Bangladesh Rice J. 25 (2) : 45-56, 2021, doi.org/10.3329/brj.v25i2.62706

Natural Groundwater Recharge: A Review on the Estimation Methods

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ABSTRACT

Groundwater recharge study is essential because it provides information on the groundwater flow and availability, and its sustainable management over many years. Groundwater recharge estimation also helps evaluating the characteristics of aquifer, such as its bearing capacity and susceptibility to contamination. Many studies so far have focused on several techniques and methods of estimation of groundwater recharge. These methods were very simple, such as seepage meter or tracer techniques, and even complex numerical modelling. However, picking up the right techniques from multiple require essential considerations such as physiography and climatic condition of the location, reliability of the technique, cost and resource availability, and other unavoidable factors that may put limitations in the applicability of a particular method. Furthermore, the reliability of a recharge estimation method also depends on the recharge rates of a particular site. Therefore, an appropriate technique of recharge estimation should be taken such that the estimation resolution of that technique is matched with the average recharge rates of that site. This paper discusses various recharge methods to select a suitable approach appropriate for the climatic condition of Bangladesh. Estimating groundwater recharge by only one method may result in several errors and draw a wrong conclusion. Applying multiple approaches can minimize these errors and enhance the acceptability of the recharge estimates.

Key words: Water balance, water table, aquifer, tracer, lysimeter

INTRODUCTION

Groundwater recharge is the downward movement of water through the unsaturated zone in the subsurface to the saturated zone beneath the water table (Acharya *et al*., 2018). There are some other terminologies regarding the groundwater recharge. 'Net infiltration', 'drainage', 'percolation', and 'residual flux' are often used to indicate the groundwater recharge (Scanlon *et al*., 2002). Assessment of groundwater recharge is an essential requirement for managing groundwater resource sustainably and efficiently. Attention has been given to this assessment, particularly in regions where groundwater supplies are in high demand, such as the North-west region of Bangladesh, where such resources are the key to crop production, industrial and household use, and hence economic development. Quantity of groundwater recharge also estimates the sustainable yield of an aquifer. The sustainable yield indicates a consistent water withdrawal rate, which can cause no adverse effects of an aquifer (Sophocleous, 1992). Such effects could be decline in aquifer water levels. The negative effects of over withdrawal of water also include declines in water flows of streams that are hydraulically connected to the aquifer. In addition, water quality may deteriorate due to over withdrawal of water from an aquifer. However, the rate at which the aquifer is recharged is an essential factor in assessing groundwater resources.

The location and timing of recharge, and thus the choice of recharge estimating technique, is influenced by the climate (mainly the rainfall), geomorphological characters such as soil type, nature of the topography, amount of surface vegetation, and geological condition of a site (Scanlon *et al*., 2002). For example, humid and arid regions represent two different

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climates, the recharge quantification of which requires different approaches. The groundwater tables of humid regions are generally shallow (Takounjou *et al*., 2011). This region receives a large amount of rainfall and has a low influence of high temperature, which results in high infiltration. Eventually, the recharge in the humid region is usually high (Reese and Risser, 2010). In contrast, in the arid climate, water table depth is high. Furthermore, the precipitation in the arid region is less than 700 mm/year (Allison *et al*., 1994). Therefore, the potential evapotranspiration of the region equals the precipitation or sometimes exceeds it. As a result, the recharge amounts in an arid region usually are small compared to the resolution of the recharge estimation technique (Allison *et al*., 1984).

More than 35 % of irrigation water is lost in the irrigated rice through percolation below the root zone collectively at land preparation and during the growing season under conventional puddled transplanted rice (Mahmud *et al*., 2017) . This amount of percolation loss is even greater under strip planting (45% of irrigation water). A weak plough pan due to practising strip planting over a seven years period has increased the infiltration rate (Mahmud *et al*., 2017). However, deep percolations are not real water losses in the landscape since that water is not contaminated and would return to the groundwater creating new sources of diffuse recharge and increasing groundwater storage that is potentially available for reuse (Humphreys *et al*., 2008). Therefore, it is needed to know a suitable method that can estimate the groundwater recharge from both irrigated and rain-fed rice hydrology on a seasonal or yearly basis.

This paper aims to outline different aspects of numerous techniques used for quantification of the groundwater recharge and the reliability of the recharge estimations. This paper also discusses the important factors that the researchers should consider in choosing the method and the restrictions of using a specific technique. Since the review of techniques used in a wide range of climatic conditions (arid, semi-arid, sub-humid, and humid) is beyond the scope of this report, this paper confines the review of the recharge estimation techniques used only in the sub-humid areas such as Bangladesh.

GROUNDWATER USE WORLDWIDE

Ninety-nine percent of the earth's liquid freshwater is groundwater, which is the source of fresh drinking water to more than two billion people. Moreover, 38 % of irrigation water for the global croplands comes from groundwater (Association, 2016; Siebert *et al*., 2010). The estimated total volume of groundwater in the world is about 22.6 million km^3, which is mainly occupied in the upper two kilometres of the continental crust (Gleeson *et al*., 2016). Table 1 shows groundwater extraction by ten major countries for irrigation, domestic use, and industrial purposes. Most of the countries use more than 50 % of the groundwater resources for the irrigation, and more than 20 % for domestic purposes. When groundwater withdrawal rate is greater than the natural recharge rate, groundwater mining occurs, which causes aquifer depletion in different countries of the world (Siebert *et al*., 2010). For example, total groundwater depletion in subhumid to arid regions was 126 km^3 year^{-1} in 1960 which was increased to 283 km^3 year^{-1} in 2000 (Wada *et al*., 2010). Dey *et al*. (2017) carried out a study on the groundwater table fluctuation in the north-west districts of Bangladesh (Rajshahi, Pabna, Bogura, Dinajpur, and Rangpur) over 33 years (1981-2014). The findings revealed a declining trend of groundwater level in Rajshahi district from 4 to 12 meter from the surface over the study period (Fig. 1), which mainly attributed to over withdrawal of groundwater than recharging aquifer.

Table 1. Ten nations with the greatest withdrawal of groundwater.
Data taken from National Groundwater Association (Association, 2016).

County	Population in 2010 (thousand)	Groundwater use in 2010 (km^3 year^{-1})	Groundwater use by sectors		
			Irrigation (%)	Domestic use (%)	Industrial use (%)
India	1224614	251.00	89	9	2
China	1341335	111.95	54	20	26
United States	310284	111.70	71	23	6
Pakistan	173593	64.82	94	6	0
Bangladesh	148692	30.21	86	13	1
Mexico	113423	29.45	72	22	6
Saudi Arabia	27448	24.24	92	5	3
Indonesia	239871	14.93	2	93	5
Japan	126536	10.94	23	29	48
Thailand	69122	10.74	14	60	26

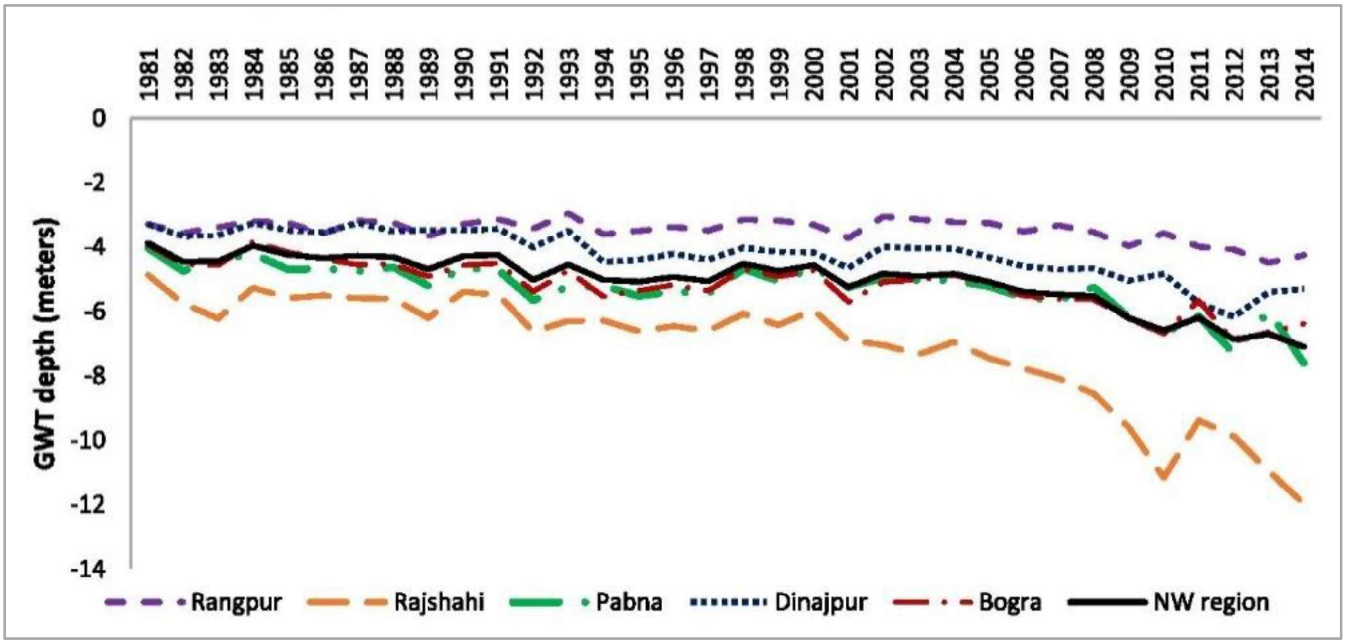

Fig. 1. Changes in groundwater table depths (January to May) from 1981 to 2014. Measurements are the average of maximum and minimum of groundwater depths of the corresponding districts. The figureis adopted from Dey *et al*. (2017).

GROUNDWATER RECHARGE

Processes and mechanisms

Precise understanding of the fundamental mechanism of recharge for a particular area is required at the beginning to estimate the groundwater recharge more accurately. De Vries and Simmers (2002) gave an overview of the processes and mechanisms of groundwater recharge. According to their description, groundwater recharge is the amount of water that flows downward through the unsaturated zone beyond the rooting depth reaches the water table, making contribution to the groundwater reservoir. When rain occurs or irrigation water is applied, a part of the water is used to fulfill the soil water deficit, goes to the atmosphere through evapotranspiration. More than these two uses, water percolates downward (infiltration) to the water table and recharge takes place. From this definition it is considered that groundwater recharge over an area is equal to the infiltration for the same area. However, not necessarily all infiltration water reaches the groundwater table. The infiltration might be restricted by the impermeable or semipermeable layer that has a low water conductivity. The water then moves horizontally and flows to a nearby local depression, such as a pond, where it runs off and evaporates and not contributes to the groundwater reservoir. In an area with a shallow aquifer compared to the landscape, the recharged aquifer with a shallow water table may create a groundwater system where horizontal water flow or an associated seepage might take place within the area. In a high water table aquifer, when time scale is considered, water might be extracted by evapotranspiration immediately after reaching the water table.

Carreira *et al.* (2010) explains how amount of rainfall effects whether there is recharge or not. In areas ranging from humid to sub-humid, yearly precipitation is greater than the potential evapotranspiration, which results in continuous recharge. In contrast, in low rainfall areas, such as arid and semi-arid, rainfall does not exceed the evapotranspiration that contributes to the yearly groundwater recharge. But, over many years the precipitation and the preferential flow of groundwater flow can be the source of recharge.

Groundwater recharge types

According to the water sources, groundwater recharge can be classified into three types: direct or diffuse recharge, localized recharge, and indirect or non-diffuse recharge (Acharya *et al.*, 2018; De Vries and Simmers, 2002; Sibanda *et al.*, 2009) (Fig. 2). Direct recharge is the water contributed to the groundwater reservoir from rain or irrigation by direct percolation through the unsaturated zone after separating from the other water balance components (soil water deficits, surface runoff and evapotranspiration). Localized recharge is the amount of water percolation that is resulted from horizontal surface concentration or depression of water (such as ponding in the rice field). Indirect recharge refers to the amount of water added to the groundwater reservoir by percolation through the beds of rivers and canals or other waterbodies.

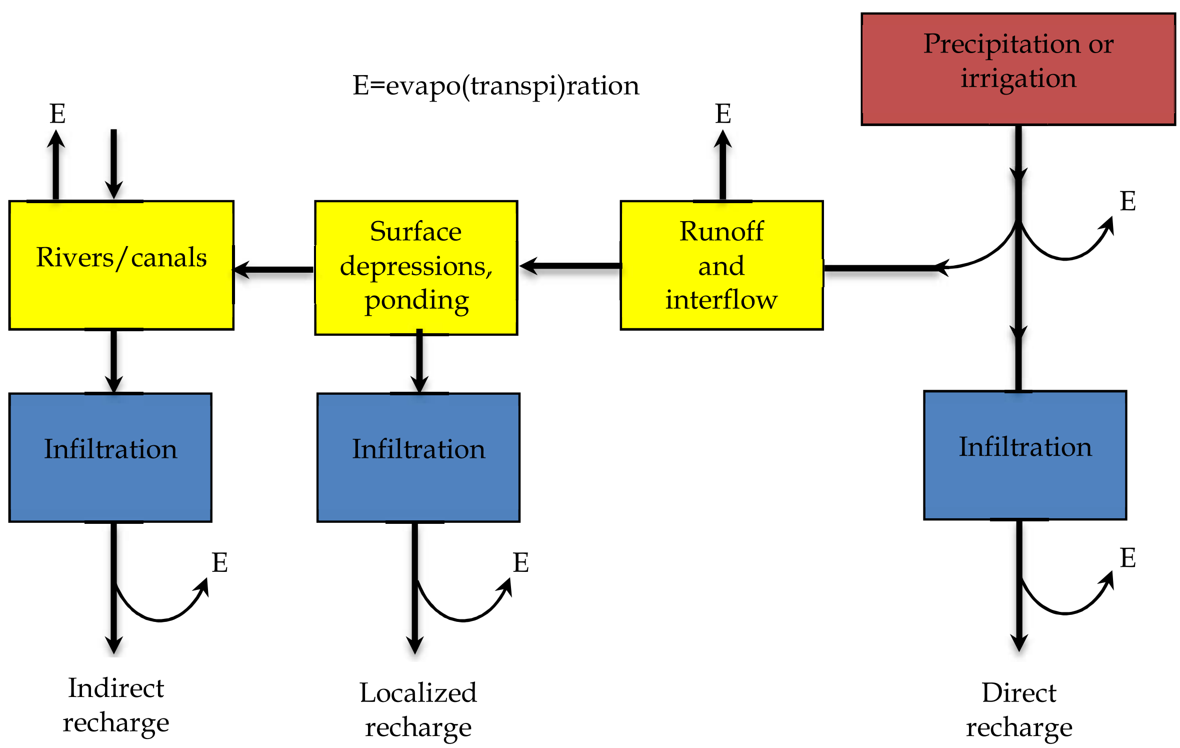

Fig. 2. A flow diagram of different mechanisms of groundwater recharge in a semi-arid area (Lerner, 1997).

Groundwater recharge estimation

Groundwater recharge estimation is primarily classified as direct and indirect methods. Examples of direct physical methods are the Lysimeter method, and direct chemical methods are tracer techniques, either applied or historical. Whereas indirect physical methods are soil water balance, water budget method, groundwater table fluctuation method etc.

Groundwater recharge estimation techniques can also be classified according to regions where arid, semi-arid and humid climates are present. For arid and semi-arid climates, water budget method, isotopic tracers, lysimeters, Darcy's law, and other numerical models are applicable. For humid climates soil water balance, water budgets, lysimeters, Darcy's law, applied tracers, water table fluctuations, and numerical models are appropriate (Scanlon *et al*., 2002).

Factors affecting groundwater recharge

Factors that influence groundwater recharge include climate, land use, land cover or vegetation, geology, topography, soil texture, soil structure or strength, irrigation water use (Acharya *et al*., 2018), depth of water table (Brini and Zammouri, 2016), soil moisture, properties of the geological materials, and the existence of nearby waterbodies (Ali and Mubarak, 2017). These factors work individually or as a combined effort interacting with each other affecting the recharge. However, climate, soil texture, surface cover has been put forward, among other factors affecting groundwater recharge. Climatic factors include precipitation and evapotranspiration since these two variables influence the abundance of water at the soil surface, which eventually controls the groundwater recharge (Scanlon *et al*., 2002).

Soil textural parameters such as porosity and pore size distribution affect water holding capacity, infiltration and transpiration, eventually affecting groundwater recharge (Jobbágy and Jackson, 2004). For instance, sandy soils have more pore spaces and greater hydraulic conductivity; thus, groundwater recharge is higher. In contrast, clayey soils also have tiny pores and greater surface tension that slows down the vertical movement, inhibiting lower infiltration and recharge. In addition, plant available water is higher in clayey soil because of greater micropores than coarse-textured soil; therefore, the evapotranspiration is higher, and groundwater recharge is lower in clayey soil.

Table 2. Summary of the recharge estimated in some humid regions using different estimation methods.

Country/region	Yearly average rainfall	Recharge estimation methods	Recharge mm/year	Coefficient of recharge	Source
USA, Pennsylvania	1069 mm	Lysimeter	311	29 %	Risser *et al*. (2009)
		Water budget	308	29 %	
		WTF*	252	24 %	
USA, North Carolina	1170 mm	WTF	140	12 %	Coes *et al*. (2007)
		Darcy's law	110	9 %	
North-east Bangladesh	1050 mm	Chloride tracer	49	4.7 %	Ali (2010)
		Water balance	59	5.6 %	Ali *et al*. (2019)
Western Australia	775 mm	Environmental chloride	116	15 %	Sharma and Hughes (1985)
USA, Minnesota	500-900 mm	WTF		16-26 %	Delin *et al*. (2007)
USA, Wisconsin	750-900 mm	Numerical Model	110		Cherkauer (2004)
Argentina, Pampa plain	1064 mm	WTF, S_y=0.09	210	18 %	Varni *et al*. (2013)
		WTF, S_y=0.07	164	14 %	

*WTF= water table fluctuation

The density and type of surface cover or vegetation largely influences groundwater recharge (Ali and Mubarak, 2017). The runoff component of the rain or irrigation, and soil evaporation are largely governed by the soil cover and the plant leaf canopy, and thus groundwater recharge may be variable. Generally, the recharge is more remarkable in an area with less vegetation than in a surface with good vegetation of annual crops or grasslands. Mathenge *et al*. (2020) observed the groundwater recharge of Stony Athi sub-catchment of Kenya. They reported 197 mm/year recharge on sandy loam soil with forest cover compared to 36 mm/year recharge on clay soils with impervious layers. Higher recharge on the forest cover was attributed to vegetation interrupting the surface runoff and enhancing water infiltration through the sandy soil.

GROUNDWATER RECHARGE ESTIMATION METHODS

Lysimeter method

The lysimeter method is a popular and repeatedly used groundwater recharge estimating method where all the water balance components (precipitation, irrigation, evapotranspiration, and the change in soil water storage) in the lysimeter zone are measured (Ali and Mubarak, 2017). The remaining component, i.e., the deep percolation, which is the recharge, is then calculated as the residual of the following water balance equation.

$$R = P + I - ET \text{ or } E \pm \Delta S \quad (1)$$

Where R = recharge, P = precipitation; I = irrigation, ET = evapotranspiration, E = evaporation, if there is no crop or vegetation only evaporation should be considered instead of evapotranspiration. $\pm\Delta S$ = changes in soil water storage (calculated from the differences in initial to the final soil water content in the lysimeter zone).

The water balance method of estimating groundwater recharge is direct and depends on reliable and precise data of the water flux in the lysimeter. Hence, the data from lysimeter methods can be used as typical, referring to which data generated from other estimating methods can be verified and calibrated (Rosenberg *et al*., 1983). Furthermore, mini lysimeters can provide direct measurements of percolation at the root zone. In comparison, deep drainage-type lysimeters provide measurements of percolation below the root zone (Kitching *et al*., 1980).

The problems associated with this method are the high expense of constructing and maintaining the lysimeter. Since the soil and vegetation are disturbed during sampling, soil profiling and density are not identical to the natural soil. In addition, the drainage conditions confine to the lysimeter zone, and the bottom of the lysimeter is considered the lower boundary (Gee and Hillel, 1988). There is also a possibility of the flow through the sidewalls of the lysimeter that can overestimate the actual recharge (Ali and Mubarak, 2017).

Water balance methods

The water balance method of estimating groundwater recharge is a residual approach of water balance equation similar to the lysimeter method except for the soil water storage component, where the changes in water storage are determined for the entire unsaturated or vadose zone. This method also considers the runoff component. The simple water balance equation for a basin is as follows:

$$R = P + I - ET \text{ or } E - R_o \pm \Delta S \quad (2)$$

Where R = recharge, P = precipitation; I = irrigation, i.e., the amount of water added, ET = evapotranspiration, E = evaporation when there is no crop or vegetation on the surface, R_o= runoff $\pm\Delta S$ = changes in soil water storage (calculated from the differences in initial to the final soil water content in the unsaturated or vadose zone).

Measurements of the components at the right side of the water balance equation are subject to significant errors that may lead to errors in determining the component at the left side, i.e., the recharge. Therefore, the reliability of the water balance method largely depends on how accurately water balance components in the equation is measured or estimated (Sophocleous, 1991).

The unsaturated zone or the vadose zone of a soil profile is the crucial zone. In humid climates, the unsaturated zone allows a favourable condition for infiltration of the adequate rainfall, and thus water flows effortlessly to the water table. In contrast, in the arid region, ET is >90% of the precipitation, and hence there is little water left for recharging the groundwater (Acharya *et al.*, 2018). Thus, the arid region requires a more precise measurement of the recharge. Therefore, the water balance methods of estimating groundwater recharge are suitable more in humid regions than in arid climates (Knutsson, 1988).

Water budget method

The water budget method of estimating groundwater recharge is the most common, indirect, and residual approach. This method uses a conceptual hydrologic model, where all of the components in the water budget equation are measured or estimated, and calculation of the residual determines the residual (Scanlon *et al.*, 2002). The following equation is the water budget equation for a basin or site:

$$P + Q_{on} = ET + Q_{off} + \Delta S \tag{3}$$

Where P= precipitation (and/or irrigation); Q_{on} = water flow onto the basin or site and Q_{off} = off the basin or site; ET = evapotranspiration, and ΔS = change in water storage. Unit of all components is as mm/day or mm/year. Some of the individual components of the equation consist of subcomponents. Q_{on} is written as the surface water flow (Q_{on}^{sw}), plus the groundwater flow (Q_{on}^{gw}). Q_{off} is written as the surface water flow off the site (Q_{off}^{sw}) which is equal to the R_o (runoff), plus the groundwater flow off the site (Q_{off}^{gw}). ET is classified according to the source of evaporated water such as surface water evapotranspiration (ET^{sw}), evapotranspiration from the unsaturated zone (ET^{uz}), and/or evapotranspiration from the saturated zone, i.e., the groundwater (ET^{gw}). Water storage is also classified as surface-water storage (ΔS^{sw}), storage in the unsaturated zone (ΔS^{uz}) and storage in the saturated zone i. e., the groundwater (ΔS^{gw}). Rewriting the water budget equation incorporating the abovementioned subcomponents results in:

$$P + Q_{on}^{sw} + Q_{on}^{gw} = ET^{sw} + ET^{uz} + ET^{gw} + R_o + Q_{off}^{gw} + Q^{bf} + \Delta S^{sw} + \Delta S^{uz} + \Delta S^{gw} \tag{4}$$

Where Q^{bf} = baseflow (i.e., groundwater flow to nearby streams, rivers, or springs).

The above equation gives the following equation form which, groundwater recharge, R, can be calculated (Schicht and Walton, 1961):

$$R = Q_{off}^{gw} - Q_{on}^{gw} + Q^{bf} + ET^{gw} + \Delta S^{gw} \tag{5}$$

This equation states that all water flowing into the water table (Q_{on}^{gw}) either flows out of the reservoir as groundwater flow (Q_{off}^{gw}), is discharged as streams or rivers to the surface (Q^{bf}), is evapotranspirated (ET^{gw}), or is reserved in storage (ΔS^{gw}). Substituting this equation into Eq. (4), the water budget equation becomes as follows:

$$R = P + Q_{on}^{sw} - R_o - ET^{sw} - ET^{uz} - \Delta S^{sw} - \Delta S^{uz} \tag{6}$$

For a given location or site, some parts in Eq. (6) are negligible and may be ignored.

The water budget method is preferable due to its flexibility and the assumptions are inherent for the terms in the water budget equation. Hence, this method is useful for a wide range of space and time. For example, using in lysimeters, the recharge could be cm/seconds, extending to kilometers /centuries in a global climatic model.

The limitation of this method is like other residual approaches of estimating groundwater recharge. The accuracy of the estimated recharge depends on how precisely other components in the water budget equation are measured. This limitation is problematic when the amount of recharge rate is relatively smaller than that of the ET. Therefore, the usefulness of water budget methods in arid and semi-arid regions is a big concern (Gee and Hillel, 1988).

Water table fluctuation methods

Healy and Cook (2002); Nonner (2006); Scanlon *et al*. (2002) suggested an approach of Groundwater recharge by the analysis of water table fluctuation (WTF) in an unconfined aquifer. Hydrographs of water table in observation wells and the concept of the specific yield of an aquifer are used in WTF methods. The underlying hypothesis is that a water level rise in an unconfined aquifer is resulted from recharge water coming to the water table (Acharya *et al*., 2018; Sophocleous, 2004). In this hypothesis groundwater plumage, evapotranspiration, and net horizontal flow are considered negligible (Scanlon *et al*., 2005), and the specific yield is unitless constant (Yin *et al*., 2011). The WTF method of groundwater recharge estimation has been practiced since the 1920s (Healy and Cook, 2002).

Recharge is calculated as:

$$R = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \qquad (7)$$

Where, R = recharge rate in m/day, S_y= specific yield (unitless), Δh = water table height measured in m, and Δt = time (day).

Freeze and Cherry (1979) defined specific yield as the volume of water discharged from an aquifer storage by gravity flow per unit area of that aquifer per unit drop in the water table. Specific yield can be determined by performing a pumping test and can be estimated using the following equation (Neuman, 1987)

$$S_y = \frac{V_w}{V_c} \qquad (8)$$

Where: V_w = cumulative volume of discharge from the pumping well and

V_c = volume of cone of depression from a water table.

Δh in the recharge equation is measured as the difference between the peak of the water table in response to the rainfall and the low point in the extrapolated recession curve (Lutz *et al*., 2015) as shown in Figure 4.

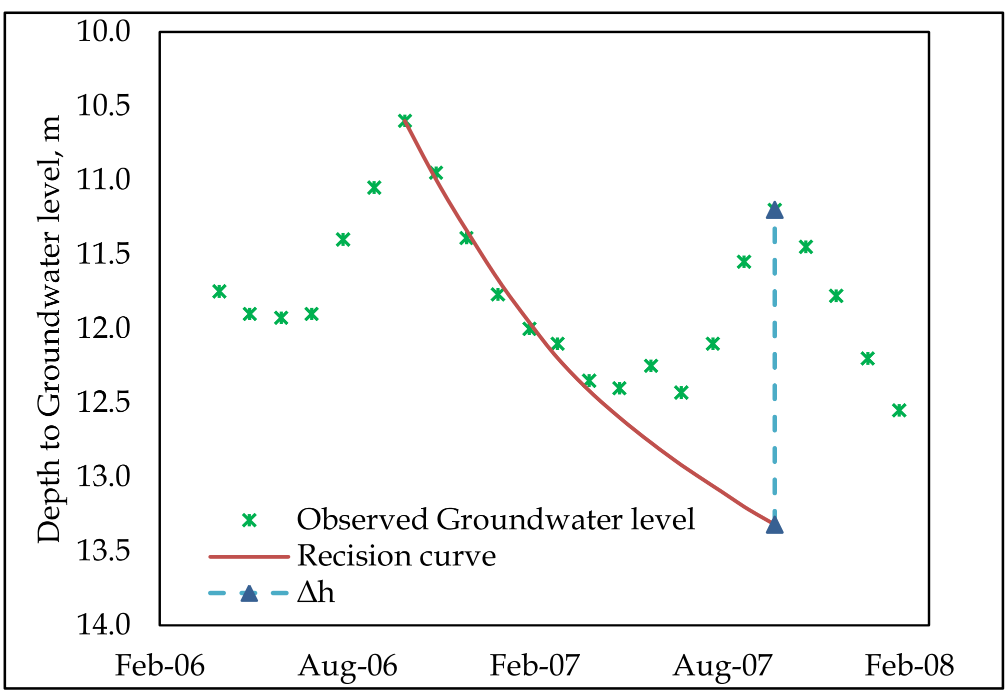

Fig. 3. The peak point of the water table and the low point drawn from the extrapolated recession curve used to determine Δh for recharge estimations. Figure taken from Lutz *et al*. (2015).

Applied tracer technique

This method of estimating groundwater recharge involves the application of tracer materials at a certain point or over an area representing a small region. The estimated value represents the groundwater recharge over the time between tracer application and soil sampling. The time scale is generally a cropping season, few months, or years.

The tracer material could be built in historical chemical composition in the soil profile or applied tracer technique. A popular approach of tracer technique is to use KCl of a given concentration (1 normal), where it is injected as a pulse at 20 cm depth of the soil profile in the field. Water infiltration from the rain or irrigation transports the tracer down to the unsaturated zone. The soil samples mixed with the tracer material from the subsurface are collected after a certain period by digging a trench or performing a core sampling. The Cl ion concentration is then determined by the Mohr method, using a micro-burette with 0.01 mm resolution.

The vertical distribution of the Cl ion is used to determine the velocity (v). The recharge rate (R, mm/year) is estimated using equation 9 as Scanlon *et al*. (2002) described.

$$R = v\theta = \frac{\Delta z}{\Delta t}\theta \tag{9}$$

Where Δz = depth of the peak of the Cl ion concentration, cm, Δt = time between tracer application and soil sampling, year, and θ = average volumetric soil water content, cm^3/cm^3.

Numerous studies estimated groundwater recharge using tracer techniques. For example, Wu *et al*. (2016) estimated the mean value of recharge 124.3 and 18.0 mm/year at two sites of north China plain. Ali *et al*. (2019) reported an average recharge rate of 53.7 mm/year at Ishwardi, Bangladesh.

Use of Darcy's equation

The most straight way of assessing recharge is to estimate the water flow rate over a unit of time (water flux) through the unsaturated zone (Allison *et al*., 1983; Stephens and Knowlton Jr, 1986). Since there is no practical instrument for directly determining the flux, of hydraulic conductivity of a soil profile and the unsaturated hydraulic gradient is measured separately. According to Darcy's equation, groundwater flux (q) is the hydraulic conductivity times the hydraulic gradient.

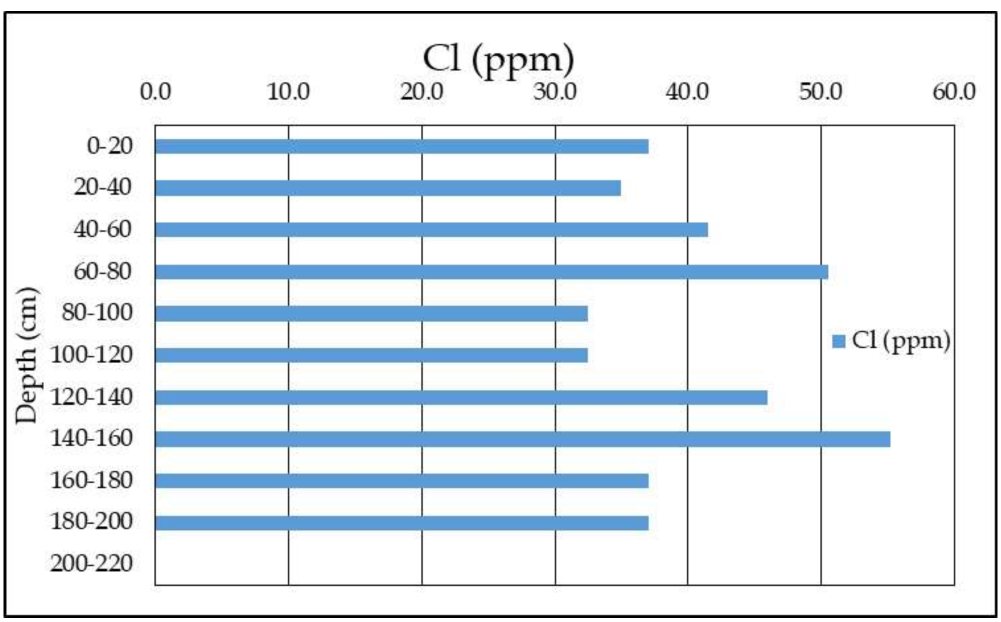

Fig. 4. Tracer concentration (Chloride Ion, parts per million) profile at 0-200 cm depth. Figure showing depth of tracer peak (Δz) at 140-160 cm. The figure is taken from Ali *et al*. (2019).

According to Darcy's law, rate of groundwater flow in volume (q) through the vertical cross section of an aquifer (A) equals the groundwater recharge rate (R) multiplied by the surface area that contributes to the flow (S) (Ali and Mubarak, 2017; Scanlon *et al.*, 2002).

$$qA = RS$$

or $R = \frac{qA}{S} = [K(\theta) \times dH/dz \times A]/S$ (10)

where, $K(\theta)$ = hydraulic conductivity at the soil volumetric water content, dH/dz = hydraulic gradient.

The hydraulic gradient in a uniform soil structure is generally near 1. In such a condition, the flux equals the hydraulic conductivity.

Darcy's method can be used for different areas ranging from an arid region where recharge rate is about 35 mm/year (Stephens and Knowlton Jr, 1986) to an irrigated region with a thin unsaturated zone where recharge rate could be 500 mm/year (Kengni *et al.*, 1994). Moreover, this method can be performed on broad spatial scales (1 to ≥ 10,000 km^2) (Ali and Mubarak, 2017). This method assumes steady-state groundwater flow is horizontal in aquifers and vertical in aquitards, and there is no groundwater extraction. Since this method is highly dependent on the hydraulic conductivity and hydraulic gradient, this technique is not useful for regions where these two parameters vary broadly with space (Yin *et al.*, 2011). Moreover, an accurate determination of the thickness and the length of the aquifer needs close consideration.

CONCLUSION

In this review, only a few methods of estimating groundwater recharge for humid climates and their advantages and disadvantages have been discussed. Recharge estimated from the residual of water balance models or water budget models may overestimate or underestimate the real magnitude. Similar errors can take place when hydraulic conductivities and the hydraulic gradients in Darcy's equation are estimated or measured. Considering the simplicity, availability of the chemicals used, and the cost of estimation, the tracer technique offers the best options for determining the recharge rate in subhumid areas. Moreover, since plenty of precipitation allows continuous recharge in the subhumid region like Bangladesh, the physical methods of estimating recharge, which relies on the direct measurement of water flux (lysimeter method and tracer technique), is more applicable than the indirect methods (WTF method). The significant challenges in the WTF estimation method is the lack of necessary data, for example, the S_y. The estimated value of S_y with errors may lead to a non-confident estimation of the groundwater recharge. However, since each approach of estimating groundwater recharge invites uncertainties, the use of multiple approaches (including tracer techniques) is recommended to overcome the constraints associated with using a single recharge estimation technique. Nonetheless, considering the advantages, limitations, and cost of each method, suitable techniques of groundwater recharge estimation in Bangladesh can be preferred.

ACKNOWLEDGEMENT

The authors express their sincere gratitude to the Agricultural Land and Water Resources Management (ALAWRM) research group members based in the Irrigation and Water Management Division, Bangladesh Rice Research Institute, for their sincere collaboration and help during writing this review paper.

REFERENCES

Acharya, B S, G Kharel, C B Zou, B P Wilcox and T Halihan. 2018. Woody plant encroachment impacts on groundwater recharge: A review. *Water* 10 (10): 1466-1491.

Ali, M H. 2010. Field Water Balance. In: Fundamentals of Irrigation and On-farm Water Management: Volume 1. *Springer*: 331-372.

Ali, M H and S Mubarak. 2017. Approaches and methods of quantifying natural groundwater recharge–A Review. *Asian Journal of Environment & Ecology* 5(1): 1-27.

Ali, M H, M H Zaman and M A Islam. 2019. Estimation of groundwater recharge using tracer and water balance method at Ishwardi, Bangladesh. *Journal of Agricultural Engineering, The Institute of Engineers, Bangladesh* 42/AE: 75-82.

Allison, G B, C J Barnes, M W Hughes and F W J Leaney. 1984. Effect of climate and vegetation on oxygen-18 and deuterium profiles in soils. Isotope Hydrology. *International Atomic Energy Agency*: 105-123.

Allison, G B, J S Colville and E L Greacen. 1983. Water balance and groundwater studies. In: Soils—An Australian Viewpoint, Academic Press, London, UK, pp. 531–548.CSIRO.

Allison, G B, G W Gee and S W Tyler. 1994. Vadose-zone techniques for estimating groundwater recharge in arid and semiarid regions. *Soil Science Society of America Journal* 58: 6-14.

Brini, N and M Zammouri. 2016. Groundwater recharge modelling in semi-arid regions; a case study of El Khairat alluvial plain (Tunisia). *Quarterly Journal of Engineering Geology and Hydrogeology* 49: 229-236.

Carreira, P M, J M Marques, A Pina, A M Gomes, P A G Fernandes and F M Santos. 2010. Groundwater assessment at Santiago Island (Cabo Verde): a multidisciplinary approach to a recurring source of water supply. *Water Resources Management* 24: 1139-1159.

Cherkauer, D S. 2004. Quantifying ground water recharge at multiple scales using PRMS and GIS. *Ground Water* 42: 97-110.

Coes, A L, T B Spruill and M J Thomasson. 2007. Multiple-method estimation of recharge rates at diverse locations in the North Carolina Coastal Plain, USA. *Hydrogeology journal* 15: 773-788.

De Vries, J Jacobus and I Simmers. 2002. Groundwater recharge: an overview of processes and challenges. *Hydrogeology journal* 10: 5-17.

Delin, G N, R W Healy, D L Lorenz and J R Nimmo. 2007. Comparison of local-to regional-scale estimates of ground-water recharge in Minnesota, USA. *Journal of Hydrology* 334: 231-249.

Dey, N C, R Saha, M Parvez, S K Bala, A K M Saiful Islam, J K Paul and M Hossain.2017. Sustainability of groundwater use for irrigation of dry-season crops in northwest Bangladesh. *Groundwater for Sustainable Development* 4: 66-77.

Freeze, R A and J A Cherry. 1979. Groundwater. Prentive-hall, Englewood cliffs, NJ, 604p.

Gee, G W and D Hillel. 1988. Groundwater recharge in arid regions: review and critique of estimation methods. *Hydrological processes* 2: 255-266.

Gleeson, T, K M Befus, S Jasechko, E Luijendijk and M B Cardenas. 2016. The global volume and distribution of modern groundwater. *Nature Geoscience* 9: 161-167.

Healy, R W and P G Cook. 2002. Using groundwater levels to estimate recharge. *Hydrogeology journal* 10: 91-109.

Humphreys, E, S S Kukal, K Amanpreet, T Sudhir, Y Sudhir, S Yadvinder, S Balwinder, J Timsina, S S Dhillon and A Prashar. 2008. Permanent beds for rice–wheat systems in Punjab, India. 2: Water balance and soil water dynamics. In: Permanent beds for rice–wheat systems in Punjab, India. 2: Water balance and soil water dynamics. *ACIAR Proceedings Series*, 37-61.

Jobbágy, E G and R B Jackson. 2004. Groundwater use and salinization with grassland afforestation. *Global Change Biology* 10: 1299-1312.

Kengni, L, G Vachaud, J L Thony, R Laty, B Garino, H Casabianca, P Jame and R Viscogliosi. 1994. Field measurements of water and nitrogen losses under irrigated maize. *Journal of Hydrology* 162: 23-46.

Kitching, R, W M Edmunds, T R Shearer, N R G Walton and J Jacovides. 1980. Assessment of recharge to aquifers/Evaluation de recharge d'aquifères. *Hydrological Sciences Journal* 25: 217-235.

Knutsson, G. 1988. Humid and arid zone groundwater recharge—a comparative analysis. In Estimation of Natural Groundwater Recharge. *Springer*: 493-504:.

Lerner, D N. 1997. Groundwater recharge. In: Saether O M, de Caritat P (eds), Geochemical processes, weathering and groundwater recharge in Catchments. Rotherdam.

Lutz, A, S Minyila, B Saga, S Diarra, B Apambire and J Thomas. 2015. Fluctuation of groundwater levels and recharge patterns in Northern Ghana. *Climate* 3: 1-15.

Mahmud, M N H, R W Bell, W Vance and M E Haque. 2017. Effect of minimum tillage systems on water balance for rice-based rotations in Northwest Bangladesh. In: M E Haque, R W Bell and W H Vance (eds), 2nd Conference on Conservation Agriculture for Smallholders (CASH-II), 62-64. Mymensingh, Bangladesh.

Mathenge, M W, G M Gathuru and E L Kitur. 2020. Spatial-temporal variation of groundwater recharge from precipitation in the stony athi sub-catchment, Kenya. *International Journal of Environmental Sciences* 3: 21-41.

National Groundwater Association. 2016. Facts about global groundwater usage. URL: http://www. ngwa. org/Fundamentals/Documents/global-groundwater-use-fact-sheet. pdf.

Neuman, S P. 1987. On methods of determining specific yield. Groundwater 25: 679-684.

Nonner, J C. 2006. Introduction to hydrogeology: unesco-IHE delft lecture note series. London. *Taylor and Francis*.

Reese, S O and D W Risser. 2010. Summary of groundwater-recharge estimates for Pennsylvania. Pennsylvania Geological Survey.

Risser, D W, W J Gburek and G J Folmar. 2009. Comparison of recharge estimates at a small watershed in east-central Pennsylvania, USA. *Hydrogeology journ*al 17: 287-298.

Rosenberg, N J, B L Blad and S B Verma. 1983. Microclimate: the biological environment. *John Wiley & Sons*.

Scanlon, B R, R W Healy and P G Cook. 2002. Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology journal* 10: 18-39.

Scanlon, B R, R C Reedy, D A Stonestrom, D E Prudic and K F Dennehy. 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology* 11: 1577-1593.

Schicht, R John and W C Walton. 1961. Hydrologic budgets for three small watersheds in Illinois. Illinois State Water Survey.

Sharma, M L and M W Hughes. 1985. Groundwater recharge estimation using chloride, deuterium and oxygen-18 profiles in the deep coastal sands of Western Australia. *Journal of Hydrology* 81: 93-109.

Sibanda, T, J C Nonner and S Uhlenbrook. 2009. Comparison of groundwater recharge estimation methods for the semi-arid Nyamandhlovu area, Zimbabwe. *Hydrogeology journal* 17: 1427-1441.

Siebert, S, J Burke, J Faures, K Frenken, J Hoogeveen, P Döll and F T Portmann. 2010. Groundwater use for irrigation—a global inventory. *Hydrology and earth system sciences* 14: 1863-1880.

Sophocleous, M. 2004. Groundwater recharge. *In:* Encyclopedia of life support systems (EOLSS). Eolss Publishers, Oxford.

Sophocleous, M A. 1991. Combining the soilwater balance and water-level fluctuation methods to estimate natural groundwater recharge: practical aspects. *Journal of Hydrology* 124: 229-241.

Sophocleous, M A. 1992. Groundwater recharge estimation and regionalization: the Great Bend Prairie of central Kansas and its recharge statistics. *Journal of Hydrology* 137: 113-140.

Stephens, D B and R Knowlton Jr. 1986. Soil water movement and recharge through sand at a semiarid site in New Mexico. *Water Resources Research* 22: 881-889.

Takounjou, A F, J R N Ngoupayou, J Riotte, G E Takem, G Mafany, J C Maréchal and G E Ekodeck. 2011. Estimation of groundwater recharge of shallow aquifer on humid environment in Yaounde, Cameroon using hybrid water-fluctuation and hydrochemistry methods. *Environmental Earth Sciences* 64: 107-118.

Varni, M, R Comas, P Weinzettel and S Dietrich. 2013. Application of the water table fluctuation method to characterize groundwater recharge in the Pampa plain, Argentina. *Hydrological Sciences Journal* 58: 1445-1455.

Wada, Y, P H Ludovicus, V Beek, M Cheryl, V Kempen, J W T M Reckman, S Vasak and M F P Bierkens. 2010. Global depletion of groundwater resources. Geophysical research letters 37.

Wu, Q, G Wang, W Zhang and H Cui. 2016. Estimation of groundwater recharge using tracers and numerical modeling in the north china plain. Water 8: 353.

Yin, L, G Hu, J Huang, D Wen, J Dong, X Wang and H Li. 2011. Groundwater-recharge estimation in the Ordos Plateau, China: comparison of methods. *Hydrogeology journal* 19: 1563-1575.