and space of renewal are extremely heterogeneous and anisotropic in time and space.

Difficulties in direct measurement of groundwater recharge and its enormous temporal and spatial variation account for the complexity in recharge rate estimation processes (Healy 2010). In absence of availability of high resolution, local-scale datasets for aquifer properties, climatic parameters, and other influencing factors that could be used in a complicated calculation of recharge, a simple method like WTF has been preferably used in many studies because of the minimal assumptions associated with it. Recharge estimation techniques based on observed groundwater data collected below the water table or piezometric surface provide actual recharge rates (Rushton 1997; Scanlon et al. 2002). Out of these, in spite of several limitations, water table fluctuation (WTF) method might be the most widely used technique for estimation of groundwater recharge (Healy and Cook 2002). Moreover, WTF method can be successfully executed over a large area (Healy and Cook 2002), simultaneously.

Recharge can be estimated by balancing all of the hydrological components in the form of input and output of water by water budget method. Scanlon et al. (2002) extensively described balancing techniques between various hydrologic parameters; however, lack of accurate measurement of hydrologic parameters introduces errors

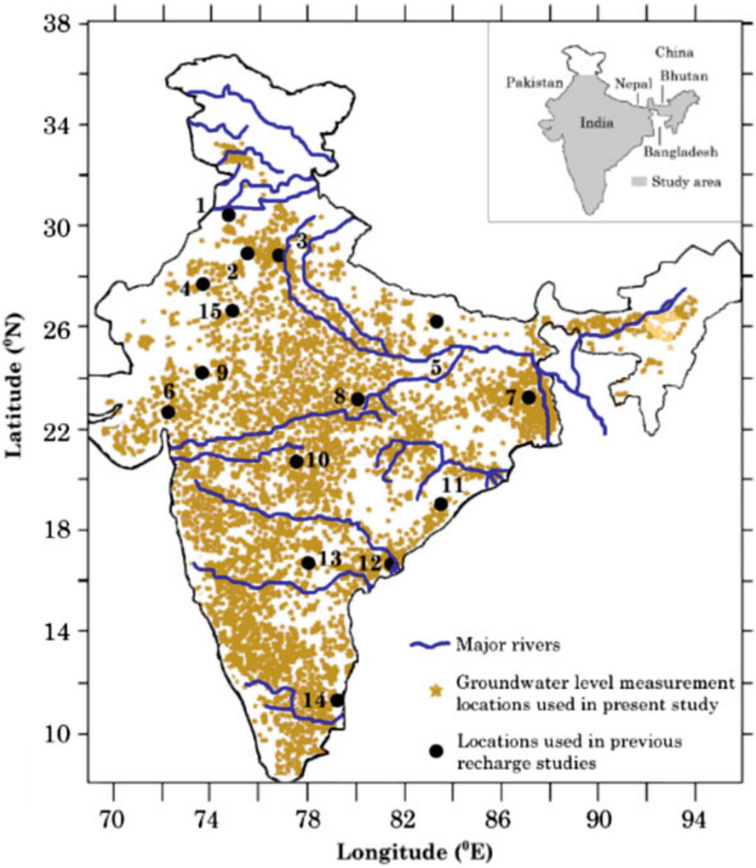

Fig. 3.1 Map of the study area showing locations of groundwater level measurement that are used in this study. Groundwater recharge estimates using chemical tracer method in 15 different locations obtained from previous studies are marked with black filled circles. The numbers beside these locations correspond to serial numbers in Table 3.1

in the recharge estimation through water budget method. As recharge rate is small compared to most of the other influencing parameters, particularly evapotranspiration, small uncertainty in these parameter values can create enormous error in recharge estimation. Therefore, some authors (e.g., Gee and Hillel 1988; Lerner et al. 1990; Hendrickx and Walker 1997) questioned about the usefulness of water budget methods. However, recent advancement in geophysical techniques, remote sensing, and modeling has lowered the magnitude of error; hence, the simplistic water budget method becomes the backbone of most of the hydrological modeling studies (Healy 2010). This recharge process can be termed as direct recharge by meteoric inflow only (Mukherjee et al. 2007), as it deals with the precipitated water and neglects any other type of inflows.

In this study, groundwater recharge is estimated for the present time for a large part of the densely populated India (Chap. 1, Fig. 1.1) from numerous ground-based water level measurements. Direct groundwater recharge by meteoric inflow is also estimated through a combination of satellite and model-based approach. Finally, recharge information from both of the estimation methods is compared over the entire study region to indicate the discrepancies of result of these studies. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

3.2 Methods

3.2.1 Study Area

Groundwater recharge dominantly takes place over the study area from monsoonal rainfall (between June and September), which accounts for most (>74%) of the annual precipitation (Guhathakurta and Rajeevan 2008; Scanlon et al. 2010). Precipitation data were obtained from the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al. 2000), a joint satellite mission between National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), that was designed to observe rainfall in the tropical countries. We have also used long-term (1961–2007) gridded precipitation data from the archives of Asian Precipitation Highly Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE) (Yatagai et al. 2012). The APHRODITE team has archived real-time precipitation measurement data through their own data collection processes and National hydrological and meteorological services (NHMs) under World Meteorological Organization (WMO) agreement (Yatagai et al. 2012). Precipitation data show distinct spatial variation (Chap. 1, Fig. 1.1) resulting to extreme humid to arid climate over the Indian region. Precipitation pattern also suggests the spatial nature of the potentially available meteoric water for groundwater recharge. The entire region is composed of various different hydrogeologic setting (CGWB 2012), varying from highly permeable fluvial sediments in the Indus–Ganges–Brahmaputra (IGB) aquifers to fractured, crystalline rock aquifers in cratonic parts of peninsular India (Chap. 1, Fig. 1.4). As a result, the IGB basin has been subjected to rapid groundwater withdrawal comparing other parts of India (Mukherjee et al. 2015).

3.2.2 Water Table Fluctuation (WTF) Method

The principle of WTF method deals with determination of groundwater recharge rates as an outcome of water level increase in an unconfined aquifer (Healy and

Cook 2002). Ground-based observation data locations ($n > 13{,}000$) were obtained from achieves of Central Groundwater Board (CGWB, Government of India) to calculate annual groundwater level changes (Δh) from 2007 to 2011. Initially, the data were screened to get temporally uniform, continuous dataset over all the selected locations ($n > 5500$, Fig. 3.1) for each year. Annual fluctuation in groundwater level at each observation location was calculated by subtracting the lowest from the highest groundwater depth for each year. In order to get error-free estimates, water level values beyond the range of third quartile (75%) of the selected locations of each year were omitted from the further analyses, resulting to at least ~4500 locations for each year. Values of Δh values were gridded by kriging ($0.1° \times 0.1°$) over the entire study region. Aquifer specific yield (S_y) values were obtained from CGWB and assigned according to aquifer characteristics. Average S_y value ranges between 0.02 and 0.13 within the study area (CGWB 2012). Gridded ($0.1° \times 0.1°$) S_y was created based on the hydrogeological setting of the study area. In each grid cell, annual recharge rate is calculated by multiplying Δh with S_y.

Minimal assumptions in the measurement techniques and lack of influence of preferential flow paths are some major advantages of using WTF method (Healy and Cook 2002). However, Healy and Cook (2002) noted some disadvantages of this method, e.g., WTF method will not be suitable in recharge estimation within confined aquifer; best recharge estimates will be found in regions with shallow water table, which perfectly represent small changes in water level associated with groundwater depletion or replenishment; the point location(s) should be the best possible representative of each grid cells; uncertainty may arise due to improper assumption of S_y. One of the major drawbacks of WTF method is the incapability of removing inter-aquifer flow from recharge calculation. Errors related to lateral flow from large surface water bodies are also debatable issue here.

3.2.3 Water Budget (WB) Method

Water budget method deals with conservation of mass of water components, i.e., total water input equals to the total water output. A simple but effective approach is used here to calculate gridded ($1° \times 1°$) groundwater recharge rate (R) by water budgeting as (Healy 2010)

$$R = P - \mathrm{ET} - \Delta\mathrm{SM} - \mathrm{SR} \tag{3.1}$$

Precipitation (P) data are used from the database of the TRMM. Evapotranspiration (ET), surface runoff (SR), and change in soil moisture storage (ΔSM) data are obtained from the archives of the Community Land Model (CLM) (Dai et al. 2003) which operates as a part of Global Land Data Assimilation System (GLDAS) (Rodell et al. 2004). The model simulates soil moisture up to a depth of 3.4 m below the ground surface; consequently, soil moisture below that depth is not considered in this study. Also, it is not possible to consider rejected recharge because of aquifer full condition, by using WB method. Unavailability of absolute quantification of irrigational groundwater withdrawal and return flow of water volumes from irrigated land restricted us to include agricultural influence in estimating recharge through WB method. The calculated recharge does not take into account the presence of near-surface confining layers, thereby adding errors in the calculation.

3.3 Result and Discussion

3.3.1 Groundwater Recharge Rate Estimates

Groundwater recharge through WTF method demonstrates high spatial variation (Fig. 3.2) for each year within the study period. High recharge rate (>300 mm/year) was observed in most of the regions of IGB basin. Apart from comparatively higher rate of precipitation, high effective porosity and permeability of the unconsolidated sediments, mostly unconfined aquifers in these basins influence higher recharge rate. Furthermore, higher groundwater withdrawal rate caused by intense irrigation over the region (Siebert et al. 2013) accelerates the depletion of water storage and level during pre-monsoon period; thus creating more recharge space, resulting to higher amount of recharge during monsoon period. On the other hand, irrigation increases recharge rate by allowing infiltration of irrigational return flow though the groundwater cultivated lands (Mukherjee et al. 2007). Thus, as a function of agricultural land use pattern, the magnitude of recharge rate is not same everywhere within IGB basin (Chap. 1, Fig. 1.3). Most of the areas on the central and southern parts of study area exhibit lower recharge rates (<200 mm/year). The crystalline rock aquifers in those regions might provide hindrance to direct infiltration of potential recharge water, thus causing an imbalance between available precipitation

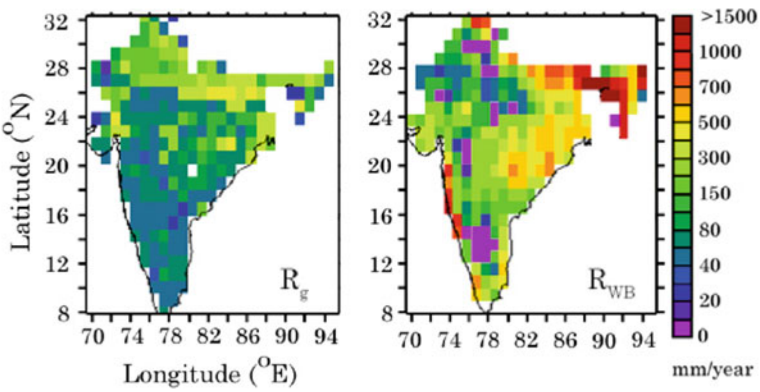

Fig. 3.2 Annual mean values of R_{WB} and R_{g}

water and fluctuation of the water table. Further, relatively lower rates of precipitation (Chap. 1, Fig. 1.1) are also a reason for lower recharge rates observed in parts of the central and southern study region.

The data obtained from this study compare well (Table 3.1) with many previous estimates of groundwater recharge reported from the region. However, recharge rates (WTF method) estimated in this study overestimate the recharge rate reported

Table 3.1 Comparison of groundwater recharge rates over parts of the Indian subcontinent

S. No.	Locations	R_g (mm/year), present study	R_{WB} (mm/year), present study	Recharge rates (mm/year) by chemical tracer methods in previous studies (study year)
1.	Punjab	205.92	207.14	56[a] (1972)
2.	Haryana	224.22	201.19	70[a] (1973)
3.	Western Uttar Pradesh	221.40	46.39	195[a] (1971)
4.	Churu District, Rajasthan	251.70	33.30	62[b] (1994–95)
5.	Nalanda district, Bihar	328.54	10.32	82[c] (1996)
6.	Sabarmati basin, Gujarat	382.50	184.56	107[d] (1973–76)
7.	Bankura district, West Bengal	462.46	549.36	179[e] (1995)
8.	Shahdol district, Madhya Pradesh	79.36	432.34	98[f] (1992)
9.	Upper Hatni watershed, Madhya Pradesh	106.15	134.36	17–275[c] (1993)
10.	Jam basin, Maharashtra	55.82	287.16	131[g] (1988)
11.	Parlijhori watershed, Odisha	51.17	454.74	166[c] (1996)
12.	East Godavari dist, Andhra Pradesh	231.76	250.82	90[c] (1997)
13.	Gaetec watershed, Andhra Pradesh	50.63	213.67	46[h] (1997)
14.	Neyveli basin, Tamil Nadu	59.07	429.68	161[g] (1985)
15.	Jaipur, Rajasthan	264.60	108.15	50–120[i] (2008)

[a]Goel et al. (1975); [b]Athavale et al. (1998); [c]Rangarajan and Athavale (2000); [d]Bhandari et al. (1982); [e]Rangarajan et al. (1997); [f]Rangarajan et al. (1995); [g]Athavale et al. (1992); [h]Rangarajan et al. (1998); [i]Scanlon et al. (2010)

in some other studies (Goel et al. 1975; Bhandari et al. 1982; Rangarajan et al. 1997; Athavale et al. 1998; Scanlon et al. 2010). This is expected as almost all of the tabulated recharge rates (Table 3.1) were calculated for the natural recharge occurring through vadose zone only using chemical tracer approach, which does not consider inter-aquifer flow, base flow and irrigational abstraction, and probably were done during a different land use/land cover pattern than present.

Groundwater recharge estimated through WB method also exhibits spatial variation (Fig. 3.2). Recharge rates show higher (>500 mm/year) values over eastern and east-central coastal regions. On the other hand, recharge rates are found to be lower (<300 mm/year) in the parts of southern region. As only meteoric recharge is considered in WB method, infiltration was solely calculated from precipitation. In WB method, hydrogeologic parameters like porosity, permeability do not influence calculation of recharge rates. Accordingly, recharge rates follow precipitation pattern on most of the grid cells. Recharge rates calculated using WB method on the corresponding grid cell overestimates the recharge rate reported in most of the earlier studies over following locations (Table 3.1).

3.3.2 Comparison Between Recharge Rates Estimated Through WTF and WB Method

Good matches were found in recharge values calculated using WB method with WTF method on the IGB basin. Recharge using WB method overestimates the recharge calculated using WTF method on east-coastal region. Most of the east-coastal region is covered by forest (Bhanja 2017) and hence canopy interception of precipitated water can be a major impediment, which was not considered for calculation owing to unavailability of suitable data. Total amount of precipitated water cannot reach ground surface due to presence of tree canopies. Eventually, the intercepted water evaporates from tree leaves and get lost in the atmosphere. Recharge rates following WB method exhibit higher values in central study region. On the contrary, recharge estimated through WTF method reveals lower value on parts of central and southern region. However, discrepancy in recharge estimates of WTF and WB methods might be arising as a result of the following factors: (i) hydrologic parameters are not used in WB method; (ii) WB method does not consider inter-aquifer flow and base flow components, it only consider diffuse recharge through precipitation only; (iii) recharge associated with irrigation, also termed as return flow, is not considered in the WB method; (iv) soil moisture information was available up to a depth of 3.4 m; hence, vadose zone extending beyond 3.4 m is out of scope in the WB method. Notwithstanding these discrepancies, our results indicate dynamic nature of groundwater recharge as a function of precipitation, land use pattern, and hydrogeologic parameters (Fig. 3.3).

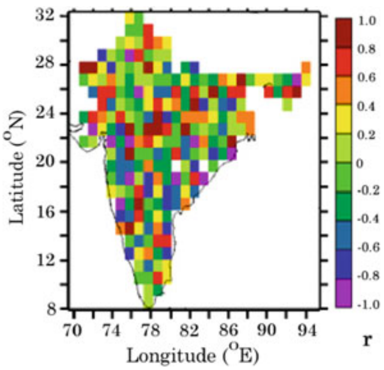

Fig. 3.3 Correlation between R_g and R_{WB}

3.4 Conclusions

In this study, groundwater recharge rates for present time are calculated between 2007 and 2011 over parts of the densely populated Indian subcontinent. On the basis of heterogeneity in geology and climate, noteworthy spatial variations were observed in groundwater recharge rates over the region. Groundwater recharge rates exhibit comparatively higher values (>300 mm/year) over the highly fertile alluvial plains of Indus–Ganges–Brahmaputra (IGB) system. High precipitation rates along with a combination of favorable hydrogeologic properties of the unconsolidated fluvial deposits and rapid groundwater withdrawal influence recharge rates in these regions. Most of the regions on the central and southern study areas are subjected to lower recharge rates (<200 mm/year). Groundwater recharge rates, calculated using WTF and WB method, respectively, match well in the IGB basin. On the other hand, recharge estimates using WB method overestimates the recharge values calculated using WTF method over natural vegetation covered east-coastal region. Reasonably comparable matches were found in calculated groundwater recharge rates using the two applied methods with previous estimates over the parts of the Indian subcontinent.

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