
***Asian Journal of Environment & Ecology***

***5(1): 1-12, 2017; Article no.AJEE.36811***
***ISSN: 2456-690X***

# Quantifying Natural Groundwater Recharge Using Tracer and Other Techniques

**M. H. Ali[1*]**

*[1]Agricultural Engineering Division, Bangladesh Institute of Nuclear Agriculture (BINA), BAU Campus, Mymensingh, Post Code: 2202, Bangladesh.*

***Author's contribution***

*The sole author designed, analyzed and interpreted and prepared the manuscript.*

***Article Information***

DOI: 10.9734/AJEE/2017/36811
Editor(s):
(1) V. Sivakumar, Center for Development of Advanced Computing (CDAC), Pune, India.
Reviewers:
(1) Suheyla Yerel Kandemir, Bilecik Seyh Edebali University, Turkey.
(2) S. O. Adesogan, University of Ibadan, Nigeria.
(3) Dorota Porowska, University of Warsaw, Poland.
Complete Peer review History: http://www.sciencedomain.org/review-history/22084

***Original Research Article***

***Received 18th September 2017***
***Accepted 24th October 2017***
***Published 28th November 2017***

## ABSTRACT

Groundwater is the main source of water supply to both urban and rural populations as well as to industry and agriculture. Among various water cycle characteristics, groundwater recharge is the leading hydrologic parameter determining groundwater resources availability and sustainability. Accurate estimation of groundwater recharge is extremely important for proper development and management of the resource. Groundwater recharge was estimated under field condition at north-eastern region (Mymensingh) of Bangladesh using tracer technique as well as water-balance and Lysimeter method. Three years average recharge rate was found as 228.7 mm/year under tracer technique; and 141.7 mm under water balance method. The lysimeter method showed lower rate, may be due to variation of subsoil condition from the field. The results of the study will be helpful for planning of sustainable groundwater in the area.

*Keywords: Groundwater; recharge; water balance; tracer; lysimeter; sustainability.*

---

**Corresponding author: E-mail: mha_bina@yahoo.com, hossain.ali.ina@gmail.com;*

## 1. INTRODUCTION

Among various water cycle characteristics, groundwater recharge is the leading hydrologic parameter determining groundwater resources availability and sustainability. Accurate estimation of groundwater recharge is extremely important for proper development and management of the resource. At present world, groundwater is the main source of water supply to both urban and rural populations as well as to industry and agriculture (Ali et al. [1]). As demand for groundwater increases, groundwater managers are faced with the difficult task of ensuring the future viability of the resource (Al-Bassam and Al-Rumikhani [2]). With the rise in public environmental awareness, groundwater managers are also concerned with protecting natural environments that are dependent upon the ground water, such as stream base-flows, riparian vegetation, aquatic ecosystems, and wetlands. Sustainable use of groundwater must ensure not only that the future resource is not threatened by overuse and depletion, but also those natural environments that depend on the resource (Al-Bassam [3]). Trade-offs between groundwater use and potential environmental impacts always will exist, and therefore a balanced approach to water-use between development and environmental requirements needs to be adopted (Ali et al. [4]). To properly manage groundwater resources, managers need accurate information about the inputs (i.e., recharge) and outputs (i.e., pumpage and natural discharge) within each groundwater basin, so that the long-term behavior of the aquifer and its sustainable yield can be estimated or reassessed (Ali and Abustan [5]; Al-Bassam [3]).

Bangladesh is an agrarian country, and 85% of its population depends on agricultural activities, whether directly or indirectly. The livelihood of the inhabitants and national development activities largely depend on the success of agricultural production. Agriculture plays a major role in the national economy and is the second largest sector in gross national product (GDP). Groundwater is the main source of water supply to both urban and rural populations as well as to industry and agriculture.

Quantitative determination of the rate of natural groundwater recharge is a pre-requisite for efficient groundwater resource management. It is particularly important in regions with large demands for ground water supplies, where such resources are the keys to economic development. Recharge is critical in any analysis of groundwater systems and the impacts of withdrawing native water from them. It is also required for robust model predictions as groundwater recharge is one of the main drivers of the hydrological system (Ali [6]). In water-resource investigations, groundwater models are often used to simulate the flow of water in aquifers, and, when calibrated, may be used to predict long-term behavior of an aquifer under various management schemes. Without a good estimate of recharge and its spatio-temporal distribution, these models become unreliable.

Numerous studies focused on various approaches and methods of recharge estimation. These range from simple seepage meter method to complex numerical modeling and isotropic tracer techniques - under different physiographic, climatic condition, technology level, and resource availability situations. Recharge has been estimated by lysimeter (Rushton et al. [7]; Xu and Chen [8]), water table fluctuation method (Callahan et al. [9]; Ordens et al. [10]), water balance method; base-flow /hydrograph-separation (Risser et al. [11]), soil moisture budget (Cuthbert et al. [12]; Bakundukize et al. [13]), Darcyan flow-net computation (Yuan et al. [14]), empirical methods (Okey et al. [15]), radioactive isotopic tracer (Jimenez-Martinez et al. [16]), stable isotopes (Yeh et al. [17]; Sukhija et al. [18]), and modeling approach (Yidana et al. [19]; Githui et al. [20]). Approaches for specific local conditions have also been advocated, such as for arid and semi-arid regions (Wood and Sanford [21]), granitic terrain (Chand et al. [22]), land-use change (Walker et al. [23]), etc. Many researchers advocated for using multiple methods to increase reliability in recharge estimate. But it involves huge cost, manpower and instruments.

Lin et al. [24] used environmental tracers (Cl, F and $SO_4$) to estimate groundwater recharge beneath irrigated farmland of North China plain. Wang et al. [25] used bromide and tritium tracers to estimate recharge in Hebei plain, China under varying land use practices. They found average recharge rate and recharge coefficient as 0.00-1.05 mm/d and 0.0 -42.5%, respectively. Sibanda et al. [26] estimated groundwater recharge from precipitation for the semi-arid Nyaqmandhlovu area, Zimbabwe using chloride mass balance, water-table fluctuation, Darcian flownet computation, $^{14}C$ age dating and groundwater modeling. The recharge rate found were 19-62, 2-50, 16-28, 22-25, and 11-26 mm/yr, respectively. They noted that, based on the groundwater modeling, a final estimate for recharge on the order of 15-20 mm/yr (2.7-3.6% of the annual precipitation of 555 mm/yr) is believed to be realistic.

Different methods have limiting conditions and varying degree of data requirement. The water-table fluctuation method can be applied only for unconfined aquifer. The flownet method needs information regarding transmissivity values and groundwater level contour lines. The groundwater dating method needs estimation of porosity of the aquifer and depth of saturation zone. Groundwater modeling approach requires calibration of the model for the study aquifer – which needs good set of data (specially permeability values). The accuracy of the water balance method depends on the accuracy of the other components in the water balance equation, specially surface runoff. The conservative tracer, like chloride, has advantages over the other methods. The applied tracer can be traced from sampling, through laboratory technique.

The objective of the present study was to estimate the yearly recharge under field condition at North-eastern region, Mymensingh District of Bangladesh. Based on the technical performance and resource availability, we used chloride tracer, water balance method, and drainage lysimeter.

## 2. MATERIALS AND METHODS

### 2.1 Description of the Study Area

#### 2.1.1 Site location

The north-eastern region of Bangladesh is part of the Ganges Alluvial Plain, and it covers the districts of Mymensingh, Sherpur, Netrakona, and Kishorgong (known as the greater Mymensingh area). This region is situated between 25°33´ to 26°32´ North and 89°55´ to 90°51´ East, and it covers a geographical area of 2.0 million hectares. The present study is, however, based on part of a configuration of Mymensingh district (Fig. 1).

#### 2.1.2 Topography and hydro-geological conditions

The topography of the study area is plain. The surface soils are alluvial in nature, varying from sandy loam to clay loams having a deep clay profile. The sub-surface aquifers are alluvial in nature, and are composed of a heterogeneous complex mass of fine sands, coarse sands, and gravels. The hydraulic conductivity varies between 5–10 $m^3/m^2$/day, and produces a specific yield between 0.10–0.30 (Mojid [27]).

Rice, wheat, and pulses are the principal crops, with some areas also used for horticultural crops. The cropping intensity of the area is approximately 175%, with rice in common for cropping patterns both of the *kharif* (summer) and *rabi* (winter) seasons. Approximately 5% of the area of this zone is severely affected by soil and water erosion due to steep slopes and high rainfall. In most parts, the depth to the water-table is approximately 20 - 30 m, but in some places (especially in deep alluvial deposits), the underground reservoirs are deep (80 – 100 m), with water quality ranging from good to excellent in most of the region.

#### 2.1.3 Rainfall pattern of the area

The annual rainfall at the study site varies from 1,600 mm to 3,400 mm. Approximately 70% of this rainfall occurs during the months of May – August, which is noted as monsoon season (Fig. 2). The yearly rainfall fluctuates considerably.

### 2.2 Tracer Application and Principle of the Technique

Before the beginning of rainy season (in March), a rice field (medium land) was selected for tracer application. To prepare the 'Test tracer plot', a square of 1.5 m $\times$ 1.5 m was first selected and marked. At the outer edge, a 0.6 m deep small hole (6 inch wide) was dugged. A continuous polythene sheet was placed in the hole, and then the soil was covered. This was done to eliminate the lateral flow of water and chloride from the 'Test' unit. Wthin the test plot, chloride ion solution [prepared by dissolving analytical grade KCL in distilled water, with sufficient concentration, about 250 ppm, so that it can be traced easily] was applied/pushed at 20 cm soil depth by 'siring/hand-pump', at the centre and four mid-corner (Fig. 3). At each point, the amount was about 25 ml. The tracer was applied at 20 cm soil depth to avoid surface runoff of the applied tracer.

Infiltration of precipitation/rainfall transports the tracer downward. At the end of rainy season (in October), a trench was dugged at the centre of the 'test plot' and samples were collected up to 200 cm, at 10 cm interval. The Cl concentration of the collected samples were determined by Mohr method (Doughty [28]; Harris [29]), using micro-burette having 0.01 mm readable facility. The subsurface distribution of applied tracer was determined from the concentration graph of chloride.


**Fig. 1. Map of Bangladesh showing study area (● Black Mark)**

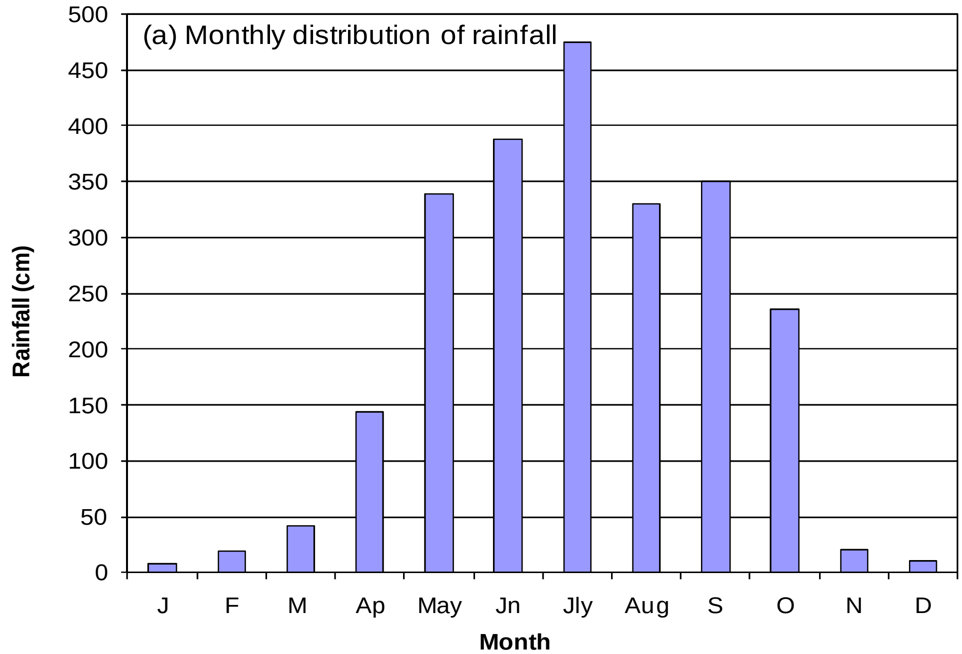


**Fig. 2. Long-term monthly average rainfall in the study area**

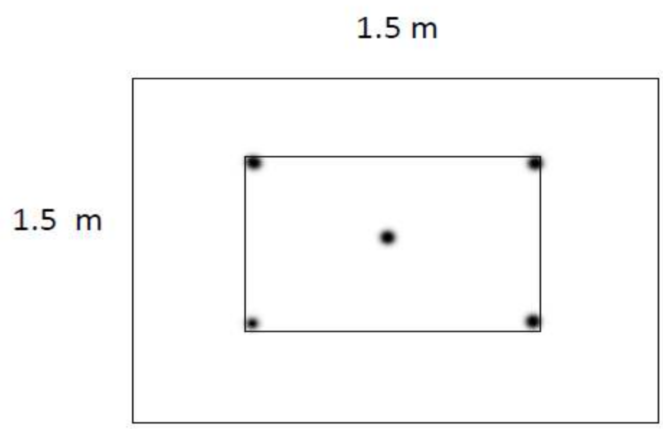


**Fig. 3. Schematic of tracer test unit (indicating tracer application point)**

The vertical distribution of the tracer was used to estimate the velocity (v), and the recharge rate (R) was calculated as (Chand et al. [22]; Scanlon et al. [30]):

$$R = v\theta = \frac{\Delta z}{\Delta t}\theta \quad (1)$$

Where, $\Delta z$ is the depth of the tracer peak, $\Delta t$ is the time between tracer application and sampling, and $\theta$ is the average volumetric water content.

### 2.3 Lysimeter Method

In two series, 10 Lysimeter boxes (5 in each series, 2 m × 1 m × 1.5 m each) were used in this study. Drainage was collected and the volume was measured from each Lysimeter box, on the next day of each heavy rainfall events (to avoid restriction on bottom boundary layer), and 7 days interval for the remaining days (including moderate rainy days). The volume was converted to depth of water (mm) by dividing the area of the lysimeter box. The collected drainage was considered as equivalent of recharge.

The depth to the water-table was recorded in observation well using Water-level indicator.

## 2.4 Water Balance Method

A simplified form of water balance equation (Yin et al. [31]) was used to estimate recharge:

$$P = R_0 + R + ET_a + \Delta SM \qquad (2.1)$$

where: P = rainfall (mm), $R_0$= surface runoff (mm), R = recharge, $ET_a$ = actual evapo-transpiration (mm), and ΔSM= change in soil moisture (mm) for the specified time interval. Neglecting the change in soil moisture, and re-arranging, the recharge (R) can be expressed as:

$$R = P - R_0 - ET_a$$

### 2.4.1 Runoff estimation – a modified SCS method

The USDA-SCS runoff equation is (USDA-SCS [32]):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (2.2)$$

Where: Q= runoff (mm), P = rainfall (mm), S= potential maximum retention after runoff begins (mm). The potential retention (*S*) can range from zero on smooth, impervious surface to infinity in deep gravel.

In the present study, a modified form of USDA-SCS method is used [subtracting the ‘actual evapotranspiration ($ET_a$)’ from ‘Rainfall (P)’ in equation (2.1)]:

$$Q = \frac{[(P - ETa) - 0.2S]^2}{(P - ETa) + 0.8S} \qquad (2.3)$$

Based on the field condition during the monsoon rainfall (i.e. grassy/cropped), the ‘S’ value is considered as 3.0 cm; and monthly values of runoff (and hence monthly recharge) was calculated.

### 2.4.2 $ET_a$ calculation

Daily reference crop evapotranspiration ($ET_0$) was calculated using ‘*$ET_0$ Calculator*’ software of FAO (FAO [33]). Traditionally, actual crop evapotranspiration ($ET_a$) is calculated as:

$$ET_a = ET_0 \times K_c \times K_s = (ET_0 \times K_c) \times K_s = ET_p \times K_s$$

where: $ET_0$ is the reference crop evapotranspiration (mm), $K_c$ is the crop coefficient, $K_s$ is the soil moisture stress factor (or dryness factor), $ET_p$ is the potential crop evapotranspiration.

From daily values, monthly values of $ET_a$ were calculated. Based on the ‘dryness (or water deficit)’ and ‘wetness (or water surplus)’ condition (i.e. P - $ET_p$, P is the rainfal), the monthly actual crop evapotranspiration ($ET_{am}$) was calculated as:

$$\begin{aligned} ET_{am} &= ET_{mp}, \quad \text{If } P_m > ET_{mp} \quad (\text{i.e. } K_s = 1) \\ &= P_m, \quad \text{If } P_m < ET_{mp} \end{aligned} \qquad (2.4)$$

where: $P_m$ is the monthly rainfall, $ET_{mp}$ is the monthly potential evapotranspiration.

## 2.5 Lysimeter Method

In two series, 10 Lysimeter boxes (5 in each series, 2 m × 1 m × 1.5 m each) were used in this study. Drainage was collected and the volume was measured from each Lysimeter box, on the next day of each heavy rainfall events (to avoid restriction on bottom boundary layer), and 7 days interval for the remaining days (including moderate rainy days). The volume was converted to depth of water (mm) by dividing the area of the lysimeter box. The collected drainage was considered as equivalent of recharge.

The depth to the water-table was recorded in observation well using Water-level indicator.

# 3. RESULTS AND DISCUSSION

## 3.1 Rainfall, ET0 and Groundwater Level Fluctuation Pattern during the Study Period

The yearly total rainfall during 2014, 2015 and 2016 were 1916 mm, 2077 mm and 1934 mm, respectively. The distribution of rainfall throughout the year varied considerably (Fig. 4). The atmospheric water demand, that is, reference crop evapotranspiration (ET0) during the years are depicted in Fig. 5.

The perched/artician water-table near the study field, in response to recharge from rainfall, is depicted in Fig. 6.

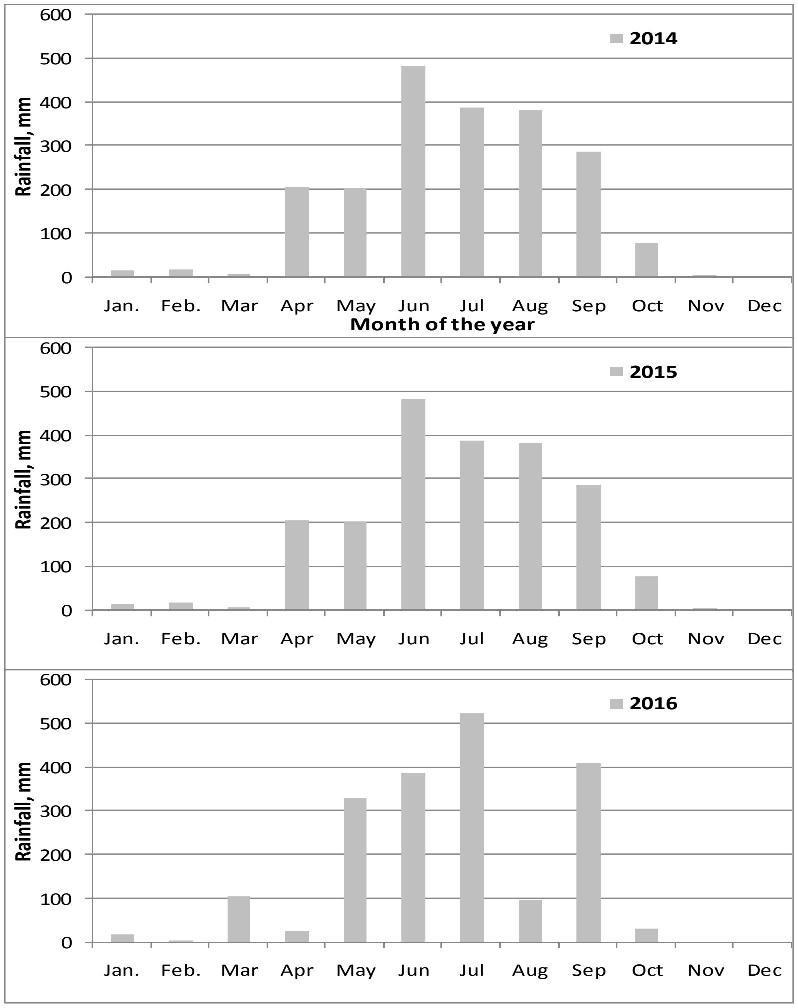


**Fig. 4. Monthly total rainfall during the study period**

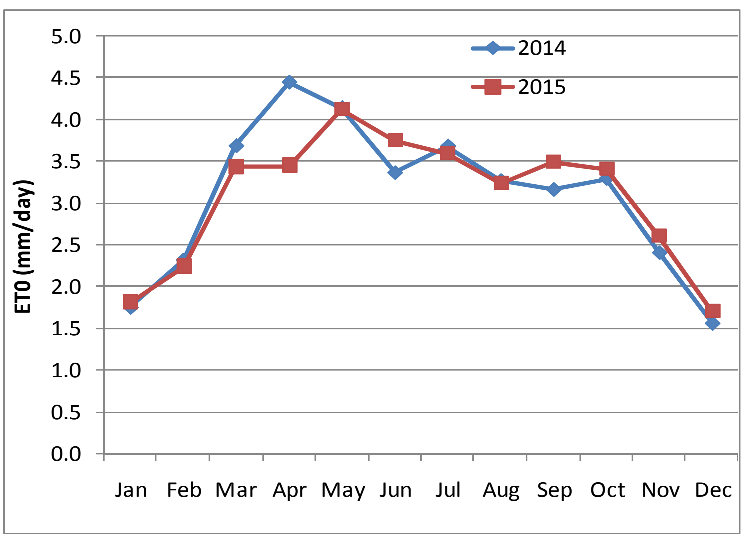


**Fig. 5. Monthly total ET0 pattern during the study period**

### 3.2 Recharge from Lysimeter Study

#### 3.2.1 Year 2014

The annual recharge pattern is depicted in Fig. 7. The mean value is 37.8 mm (with SD 21.5 mm and CV 57%), which is 1.97% of yearly rainfall. In this method, the mean annual recharge was estimated as 39 mm, which is about 2% of yearly rainfall.

### 3.3 Recharge from Water-balance Method and Tracer Technique

The tracer concentration profile at the sampled sites is depicted in Fig. 8. The recharge rate found using tracer and water balance method for the year 2014, 2015, and 2016 are summarized in Table 1.

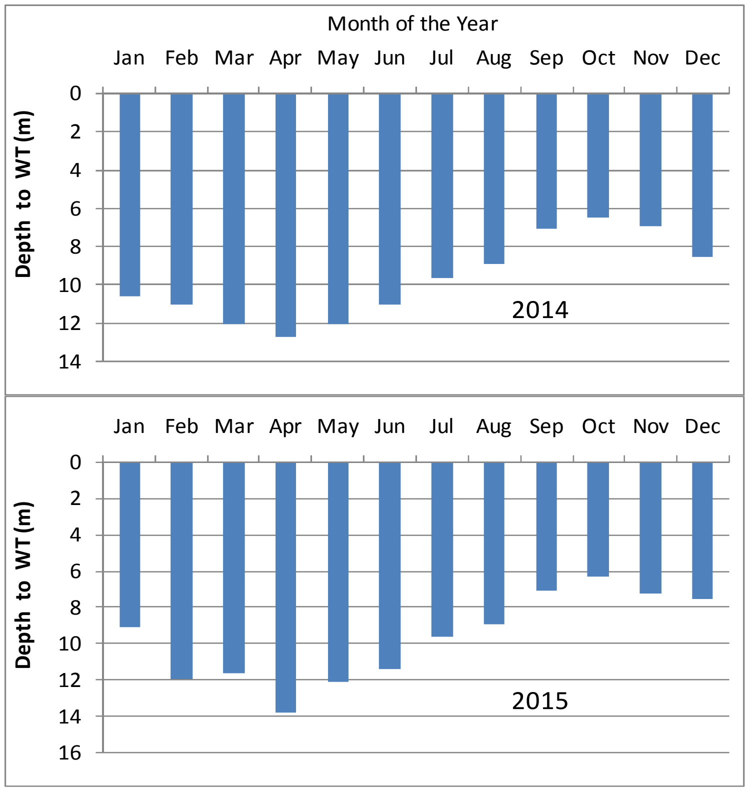


**Fig. 6. Water-table patter near the study field**

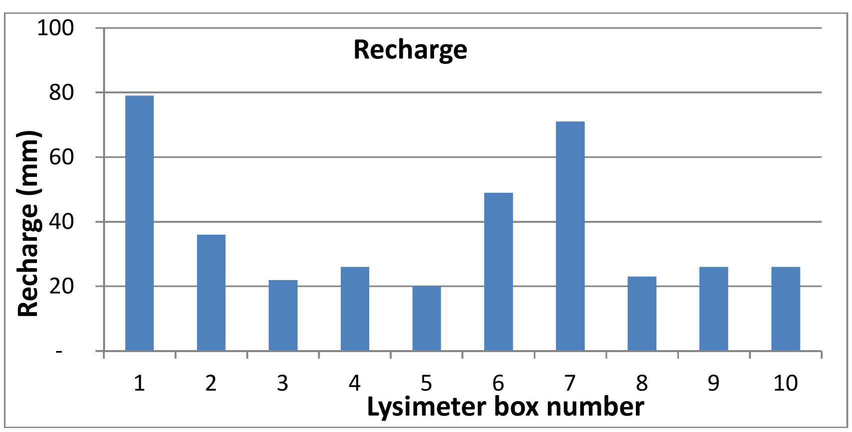


**Fig. 7. Pattern of recharge amount under different lysimeter boxes**

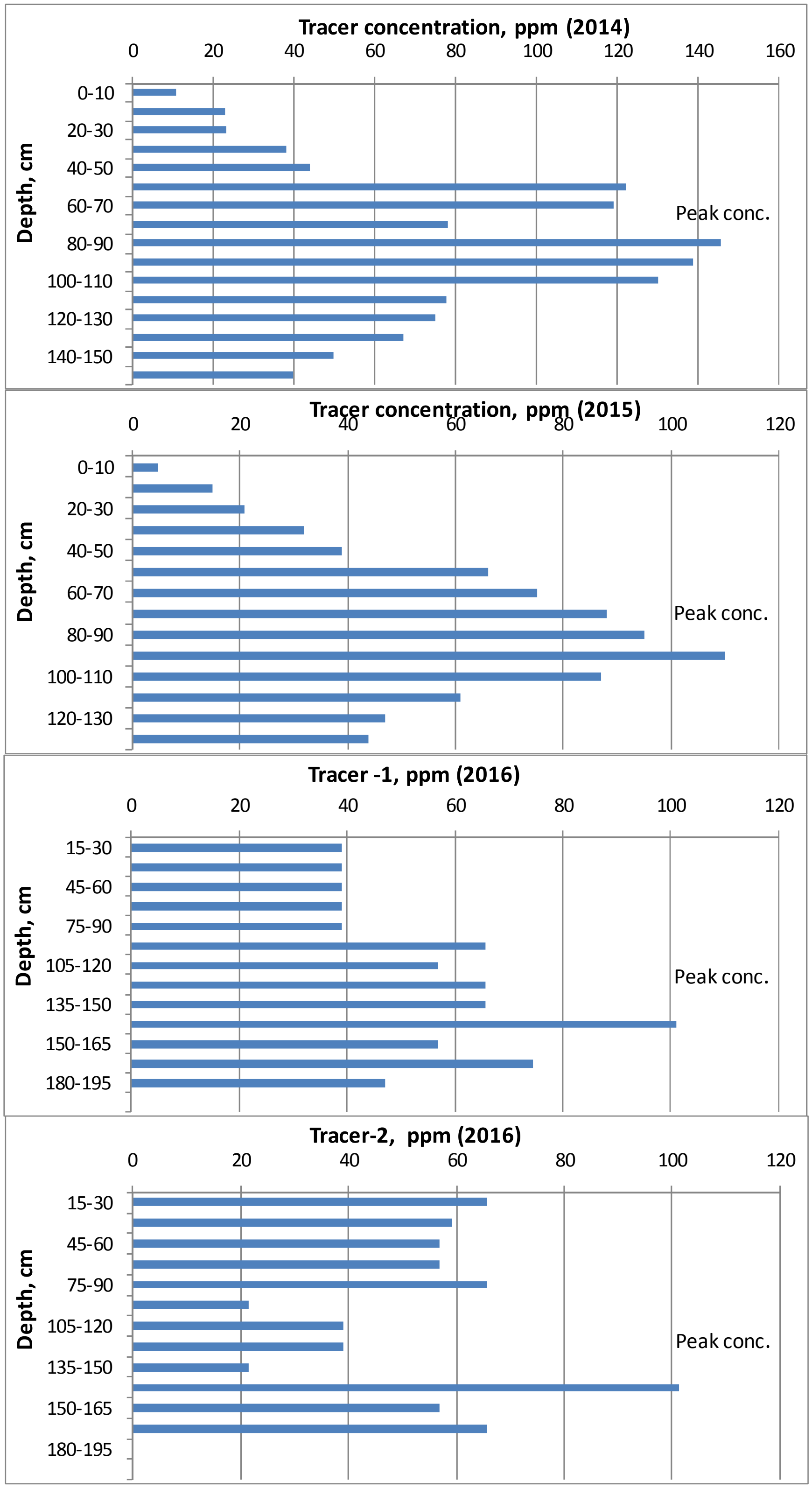


**Fig. 8. Concentration profile of chloride in different years**

**Table 1. Recharge rates under different methods and years**

| Year | Rainfall, mm | Recharge rate, mm/yr | | Recharge rate, % of rainfall | | Average recharge rate, mm/yr | |
|---|---|---|---|---|---|---|---|
| | | Tracer | Water balance | Tracer | Water balance | Tracer | Water balance |
| 2014 | 1916 | 196 | 139 | 10.2 | 7.3 | 228.7 | 141.7 |
| 2015 | 2068 | 257 | 156 | 12.4 | 7.5 | | |
| 2016 | 1934 | 233 | 130 | 11.0 | 6.7 | | |

The recharge rate found using tracer technique ranged from 196 mm to 257 mm under the rainfall range of 1916 mm to 2068 mm, which in terms of percentage of rainfall, ranged from 10.2% to 12.4%.

The recharge rate found using water balance method ranged from 130 mm to 156 mm under the rainfall range of 1916 mm to 2068 mm, which in terms of percentage of rainfall, ranged from 6.7% to 7.5%.

When averaged over years, the recharge rate under tracer technique was found as 228.7 mm/year; and 141.7 mm under water balance method. The recharge rate found from Lysimeter was much lower than those of water balance and tracer technique. This may be due to compaction, or not representative of field condition. Lysimeter soils cannot represent spatial variability produced by natural and human-induced changes in surface- and subsurface-flow pathways.

When compared the 'Water Balance' and 'Tracer technique', the differences are reasonable. In terms of accuracy, the tracer technique can be considered more reliable than the 'Water Balance' method. It is to be mention here that, in water balance method, the runoff equation of USDA-SCS has been modified by incorporation (substraction) of actual ET. Accuracy of recharge estimates using this approach depends on accuracy of other components. It is not easy to measure all the components with sufficient accurately. Water budget method yields reasonable estimates of recharge when the precipitation exceeds actual evapotranspiration (ETa). However, if the ETa is similar magnitude to precipitation (such as under semi-arid conditions), the recharge estimated by this approach must be treated with caution (Sharma 1986; Lerner et al. 1990). But in our study area, the ETa was much lower than precipitation. As a result, the modified equation yielded better results.

The tracer technique is based on the conservation of mass of the tracer, and the assumption that the tracers moves freely with water, no other sources of the tracer nor no absorption or uptake by the soil/rock or by vegetation. Applied tracers give more accurate recharge estimates because it is driven by recharge component (i.e. independent of runoff). The main advantages of the applied tracers are that the investigators have control over the timing, placement, and amount of tracer (Wang et al. [25]). In addition, the complexities of the top meter of soil (action of roots, and cultural disturbances) can be avoided if tracers are injected below disturbance layer (runoff or root).

## 4. CONCLUSION

Recharge is a major component of the groundwater system, and has important implications for shallow groundwater quality. Quantitative determination of the rate of natural groundwater recharge is a pre-requisite for efficient groundwater resource management. Applied tracer technique gives more accurate recharge estimates under both conditions of ET>rainfall and ET<rainfall. The three years average of recharge rate at Mymensingh location was found as 228.7 mm/year under tracer technique; and 141.7 mm under water balance method.

Accuracy of recharge estimates using water balance approach depends on the accuracy of other components. Water balance method yields reasonable estimates of recharge when the precipitation exceeds actual evapotranspiration (ETa). Thus, among the methods, I recommend the tracer technique as first option. The second option is 'Water balance method' subject to accurate estimation of the water balance components.

## COMPETING INTERESTS

Author has declared that no competing interests exist.

## REFERENCES


1. Ali MH, Sarkar AA, Rahman MA. Analysis on groundwater-table declination and quest for sustainable water use in the North-western region (Barind area) of Bangladesh. J. of Agril. Sci. and Applications. 2012;1(1):26-32.
2. Al-Bassam A, Al-Rumikhani YA. Integrated hydrochemical method of water quality assessment for irrigation in arid areas: Application to the Jilh aquifer, Saudi Arabia. J. African Earth Science. 2003;36(4):346-356.
3. Al-Bassam A. Hydrochemical evaluation of the Miocene-Pliocene aquifer system in northern Saudi Arabia. Earth Sciences. 2005;16(1):1-20.
4. Ali MH, Abustan I, Rahman MA, Haque AAM. Sustainability of groundwater resources in the north-eastern region of Bangladesh. Water Resour. Manage. 2011;26:623-641.
5. Ali MH, Abustan I. Methods and approaches of groundwater investigation, development, and management. In: Dominic P. Torres (Edit.) Water Engineering. Nova Science Publishers, Inc, NY. 2011;1-122.
6. Ali MH. Principles and practices of water resources development and management. Nova Science Publishers, Inc, NY, USA; 2016. ISBN: 978-1-63485-175-6
7. Rushton KR, Eilers VHM, Carter RC. Improved soil moisture balance methodology for recharge estimation. J. Hydrol. 2006;318:379-399.
8. Xu CY, Chen D. Comparison of seven models for estimation of evapotranspiration and groundwater recharge using lysimeter measurement data in Germany. Hydrol. Process. 2005;19:3717–3734.
9. Callahan TJ, Vulava VM, Passarello MC, Garrett CG. Estimating groundwater recharge in lowland watersheds. Hydrol. Process. 2012;26:2845-2855.
10. Ordens CM, Werner AD, Post VEA, Hutson JL, Simmons CT, Irvine BM. Groundwater recharge to a sedimentary aquifer in the topographically closed Uley south Basin, South Australia. Hydrogeol. J. 2012;20:61-72.
11. Risser DW, Gburek WJ, Folmar GJ. Comparison of recharge estimates at a small watershed in east-central Pennsylvania, USA. Hydrogeol. J. 2009;17:287–298.
12. Cuthbert MO, Mackay R, Nimmo JR. Linking soil moisture balance and source-responsive models to estimate diffuse and referential components of groundwater recharge. Hydrol. Earth syst. Sci. 2013;17: 1003-1019.
13. Bakundukize C, Camp MV, Walraevens K. Estimation of groundwater recharge in Bugesera region (Burundi) using soil moisture budget approach. Geologica Belgica. 2011;14(1-2):85-102.
14. Yuan R, Song X, Han D, Zhang Y, Zhan L, Zhang B, Long X, Yu Y. Rate and historical change of direct recharge from precipitation constrained by unsaturated zone profiles of chloride and oxygen-18 in dry river bed of North China plain. Hydrol. Process. 2012;26:1291-1301.
15. Oke MO, Martins O, Idowu O, Aiyelokun O. Comparative analysis of empirical formulae used in groundwater recharge in Ogun –Oshun River Basins. Journal of Scientific Research & Reports. 2013;2(2):692-710.
16. Jimenez-Martinez J, Tamoh K, Candela L. Vadose zone tritium tracer test to estimate aquifer recharge from irrigated areas. Hydrol. Process. 2013;27(22):3150-3158.
17. Yeh HFu, Haw LC, Hsu K. Chin, Chang P. Hsun, Wang C. Ho. Using stable isotopes for assessing the hydrologic characteristics and sources of groundwater recharge. J. Environ. Eng. Manage. 2009;19(4):185-191.
18. Sukhija BS, Reddy DV, Nagabhushanam P, Bhattacharya SK, Jani RA, Kumar D. Characterisation of recharge processes and groundwater flow mechanisms in weathered-fractured granites of Hyderabad (India) using isotopes. Hydrogeol. J. 2006;14:663–674.
19. Yidana SM, Fynn OF, Chegbeleh LP, Nude PM, Asiedu DK. Hydrological conditions of a crystalline aquifer: Simulation of optimal abstraction rates under scenarios of reduced recharge. The Scientific World Journal; 2013.
    DOI:http://dx.doi.org/10.1155/2013/606375
20. Githui F, Selle B, Thayalakumaran T. Recharge estimation using remotely sensed evapotranspiration in an irrigated catchment in southeast Australia. Hydrol. Process. 2012;26:1379-1389.
21. Wood WW, Sanford WE. Chemical and isotopic methods for quantifying groundwater recharge in a regional,

semiarid environment. Ground Water. 1995;33(3):458-468.
22. Chand R, Hodlur GK, Prakash MR, Mondal NC, Singh VS. Reliable natural recharge estimates in granite terrain. Current Sci. 2005;88(5):821-824.
23. Walker GR, Jolly ID, Cook PG. A new chloride leaching approach to the estimation of diffuse recharge following a change in land use. J. Hydrol. 1991;128(1-4):49-67.
24. Lin D, Jin M, Liang X, Zhan H. Estimating groundwater recharge beneath irrigated farmland using environmental tracers fluoride, chloride and sulphate. Hydrol. J. 2013;21:1469-1480.
25. Wang B, Jin M, Nimmo JR, Yang L, Wang W. Estimating groundwater recharge in Hebei Plain, China under varying land use practices using tritium and bromide tracers. J. Hydrol. 2008;356:209–222.
26. Sibanda T, Nonner JN, Uhlenbrook S. Comparison of groundwater recharge estimation methods for the semi-arid Nyamandhlovu area, Zimbabwe. Hydrogeology J. 2009;17:1427-1441.
27. Mojid MA, Talukder MSU, Ahmed M, Alam MS. Recharge and depletion characteristics of Muktagacha aquifer, Mymensingh. Bangladesh J Agril Sci. 1994;21(1):49-59.
28. Doughty HW. Mohr's method for the determination of silver and Halogens in other than neutral solutions. JACS. 1929;46:277-2709.
29. Harris DC. Quantitative chemical analysis. Seventh Edition, Freeman & Co., NY, Section 26-5; 2007.
30. Scanlon BR, Healy RW, Cook PG. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 2002;10:18-39.
31. Yin L, Hu G, Huang J, Wen D, Dong J, Wang X, Li H. Groundwater-recharge estimation in the Ordos Plateau, China: Comparison of methods. Hydrogeol. J. 2011;19:1563-1575.
32. USDA-SCS. National engineering handbook, section 4 – hydrology. Washington, D.C., USDA-SCS; 1985.
33. FAO. ET0 software. FAO, Rome, Italy; 2012.



*Peer-review history:*
*The peer review history for this paper can be accessed here:*
*http://sciencedomain.org/review-history/22084*