Comparison of Quantifying Groundwater Recharge

by Doddy Heka Ardana

Comparison of Quantifying Groundwater Recharge

Putu Doddy Heka Ardana[1,4], Wayan Redana[2], Mawiti Infantri Yekti[2], Nengah Simpen[3]
{doddyhekaardana@unr.ac.id[1], iwayanredana@yahoo.com[2], mawiti91@gmail.com[3],
simpen.nengah@yahoo.com[4]}

Doctor of Engineering Study Program, Udayana University, Bali[1], Civil Engineering Study Program of Udayana University, Bali[2], Faculty of Math and Natural Sciences of Udayana University, Bali[3],
Civil Engineering Study Program of Ngurah Rai University, Bali[3]

Abstract. Groundwater recharge is an essential component in groundwater systems and central to confirming the suitable management of aquifers. Several approaches in selecting a method approximations based on a different method, other factors limit the application of the method. Research of the groundwater recharge is important to be used in determining the scale of space/time of the recharge estimates. In this study, multiple recognized methods for predicting groundwater recharge were discussed, involving the fluctuated of water-table method (WTF), Darcian approach, the water budget, soil water balance approach, rainfall infiltration factor, tracer techniques which involving chloride mass-balance and isotope dating method, all of which approached with dissimilar assumptions and data requirements. In this paper, various techniques for predicting groundwater recharge are outlined and critically assessed concerning their limitations.

Keywords: Groundwater recharge, WTF method, Darcian approach, the water budget, soil water balance, rainfall infiltration factor, tracer techniques

1 Introduction

Development sustainability in any area is influenced by the availability and renewability of freshwater resources. The freshwater can be used by humans to carry out of life. Freshwater comes from two sources, surface water and groundwater. Groundwater is an imperative natural source and a main factor of the hydrologic system. Groundwater is very important and has become most precious natural resources to support human health, economic development and ecological variety. Groundwater utilization for humans life has been used for a long time. The consumption of groundwater has risen rapidly over time, so in the last few decades, it has become a limited source of water and is vulnerable to contamination. Therefore, these vital natural resources must be protected. One of the most main elements in groundwater supply valuation or aquifer susceptibility is the value at which water in the system is refilled or called the rate of groundwater recharge [1].

In a groundwater system, groundwater recharge is the most central factor in the water budget. The fundamental for every analysis in the sustainability of groundwater sources is to understand and quantifying the groundwater recharge processes [2]–[4]. The assessment of the sustainable yield of groundwater aquifers is depended on the form the measurement of the recharge. The information of aquifer sustainable yield is significant for utilization of the groundwater resources reasonability and sustainability [3]–[5]. Groundwater recharge is described as the total precipitation element falling into a drainage basin which eventually reaches the water table in the phreatic zone from any direction defined by the hydraulic requirement [6]–[8]. In the calculation of the groundwater recharge, the study area is the main consideration. In further, the variable of groundwater recharge is at all scales, in both space and time and that also means the recharge predicting includes be around some quantifiable factors in period and area [2]. The recharge estimates in scales of space/time are central because diverse research goals involve recharge estimates over different space and/or time scales [3]. Besides space and time scales, some control variables also affect recharge estimate. Some factors that influence the groundwater recharge estimation including the rainfall, evapotranspiration, infiltration, percolation, the humidity , geology, the nature of the soil, groundwater level and aquifer characteristics, herbs and area usability, land slope and landform [3], [9], [10]. Based on the complexity of the control variables and the uncertainty of the recharge estimate, it is one of the most vital elements in groundwater research. However, the recharge is also one of the least understandable, largely because recharge rates vary widely in space and time, and the value is difficult to directly measure [1].

Various complexity methods are used to estimate groundwater recharge wich cannot be calculated directly [3]. Variances in sources and procedures of groundwater recharge will mean that the appropriate rate of obtainable estimation methods will differ. The method used by a hydrologist is usually based on the best estimation with a method that is relatively easy to apply with hydrological data availability. The various techniques which usually used to quantify recharge from the various sources are direct measurement, water balance methods, Darcian approaches, water table fluctuation method, a fixed factor of annual rainfall, tracer techniques (i.e isotope dating and chloride mass balance equations), analysis of baseflow hydrographs, spring discharges, water-table fluctuations, empirical methods, numerical modelling, water budgeting [3], [9]–[12].

Because recharge is a significant element of groundwater and various approaches commonly apllicated to predict it, in this study discussed how the recharge represented and estimated. The aims of this study are to delineate the aspects of the several methods used in the assessment of recharge based on the suitability of the space and time scale and advantages or limitations of a specific method.

2 Methods

The methodology adopted in this study was traditional literature review of descriptive exploratory character. The number of techniques is obtainable in the literature for the estimation of groundwater recharge to the aquifer, depends on data availability, geographic area and topographic, consideration of spatial and temporal and dependability of results acquired by various techniques. The techniques of recharge estimation can be categorized according to hydrogeological area [13], hydrologic zones [3], physical, numeric modelling, and tracer techniques [3], [13], [14]. Further will be explained about various techniques of recharge estimate.

2.1 Water Table Fluctuation (WTF) Method

Water table fluctuation (WTF) method. This technique is one of a physical method in the saturated zone or unconfined aquifer. The main indicator of actual aquifer recharge in the WTF method is the water table rise after precipitation events. The fluctuating of water levels depend on form recharge and discharge, and the range of the effect of two these elements is controlled by specific yield factor (S_y) which it depends on the structure and the texture of the sediments of the aquifer. Thus, the WTF method principle is the rises of groundwater table in an unconfined aquifer and shallow unsaturated (vadose) zone as a result of water being added to the water table [1][15]. The recharge estimation is given in equation (1)

$$R = S_y . \frac{dh}{dt} = S_y . \frac{\Delta h}{\Delta t} \quad . \tag{1}$$

With S_y is specific yield and ΔH is water level fluctuation in interval Δt. This method assumption is water table rising when the unconfined aquifer receives more water by recharging, see **Figure 1**, the previous decline curvature is the track that the hydrograph will be monitored in the lack of the recharging rainfall [15][16].

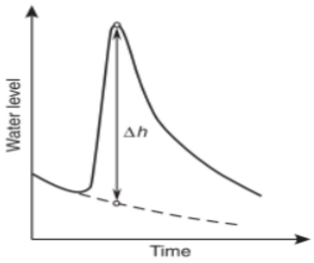

Fig. 1. Assumtion of water table fluctuation method in response to rainfall.

The assumption of derivation in equation (1) that water reaching the water table goes immediately into storage and sufficient time is required for the entry process. Some elements that cause the need for time including baseflow, groundwater evaporation, and net sub-surface flow in the area. The difference between peak water level rise and the value of the antecedent recession curve that is extrapolated at the peak is a calculation of the increase in water level. The methods usually used to predict water table escalation are graphical extrapolation and calculation from a master recession curve (MRC).

The other important factor in the use of water table fluctuation techniques in recharge estimation is specific yield (S_y). The specific yield, S_y, is the fraction of water that will drain by gravity from a volume of soil or rock or the difference among total porosity and the contentment of water at field capacity, see equation (2).

$$S_y = \phi - S_r \quad . \tag{2}$$

Where ϕ is porosity and S_r is specific retention (the volume of water retained by the rock per unit volume of rock). For the unconfined aquifers, the S_y values range from 0.01 to 0.30, which they are much greater than the values of storativities of confined aquifers [17]. The rock type or the unconsolidated sediments very influential on specific yield value, and the connection between porosity and specific yield is complex depending on the effect of certain deposit texture [18], [19] see **Table 1**, cementation and compaction [20].

Table 1. The value of Sy [18].

Soil Type	Average specific yield	Coefficient of variations (%)	Minimum specific yield	Maximum specific yield	Number of determinations
Clay	0.02	59	0.0	0.05	15
Silt	0.08	60	0.03	0.19	16
Sandy clay	0.07	44	0.03	0.12	12
Find sand	0.21	32	0.10	0.28	17
Medium sand	0.26	18	0.15	0.32	17
Coarse sand	0.27	18	0.20	0.35	17
Gravelly sand	0.25	21	0.20	0.35	15
Fine gravel	0.25	18	0.21	0.35	17
Medium gravel	0.23	14	0.13	0.26	14
Coarse gravel	0.22	20	0.12	0.26	13

Because no hypotheses are made on the procedure by which water reaches to groundwater causing the WTF techniques is quite easy to use. Another side, the method has some weaknesses also. Water table fluctuation method is appropriate to only unconfined aquifers and the techniques can not measure for a stable recharge rate. Other weaknesses arise in the calculation of specific yield rates.

Many researchers have tried this method to predict the phenomena. The watertable fluctuation approach was used to assess the periodic and yearly variants in increase of water table and to predict the replenishment [21][22]. Quantification of the natural recharge from precipitation in the south-middle part of Erbil basin – Iraq was used the WTF method [15]. Quantitative groundwater recharge estimation in a shallow unconfined aquifer in Bangladesh is presented in details by the analysis of observed precipitation and water level fluctuations records [23]. The combination of WTF approach and Boussinesq formula also aplicated by [24] to predict groundwater replenishment. [25] presented a quantitative and qualitative analysis of water table fluctuations of the shallow aquifer of the Gulf of Urabá in Antioquia – Colombia, using the hourly water table records and daily aggregated records. The rainfall was found as the most influential meteorological variable in the water table fluctuations. The water-table fluctuation method has been used too for estimating groundwater recharge by analysis of water level measurements in observation wells in Korea with consideration regarding the effect of stream-aquifer interactions [26]. Extensive reviews on the groundwater recharge estimation that are based on the variations in water table level and uses of specific yield were provided by [16].

2.2 Darcian Method

Darcian method. This method based on the Darcy Law which applied to predict flow through in the aquifer. It is one of a physical method in the saturated zone or unsaturated zone. Groundwater replenishment can be estimated if each of the top gradients and hydraulic conductivity is regarded. That is suitable with Darcy's equation for liquid flow. Darcy's law is used to estimated recharge (R) in the unsaturated zone based on the equation (3).

$$
\begin{aligned}
R = -K(\theta)\frac{dH}{dz} &= -K(\theta)\frac{d}{dz}(h+z) \\
&= -K(\theta)\left(\frac{dh}{dz}+1\right)
\end{aligned}
\quad . \tag{3}
$$

where K(θ) is the hydraulic conductivity at the ambient water content, θ; H is the total head; h is the matric pressure head; and z is the horizontal distance between the two points where the hydraulic head is measured [3], [14]. This approach was used in many reasearch in arid and semiarid area or humid conditions which explained in [3], [27]. The Darcian method also applied to estimate the groundwater recharge at Yuca Mountain, Nevada and be compared with the other methods [28]. For the saturated zone, Darcy's law approach was used by [29] in [1] which measured the value of flow through the aquifer was separated by the contributing upgradient zone to contribute an estimate of replenishment.

2.3 Water Budget Method

Water budget method. A water budget is a calculating of flow mobility inside and outside, and retention alteration within, some control volume and it is fundamental to the conceptualization of hydrologic systems at all scales [1]. This approach equation showing in (4):

$$
Water\ input - water\ output = change\ in\ storage \tag{4}
$$

According to [1], much hydrological research used a simple water budget analysis according to the descending of soil column from ground level to a certain extent and showing in equation (5):

$$
P = ET + \Delta S + R_{off} + D \tag{5}
$$

where P is rainfall; ET is evaporation and transpiration; ΔS is water stowage fluctuation; R_{off} is direct surface runoff (precipitation that does not infiltrate), and D is drainage out of the bottom of the column. The main elements in the water budget method can be seen in **Figure 2**.

The water budget methods in a basin-scale are based on water budget equation, see equation (6).

$$
P + Q_{in} = ET + Q_{out} + \Delta S \tag{6}
$$

where P is precipitation; Q_{on} and Q_{off} are water flow (in or out); ET is evapotranspiration; ΔS water stowage fluctuation [3], [31].

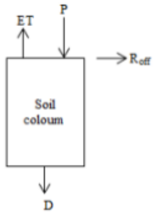

Fig. 2. Schematic diagram of water budget.

Corcerning to groundwater recharge, infiltration is an important factor which affects in achieving water in the saturated zone and can be written in equation (7) [32] in [31].

$$R = \left(Q_{off}^{gw} - Q_{in}^{gw}\right) + Q^{bf} + ET^{gw} + \Delta S^{gw} \qquad (7)$$

where R is recharge; $\left(Q_{off}^{gw} - Q_{in}^{gw}\right)$ are net surface flow from the basin; Q^{bf} is base flow; ET^{gw} is groundwater evaporation; and ΔS^{gw} is variation in subsurface stowage. Except for recharge, all elements in the above method can be estimated. This technique can be implemented for a varied range of spatial and temporal scales. However, the main limitation of this method is that the accuracy of the recharge estimates depends on the accuracy with which other elements of the water balance equation and measured [31].

The degree of connection between surface water and groundwater systems status is related to recharge and surface-water bodies. According to [8], [13], recharge estimation techniques for surface water-based and unsaturated zone based on water budget can be written in equation (8).

$$R = Q_{up} - Q_{down} + \sum Q_{in} - \sum Q_{out} - E_a + \frac{\Delta S}{\Delta t} \qquad (8)$$

with R is replenishment value; Q is stream value; Q_{up} and Q_{down} is upstream and downstream flow; ΣQ_{in} and ΣQ_{out} is in or out flow; E_a is the evaporation, and ΔS change of stowage over the variation in time (Δt)

2.4 Tracer Techniques

Tracer Techniques. Environmental, chemical, and heat tracers have been imperative in groundwater sustainability research, as they give answers around modern and noteworthy revive values at range of period changing for a long time. Determining the concentration of the environment tracers that designate groundwater age has been a popular approach in this field. In estimating groundwater recharge, approaches based on heat, isotopes, chemical tracers or natural tracers play an important role. Tracers have an extensive many uses in hydrological research: including predicted of replenishment based on quantifiable or quality, recognizing cause of replenishment, providing information on velocities and travel times of water movement, measuring the significance of preferential flow paths, presenting information on hydrodynamic dispersion, and providing data for calibration of water flow and solute transport models [3].

There are several tracers usually used in the research of groundwater recharge such as tritium (^3H), oxygen-18 (^{18}O), and deuterium (^2H), which are elements of the water molecule (H_2O) and are including in geochemical; environmental tracers as chloride (Cl^-) and bromide (Br^-); chemicals tracers such as nitrate (NO_3^-); applied organic dyes such as fluorescein ($C_{20}H_{12}O_5$); and soluble air including chlorofluorocarbons (CFC_s), sulfur hexafluoride (SF_6), and noble gases such as helium (He) and argon (Ar) [27].

The natural tracers were applied to predict groundwater replenishment while remaining a constant concentration of tracers below the rooting zone. The total chloride of ground water or ground water carried by groundwater infiltration is equivalent to the total deposition of chloride (wet and dry) on the surface of the soil. The main influenced of chloride on the surface are rainfall, aerosols, and irrigation [33]. Then, the ground water replenishment calculated by formula (9), based onthe principle of mass conservation [34].

$$P_{eff}\ x\left(Cl_p + Cl_s\right) = R\ x\ Cl_{sw} \qquad (9)$$

where P_{eff} is effective rainfall (L/T); Cl_p and Cl_s are the rainy chloride centralization and dry accumulation ($M/L^3/T$); R is the groundwater replenishment (L/T); Cl_{sw} is the chloride concentration (M/L^3).

Chloride is geochemical tracer which the most broadly used for recharge estimation. Chloride is profuse in nature, conventional in hydrologic circumstance, and readily analyzed. It techniques very beneficial in dry (arid) and semi-arid area [34]–[40]. In addition to natural and chemical tracers, heat is also useful for tracking the estimating aquifer recharge. The value of replenishment indication in superficial appereance under streams and other bases of water-based on trepidations of pure conductive dispersion of temperature variations between the land surface and the subsurface [41], [42].

2.5 Lysimeter

Lysimeter. The use of lysimeter is a method commonly used for hydrological research mainly the direct physical measurement of recharge flux (clean filtration). Lysimeter is a set of tools containing soil that is placed underground and collects water percolation. The main use of lysimeters was in agricultural studies, groundwater research for water souce and movements of pollutant. From lysimeters, the collected data is frequently used to adjust experiential formula or numerical method to verify other components such as evapotranspiration [2]. The benefit of lysimeters is the amount of water that drops through the root zone over a certain period of time can be measured directly, net infiltration flux is easily calculated, and also capture infiltration moving rapidly. While the weaknesses of lysimeters are their construction price expensively and problematic maintenance requirements [43]. The estimation of groundwater recharge with lysimeter has been researched as done by [44]–[50].

2.6 Empirical Methods

Empirical methods. Periodical groundwater balance can be used to build empirical relationships between groundwater replenishment and precipitation. An empirical relationship was recommended to predict of the groundwater replenishment by suitable estimation assessments of precipitation recharge and the relating values of precipitation in the rainy season through the non-linear regression techniques. The relation between precipitation and recharge is shown by equation (10) as Kumar and Seethapathi Formula [51].

$$R_r = 0.63(P - 15.28)^{0.76} \tag{10}$$

where R_r = groundwater recharge from precipitation in the rainy season and P = mean precipitation in the rainy season. In 1936, Chaturvedi formula was found based on the water level fluctuations and precipitation values in Ganga – Yamuna. This formula derived an empiricial relationship where recharge is a function of annual precipitation [51]. The formula is shown in equation (11).

$$R = 2.0(P - 15)^{0.4} \tag{11}$$

where R = net recharge from precipitation during the year and P = annual precipitation. Many researchers have used the empirical relationship approach to estimate groundwater recharge and obtain different formulas for each study area [51]–[56].

2.7 Groundwater Model

Groundwater model. Replenishment is a major element of groundwater mechanism and it is uncertainty. Many researchers have tried and used several methods to predict the value of natural replenishment in provisional and spatial scales of aquifer systems. In groundwater modelling, several considerations are used as controls to effectively present recharge. The factors that control the recharge value are climate, topography, and the geologic framework [57] in [4]. These factors can be explained in **Figure 3** [57].

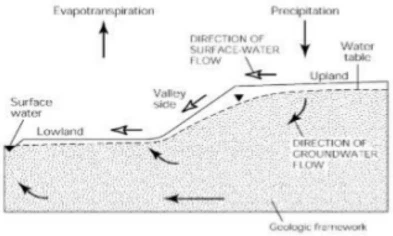

Fig. 3. The dominant factors affecting recharge and groundwater flow.

The research of groundwater systems is being used for groundwater flow and contaminant transport models extensively. Groundwater movement approach applied to estimate the value and route of groundwater transfer beyond the aquifers and limiting parts in the sub-surface. This estimate is called groundwater simulations which involve a in-depth concept of the hydrogeological attributes [14].

The accuracy of estimations depends upon successful calibration and verification of the model in deciding groundwater flow directions and transport of contaminants. In relation with groundwater models, [4] has highlighted two significant issues. Groundwater replenishment as a groundwater essential indicator while reviewing one must measure how to replenishment represented in the groundwater approaches and how the groundwater method to estimated replenishment. Use of groundwater models is very beneficial.

The purpose of groundwater flow modeling is to predict piezometric aquifers beneath many groundwater pressure conditions. Based on [58] in [59], the common three-dimensional groundwater movement approaches using identical fluid density and viscosity as in the equation (12):

$$\frac{\delta}{\delta x_i}\left(K_{ij}\frac{\delta_h}{\delta x_j}\right)+q_s = S_s\frac{\delta h}{\delta t} \tag{12}$$

where i,j is the direction of coordinate, K is hydraulic conductivity (L/T), h is hydraulic head (L), S_s is specific stowage (1/L), x is a coordinate area (L), t is time (T) and q_s iss fluid sources per unit volume (1/T). Piezometer values, K and S values, and other inflows and outflows from aquifers are used to measure recharge [59].

2.7 Infiltration Rate Method

Infiltration rate method. Infiltration rate is a vital procedure defining groundwater replenishment [60]. Infiltration is used to deliniate the flow of water downward toward to the aeration zone due to gravity through a porous medium. Infiltration water comes from precipitation, irrigation or river flow and calculated in millimetres per time interval (mm/year or mm/month) [61]. The infiltration replenishment can be measured by the water balance assumption and is shown by the equation (13):

$$W = P - E - R \pm S \tag{13}$$

with W is infiltration; P is rainfall; E is evapotranspiration; R is surface overflow and S is a exchange of humidity stowage in the unsaturated zone [61]. Based on [60], before estimating groundwater recharge utilizing the infiltration rate approach, common periodical precipitation are measured. Next, the denomination of infiltration rate is preferred depending on the type of rock occurring on the surface or the type of soil. Then the segments establish to the elected denomination of infiltration rate are clarify within the singled out rainfall zone. Equation (14) shows the basis for calculating the weighted average of the infiltration rate for each selected rainfall area.

$$\alpha_r = \frac{\sum_{i=1}^{n}\alpha_i \,.\, A_i}{\sum_{i=1}^{n} A_i} \tag{14}$$

with α_r is the mean of infiltration rate for rainfall zone (effective fraction) r; α_i is the infiltration rate for the i-lithological formation within rainfall zone, A_i is the top of the i-lithological formation (L^2) within rainfall zone r. The cumulative replenishment for a drainage basin is the quantity of the replenishment values for each rainfall zone. The formula is shown from equation (15):

$$R = \frac{\sum_{r=1}^{m} \alpha_r \, . P_r \, . A_r}{A} \tag{15}$$

with P_r is the mean periodical precipitation in the rainfall area r (L), A is the research area (L^2), m is the amount of elected rainfall areas. Several studies have used the infiltration recharge rate approach to estimate the value of groundwater recharge as done by [60]–[65].

3 Conclusions

Groundwater recharge is an essential component in groundwater systems and central to confirming the suitable management of aquifers. The groundwater recharge is uncertainty, cannot be measured directly, and very difficult to estimate reliably. The precision of the groundwater recharge estimate from different techniques is challenging to measure because the factual rate of annual recharge is unknown. So many approaches are needed to estimate the recharge rate. The choice of techniques will depend on the conceptualisation of the flow system and the accuracy required in a given situation. In any comparison of quantifying groundwater recharge, it is essential to contemplate the benefits and restrictions of each method. While natural systems are complex, models must balance complexity and simplicity to be reliable. The complexity comes at a cost: additional data requirements, computational time, and a deeper understanding of the relevant processes and variables. Models should be as simple as possible, provided they present a reasonably accurate view of reality relative to the question asked. There is no techniques that is categorized as the "best" in predicting groundwater replenishment. However, the use of several assumptions from the research will bring up the benefits, the weakness and limitations of the techniques used.

Various approaches which explained, the simplest and easiest to apply was the WTF method because it requires minimum data with simple calculations. However, the weakness in applying this method is in determining the value of specific yield (Sy). The use of the Darcian approach in estimation groundwater recharge in unsaturated zones is reliable but at high cost because the labor and equipment needed to collect data and only good for small areas (1 m2). The tracer approach especially chloride mass balance (CMB) method is used widely in the arid and semi-arid area or saturated and unsaturated. However, the data on spatial and temporal variability in chloride deposition is commonly limited and often includes only wet deposition. The use of an unnatural tracer in estimating groundwater recharge requires high costs which ultimately becomes a weakness of this approach.

From the studies, the estimated groundwater recharge by groundwater modelling has a limited form time consuming, sensitive to boundary conditions and difficult to calibrate. The data requirements in these methods vary like conceptual hydrogeological model, daily/monthly rainfall records, water levels, borehole abstractions, aquifer characteristics including storativity, hydraulic conductivity, porosity, dispersion characteristics. The use of lysimeter in calculating groundwater recharge has been widely carried out. The lineal measurement of the amount of water that drops through the root zone over a certain period of time is the benefecial of lysimeter use. Other advantages are net infiltration flux is easily calculated, and also capture infiltration moving rapidly. While the weaknesses of lysimeters are their construction price expensively and problematic maintenance requirements.

With the diversity of approaches in estimating groundwater recharge, in its application it can use more than one method or combine several methods to decrease uncertainty and escalate reliance in recharge prediction.

2.1 Acknowledgements

References

[1] R. W. Healy, *Estimating Groundwater Recharge*. New York: Cambridge University Press, 2010.

[2] N. Kresic and A. Mikszewski, “Groundwater Resources,” in *Groundwater Resources Sustainability, Management, and Restoration*, New York: McGraw-Hill Book Company, 2009, pp. 235–282.

[3] B. R. Scanlon, R. W. Healy, and P. G. Cook, “Choosing Appropriate Techniques for Quantifying Groundwater Recharge,” *Hydrogeol ogy J.*, vol. 10, pp. 18–39, 2002.

[4] W. Sanford, “Recharge and groundwater models: an overview,” *Hydrol. J.*, vol. 10, pp. 110–120, 2002.

[5] M. Sophocleous and J. Schloss, “Estimated Annual Groundwater Recharge,” 2000. [Online]. Available: http://www.kgs.ukans.edu/HighPlains/atlas/atrch.htm. [Accessed: 26-Apr-2020].

[6] J. Balek, “Estimation of Natural Groundwater Recharge,” in *Proceedings of The NATO Advanced Research Workshop on Estimation of Natural Recharge of Groundwater*, I. Simmers, Ed. Turkey: Springer, 1987, pp. 3–10.

[7] D. Jukic and V. Denic-Jukic, “A frequency domain approach to groundwater recharge estimation in karst,” *J. Hydrol.*, vol. 289, pp. 95–110, 2004.

[8] D. N. Lerner, “Groundwater Recharge,” in *Geochemical processes, weathering and groundwater recharge in catchment*, Rotterdam: Balkema, 1997, pp. 109–150.

[9] E. Obuobie, “Estimation of groundwater recharge in the context of future climate change in the White Volta River Basin , West Africa,” Rheinischen Friedrich-Wilhelms-Universität Bonn, 2008.

[10] Anilkumar, “Modelling Of Groundwater Recharge In Semi-Arid Region,” Division Of Agricultural Engineering Indian Agricultural Research Institute, 2011.

[11] N. S. Robin, *Groundwater Pollution, Aquifer Recharge and Vulnerability Geological*. London: The Geological Society, 1998.

[12] I. Simmers, “Groundwater Recharge Principles, Problems and Developments,” in *Recharge of Phreatic Aquifers in (Semi-) Arid Areas*, I. Simmers, Ed. Rotterdam: Balkema, 1997, pp. 1–16.

[13] D. Lerner, A. Issar, and I. Simmers, “Groundwater recharge. A guide to understanding and estimating natural recharge.” Verlag Heinz Heise, 1990.

[14] S. Islam, R. K. Singh, and R. A. Khan, “Methods of Estimating Ground water Recharge,” no. May, 2016.

[15] S. Qurtas, “Using groundwater levels and Specific Yield to Estimate the Recharge , South of Erbil , Kurdistan Region , Iraq,” no. February, 2019.

[16] R. W. Healy and P. G. Cook, “Using Groundwater Levels to Estimate Recharge,” *Hydrogeol. J.*, vol. 10, pp. 91–109, 2002.

[17] G. P. Kruseman and N. A. de Ridder, *Analysis and Evaluation of Pumping Test Data*. Netherlands: International Institute for Land Reclamation and Improvement, 1994.

[18] A. I. Johnson, *Specific Yield Compilation of Specific Yields for Various Materials*, 1662nd-D ed. Washington: United States Government Printing Office, 1967.

[19] A. I. Johnson, R. C. Prill, and D. . Morris, *Column Drainage and Centrifuge Moisture Content Specific Yield Column Drainage and Centrifuge Moisture Content*, 1662nd-A ed. Washington: United States Government Printing Office, 1963.

[20] R. Brasington, *Field Hydrogeology*, Fourth Edi. Wiley Blackwell, 2017.

[21] T. Atta-Darkwa, N. Kyei-Baffour, E. Ofori, E. Mensah, and W. A. Agyre, “Quantification of Groundwater Recharge In The River Oda Catchment Using The Watertable Fluctuation Method,” *Glob. J. Eng. Des. Technol.*, vol. 2, no. 1, pp. 96–103, 2013.

[22] O. Diancoumba, H. Bokar, A. Toure, N. C. Kelome, and K. Preko, “Characterization of Groundwater Recharge Using the Water Table Fluctuation Method in the Koda Catchment, Mali,” *Int. J. Adv. Earth Sci. Eng.*, vol. 8, no. 1, pp. 665–681, 2020.

[23] S. K. Adhikary, T. Chaki, M. Rahman, and A. Das Gupta, “Estimating Groundwater Recharge Into A Shallow Unconfined Aquifer In Bangladesh,” *J. Eng. Sci.*, vol. 04, no. 1, pp. 11–22, 2013.

[24] M. O. Cuthbert, “An improved time series approach for estimating groundwater recharge from groundwater level fluctuations,” vol. 46, no. September, pp. 1–11, 2010.

[25] B. B. Osejo, T. B. Vargas, and A. K. Campillo, “Analysis of Water Table Fluctuations To Improve Understanding and Quantification of The Groundawater Recharge Process In The Shallow Quifer of The Gulf of Uraba (Colombia),” in *E-proceedings of the 38th IAHR World Congress*, 2019, no. September.

[26] M. K. T. Kim and S. K. S. C. I. Kang, “Estimating Groundwater Recharge using the Water-Table Fluctuation Method : Effect of Stream-aquifer Interactions,” vol. 18, no. 5, pp. 65–76, 2013.

[27] J. R. Nimmo, R. W. Healy, and D. A. Stonestrom, “Aquifer Recharge,” *Encyclopedia of Hydrological Science*, vol. 4. Wiley, pp. 2229–2246, 2005.

[28] A. L. Flint, L. E. Flint, E. M. K. J. T. Fabryka-martin, and G. S. Bodvarsson, “Estimating recharge at Yucca Mountain , Nevada , USA : comparison of methods,” no. May 2014, 2002.

[29] C. V Theis, “Amount Of Groundwater Recharge In The Southern High Plains,” *Trans. Am. Geophys. Union*, pp. 564–568, 1937.

[30] M. S. Hantus, “Analysis of Data From Pumping Tests in Leaky Aquifers.,” *Trans. Am. Geophys. Union*, vol. 37, pp. 702–714, 1956.

[31] B. R. Scanlon and A. Dutton, *Groundwater Recharge in Texas*. Texas: Kansas Geological Survey, 2003.

[32] R. Schicht and W. Walton, “Hydrologic budgets for three small watersheds in Illinois,” Illinois, 1961.

[33] Q. Wu, G. Wang, W. Zhang, H. Cui, and W. Zhang, “Estimation of groundwater recharge using tracers and numerical modeling in the north China Plain,” *Water (Switzerland)*, vol. 8, no. 8, pp. 1–19, 2016.

[34] C. S. Ting, T. Kerh, and C. J. Liao, “Estimation of groundwater recharge using the chloride mass-balance method, Pingtung Plain, Taiwan,” *Hydrogeol. J.*, vol. 6, no. 2, pp. 282–292, 1998.

[35] I. S. Ifediegwu, “Groundwater recharge estimation using chloride mass balance: a case study of Nsukka local government area of Enugu State, Southeastern, Nigeria,” *Model. Earth Syst. Environ.*, no. 0123456789, 2019.

[36] O. Ait El Mekki, N.-E. Laftouhi, and L. Hanich, “Estimate of regional groundwater recharge rate in the Central Haouz Plain, Morocco, using the chloride mass balance method and a geographical information system,” *Appl. Water Sci.*, vol. 7, no. 4, pp. 1679–1688, 2017.

[37] E. Eriksson and V. Khunakasem, “Chloride concentration in groundwater, recharge rate and rate of deposition of chloride in the Israel Coastal Plain,” *J. Hydrol.*, vol. 7,

no. 2, pp. 178–197, 1969.

[38] C. B. Gaye and W. M. Edmunds, “Groundwater recharge estimation using chloride, stable isotopes and tritium profiles in the sands of northwestern Senegal,” *Environ. Geol.*, vol. 27, no. 3, pp. 246–251, 1996.

[39] M. L. Sharma and M. W. Hughes, “Groundwater recharge estimation using chloride, deuterium and oxygen-18 profiles in the deep coastal sands of Western Australia,” *J. Hydrol.*, vol. 81, no. 1–2, pp. 93–109, 1985.

[40] W. M. Edmunds and C. B. Gaye, “Estimating the spatial variability of groundwater recharge in the Sahel using chloride,” *J. Hydrol.*, vol. 156, no. 1–4, pp. 47–59, 1994.

[41] N. Mali, J. Urbanc, and A. Leis, “Tracing of water movement through the unsaturated zone of a coarse gravel aquifer by means of dye and deuterated water Tracing of water movement through the unsaturated zone of a coarse gravel aquifer by means of dye and deuterated water,” *J. Enviromental Geol.*, 2006.

[42] D. A. Stonestrom and J. Constantz, *Heat As a Tool For Studying The Movement of Groundwater Near Streams Circular*, Circular 1. Virginia: U.S. Geological Survey, 2003.

[43] M. Sophocleous, *Ground-water recharge and water budgets of the Kansas High Plains and related aquifers*. Kansas: Kansas Geological Survey, 2004.

[44] K. Kosugi and M. Katsuyama, “Measurements of groundwater recharge rate and unsaturated convective chemical fluxes by suction controlled lysimeter,” *IAHS-AISH Publ.*, no. 269, pp. 19–24, 2001.

[45] C. Kohfahl, L. Molano-Leno, G. Martínez, K. Vanderlinden, C. Guardiola-Albert, and L. Moreno, “Determining groundwater recharge and vapor flow in dune sediments using a weighable precision meteo lysimeter,” *Sci. Total Environ.*, vol. 656, pp. 550–557, 2019.

[46] Y. Chen *et al.*, “Assessment of alternative agricultural land use options for extending the availability of the Ogallala Aquifer in the Northern High Plains of Texas,” *Hydrology*, vol. 5, no. 4, 2018.

[47] X. Chen, Z. C. Zhang, X. N. Zhang, Y. Q. Chen, M. K. Qian, and S. F. Peng, “Estimation of groundwater recharge from precipitation and evapotranspiration by lysimeter measurement and soil moisture model,” *J. Hydrol. Eng.*, vol. 13, no. 5, pp. 333–340, 2008.

[48] C. Y. Xu and D. Chen, “Comparison of seven models for estimation of evapotranspiration and groundwater recharge using lysimeter measurement data in Germany,” *Hydrol. Process.*, vol. 19, no. 18, pp. 3717–3734, 2005.

[49] K. Schwaerzel and H. P. Bohl, “An easily installable groundwater lysimeter to determine waterbalance components and hydraulic properties of peat soils,” *Hydrol. Earth Syst. Sci.*, vol. 7, no. 1, pp. 23–32, 2003.

[50] V. Vásquez, A. Thomsen, B. V. Iversen, R. Jensen, R. Ringgaard, and K. Schelde, “Intégration du drainage au lysimètre et des mesures de flux par covariance de la turbulence dans un modèle de recharge des eaux souterraines,” *Hydrol. Sci. J.*, vol. 60, no. 9, pp. 1520–1537, 2015.

[51] C. P. Kumar, “Assessment of Natural Ground Water Recharge in Upper Ganga Canal,” no. May, 2014.

[52] S. R. Saghravani, I. Yusoff, S. Mustapha, and S. F. Saghravani, “Estimating Groundwater Recharge Using Empirical Method: A Case Study in the Tropical Zone,” *Sains Malaysiana*, vol. 42, no. 5, pp. 553–560, 2013.

[53] N. Benjamin, M. Jacques, and S. Reynauld Jean, “Groundwater recharge from rainfall

in the southern border of Lake Chad in Cameroon," *World Appl. Sci. J.*, vol. 2, no. 2, pp. 125–131, 2007.
[54] J. Wu, R. Zhang, and J. Yang, "Analysis of rainfall-recharge relationships," *J. Hydrol.*, vol. 177, no. 1–2, pp. 143–160, 1996.
[55] T. Thomas, R. K. Jaiswal, R. Galkate, and S. Singh, "Development of a rainfall-recharge relationship for a fractured basaltic aquifer in Central India," *Water Resour. Manag.*, vol. 23, no. 15, pp. 3101–3119, 2009.
[56] N. Kuruppath, A. Raviraj, B. Kannan, and K. M. Sellamuthu, "Estimation of Groundwater Recharge Using Water Table Fluctuation Method," *Int. J. Curr. Microbilogy Appl. Sci.*, vol. 7, no. 10, pp. 3404–3412, 2018.
[57] T. C. Winter, "The concept of hydrologic landscapes'," vol. 37, no. 2, pp. 335–349, 2001.
[58] J. Bear, *Dynamics of fluids in porous media*. New York: American Elsevier, 1972.
[59] S. Lorentz, R. Schulze, and G. O. Hughes, "Techniques For Estimating Groundwater Recharge At Different Scales In Southern Africa," in *Groundwater Recharge Estimation in Southern Africa*, no. May 2016, Y. Xu and H. E. Beekman, Eds. Cape Town: Unesco Paris, 2003.
[60] S. Staśko, R. Tarka, and T. Olichwer, "Groundwater recharge evaluation based on the infiltration method," in *Groundwater Quality Sustainability*, no. August, 2012, pp. 189–198.
[61] V. S. Kovalevsky, "Infiltration and Groundwater Formation," *Hdrological Cycle*, vol. III.
[62] M. U. Igboekwe and A. Ruth, "Groundwater Recharge Through Infiltration Process: A Case Study of Umudike, Southeastern Nigeria," *J. Water Resour. Prot.*, vol. 03, no. 05, pp. 295–299, 2011.
[63] Y. Ganot, R. Holtzman, N. Weisbrod, I. Nitzan, Y. Katz, and D. Kurtzman, "Monitoring and modeling infiltration-recharge dynamics of managed aquifer recharge with desalinated seawater," *Hydrol. Earth Syst. Sci.*, vol. 21, no. 9, pp. 4479–4493, 2017.
[64] T. O. Erickson and H. G. Stefan, "Groundwater Recharge from a Changing Landscape," no. 490, pp. 1–112, 2007.
[65] S. O. Grinevskii and S. P. Pozdnyakov, "Principles of regional estimation of infiltration groundwater recharge based on geohydrological models," *Water Resour.*, vol. 37, no. 5, pp. 638–652, 2010.

Comparison of Quantifying Groundwater Recharge

ORIGINALITY REPORT

10%	7%	10%	5%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Sta_ko, Stanis_aw, Robert Tarka, and Tomasz Olichwer. "Groundwater recharge evaluation based on the infiltration method", IAH - Selected Papers on Hydrogeology, 2012. Publication	2%
2	John R Nimmo, Richard W Healy, David A Stonestrom. "Aquifer Recharge", Wiley, 2006 Publication	1%
3	Submitted to University of New South Wales Student Paper	1%
4	docshare.tips Internet Source	1%
5	www.mdpi.com Internet Source	1%
6	Emmanuel Obuobie, Bernd Diekkrueger, William Agyekum, Sampson Agodzo. "Groundwater level monitoring and recharge estimation in the White Volta River basin of Ghana", Journal of African Earth Sciences, 2012 Publication	1%

7	Submitted to Kwame Nkrumah University of Science and Technology Student Paper	1%
8	unesdoc.unesco.org Internet Source	1%
9	www.science.gov Internet Source	1%

Exclude quotes	On	Exclude matches	< 1%
Exclude bibliography	On		