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Comparative Evaluation of Various Empirical Methods for Estimating Groundwater Recharge

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Authors' contributions

This work was carried out in collaboration between all authors. Author MHA designed the study, wrote the protocol and finalized the manuscript. Authors SM and MAI managed the analyses of the study. Author MAI managed the literature searches and analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

Information on groundwater recharge is essential for sustainable groundwater resources management. Estimation of recharge, by any method is normally subject to large uncertainties and errors. In this paper, various empirical methods of estimating natural groundwater recharge were compared with respect to recharge obtained by tracer technique. The comparison results showed that, Chaturvedi Formula, Modified Chaturvedi Formula, and Sehgal formula under-estimated recharge; while other formulas over-estimated. The Chaturvedi Formula under-estimated the greatest amount, while the Maxey-Eakin method over-estimated the greatest amount. The Kirchner et al. formula performed better under the study condition. Modification/adjustment of various equations was also performed based on the tracer results. The modified equations predicted the recharge with good accuracy (mostly <11% relative error). These equations can be used for similar climatic and physiographic conditions, and may be useful for estimating recharge.

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1. INTRODUCTION

Over-exploitation of groundwater has been reported in many parts of the world (Chawla et al. [1]; Gurria [2]). Several regions of Bangladesh are also experiencing a similar groundwater declining problem (Sarkar and Ali [3]; Ali et al. [4]; Ali et al. [5]). Groundwater management practices should generally be based on the safe-yield concept (Ali and Abustan, [6]).

The safe-yield of a groundwater basin is the amount of water which can be withdrawn without causing problems such as excessive water level declination, reduction of baseflow of streams, and deterioration of water quality (Ali, [7]). Sustainability of groundwater is a function of recharge (Sophocleous and Devlin [8]). Information on actual recharge is essential or sustainable use of the groundwater resources (Ali et al. [4]). It is also required for robust model predictions, as groundwater recharge is one of the main drivers of the hydrological system (Chandra [9]; Fei et al. [10]). 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 (Jimenez-Martinez et al. [11]; Callahan et al. [12]; Ordens et al. [13]; Flint et al. [14]; Rushton et al. [15]; Sharma and Hughes [16]). 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. Many researchers (Sibanda et al. [17]; Coes et al. [18]; Scanlon et al. [19]; Risser et al. [20]; Ali, [7]; Xu and Chen [21]) advocated for using multiple methods to increase reliability in recharge estimate. But such estimation involves huge cost, manpower and instruments. Simple empirical formulae have also been used by others (Saghravani et al. [22]; Oke et al. [23]).

The objective of the present study was to evaluate various empirical methods of estimating natural groundwater recharge with respect to tracer technique at North-eastern region, Mymensingh District of Bangladesh.

2. MATERIALS AND METHODS

2.1 Different Empirical Relationship/ Formulae for Recharge Estimation

Some of these empirical relationships for different hydrogeological and climatological situations are:

2.1.1 Chaturvedi formula

Based on the water level fluctuation and rainfall amounts in Ganga-Yamuna doab, Chaturvedi [24] derived an empirical relationship to arrive at the recharge as a function of annual precipitation (when rainfall exceeds 15.7 inch).

$$R = 2.0\,(P - 15)^{0.4} \qquad (1)$$

where,

R = net recharge due to precipitation during the year, in inches

P = annual precipitation, in inches

The Chaturvedi formula has been widely used for preliminary estimation of ground water recharge from rainfall.

2.1.2 Modified Chaturvedi formula

The Chaturvedi formula was later modified by further work at the U.P. Irrigation Research Institute, Roorkee (Cited by Baweja and Karanth, [25]), and the modified form of the formula is:

$$R = 1.35\,(P-14)^{0.5} \qquad (2)$$

2.1.3 Sehgal formula

Using regression analysis for certain doabs in Punjab, Sehgal developed a formula in 1973 for Irrigation and Power Research Institute, Punjab (Cited by Baweja and Karanth, [25]). The formula was found to hold good for areas were rainfall was between 23.6 and 27.5 inches.

$$R = 2.5\,(P - 0.6)^{0.5} \qquad (3)$$

where,

R & P both are measured in inches.

2.1.4 Relationship of Krishna Rao

Krishna Rao gave the following empirical relationship in 1970 (Cited by Oke et al. [23]) to determine the ground water recharge in limited climatological homogenous areas:

$$R = K (P - X) \tag{4}$$

The following relation is stated to hold good for different parts of Karnataka:

$$R = 0.20 (P – 400) \quad 400 < P < 600 \text{ mm} \tag{5}$$

$$R = 0.25 (P - 400) \quad 600 < P < 1000 \text{ mm} \tag{6}$$

$$R = 0.35 (P - 600) \quad P > 2000 \text{ mm} \tag{7}$$

Where,

R & P are expressed in millimeters

2.1.5 Maxey-Eakin approach

In essence, the Maxey-Eakin [26] method is an empirical method. The computation involves estimation of mean annual precipitation for sub-area/sub-basin, then scaling these volumes by a factor representing losses by ET and surface-water runoff, and then summing the recharge for the whole basin.

According to Maxey and Eakin [26], discharge data for 13 basins in east-central Nevada were used to determine the recharge percentages by the trial-and-error balancing of recharge with estimated ground-water discharges. Calculation of the Maxey-Eakin recharge for a given basin can be expressed in the form:

$$ME = \sum_{i=0}^{n} a_i P_i \tag{8}$$

Where,

ME = The Maxey-Eakin recharge for a basin,

P = Volume of precipitation within each zones/sub-basins,

a = Recharge coefficient (%) for each of the zones [based on the rainfall amount and other factors, 0 – 25% for Maxey-Eakin studied catchments]

2.1.6 Kirchner et al. formula

The simplest empirical formula takes recharge R as a proportion (a) of precipitation (P):

$$R = a. P \tag{9}$$

The above equation assumes that recharge is a constant fraction of rainfall. In some environments, particularly in arid and semi-arid areas, recharge may not be experienced after short, low intensity rainfall events. Rather than considering recharge from rainfall events, it is commonly averaged over a year, and mean annual precipitation (MAP) is used as the P value.

$$R = a (P – P_{min}) \quad P > P_{min} \tag{10}$$

or,

$$R = (P – P_{av}) \tag{11}$$

Where:

P min = minimum precipitation
P av = average precipitation

Kirchner et al. [27] obtained a figure of 4.6% of MAP in excess of 263 mm, in a study of De Aar and Dewetsdorp (South Africa), which focused on saturated volume fluctuations. Taking soil thickness into account, Kirchner et al. [27] produced the following formulae:

For thin soil cover: $R = 0.06 (MAP – 120)$ [mm] (12)

For thick soil cover: $R = 0.023 (MAP – 51)$ [mm] (13)

For Alluvial cover: $R = 0.12 (MAP – 20)$ [mm] (14)

2.1.7 Bredenkamp et al. formula

Many rainfall-recharge relationships have been developed for dolomitic aquifers, and not all are linear. This was adjusted by Bredenkamp et al. [28] to give the following general formula:

$$R = 0.32 (MAP – 360) \text{ [mm]} \tag{15}$$

The three main criticisms of simple rainfall-recharge formulae are: Relationships may not be transferable to areas other than those in which they were derived; They ignore temporal distribution of rainfall; Their accuracy is dependent on the accuracy of the recharge estimates from which the relationship was derived.

2.2 Recharge Data for Comparison and Features of the Location

2.2.1 Reference recharge value for comparison

Chloride has proved to be an effective tracer for quantifying water fluxes by measuring chloride concentrations in depth profiles (e.g., Zagana et al. [29]; Sharma and Hughes, [16]; Edmunds and Gaye, [30]; Reynolds and Pomeroy, [31]; Allison and Hughes [32]; Cook and Herczeg, [33]; Scanlon [19]).

The recharge values determined by Ali [34], Ali [35], and Ali [36] by tracer technique were used as reference value. The values are summarized in Table 1.

2.2.2 Location characteristics

2.2.2.1 Location

The study area was north-eastern part of Bangladesh, Mymensingh District. It is part of the Ganges Alluvial Plain. This region is situated between 25°33´ to 26°32´ North and 89°55´ to 90°51´ East.

2.2.2.2 Topography and hydro-geological conditions

The topography of the 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, [37]).

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 the region is severely affected by soil and water erosion due to steep slopes and high rainfall (but the study area/plot is flat). In most parts, the depth to the underground reservoir 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 (BINA [38]).

2.2.2.3 Rainfall and ET0 pattern of the area

The yearly rainfall fluctuates considerably. The annual rainfall at the study site varies from 1520 mm to 3236 mm (IWM, [39]); approximately 70% of this rainfall occurs during the months of May – August which is noted as monsoon season. The long-term (1991-2015) average monthly rainfall and rainfall during the study period (2014-2016) are depicted in Fig. 1 and Fig. 2, respectively.

The reference evapotranspiration (ET_0) pattern during the study period is depicted in Fig. 3.

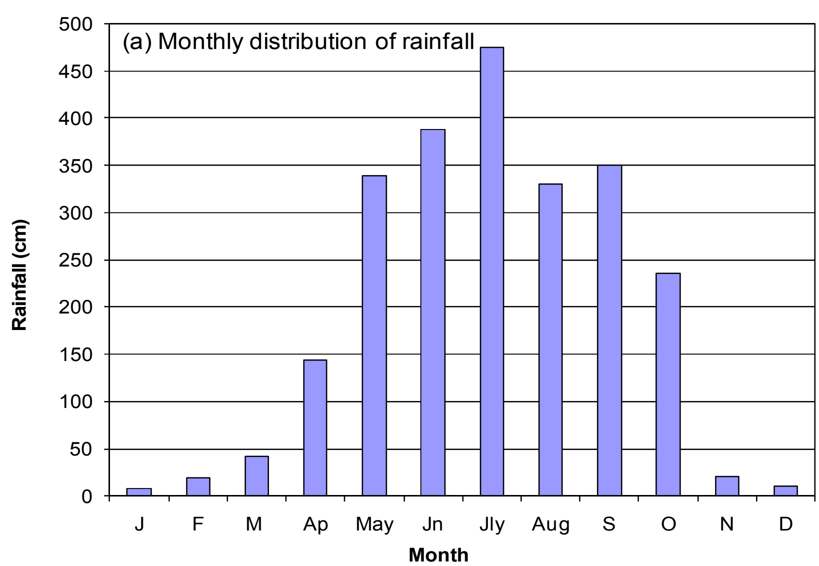

Fig. 1. Long-term monthly average (1991-2015) rainfall in the study area

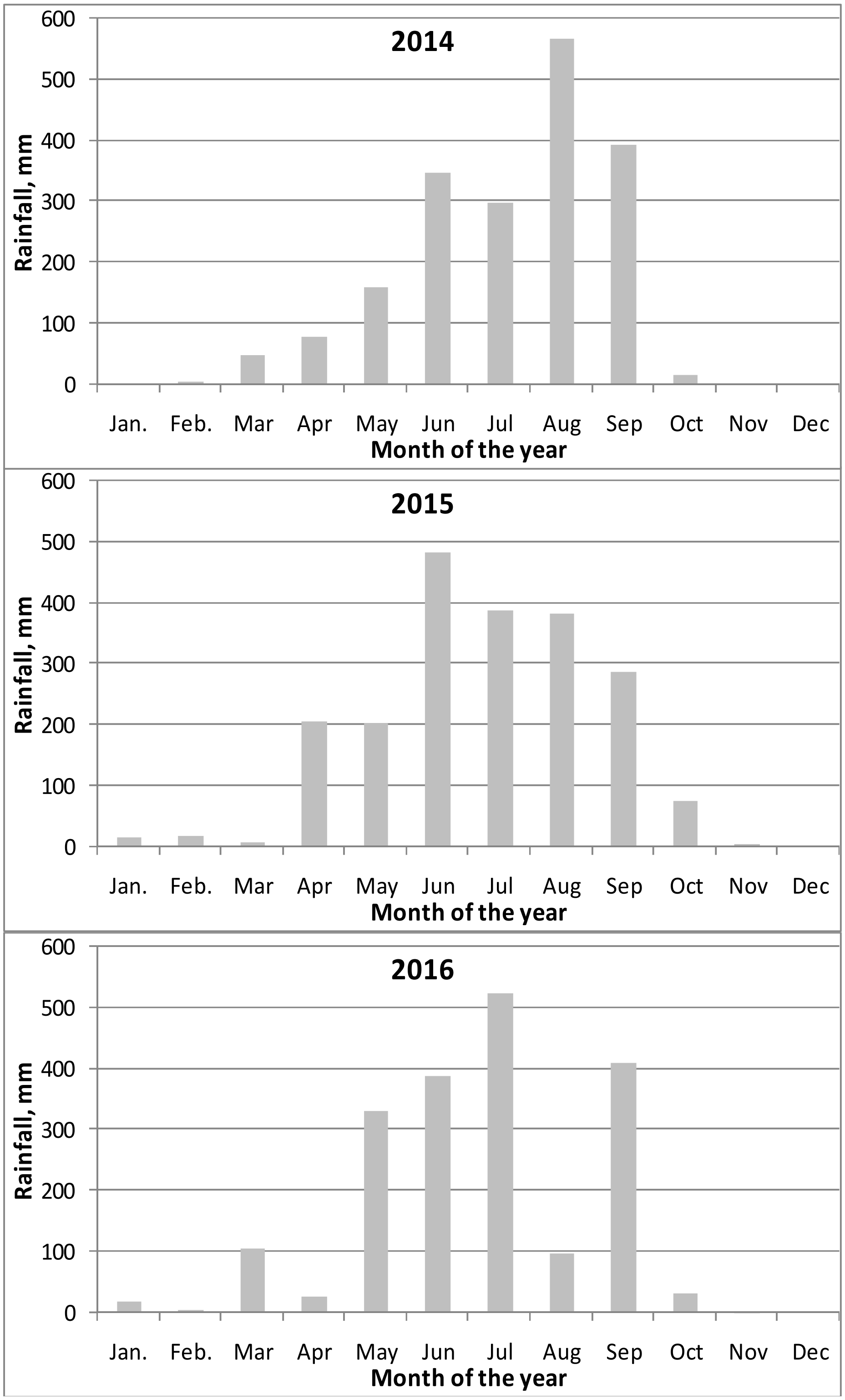

Fig. 2. Monthly total rainfall during the study period

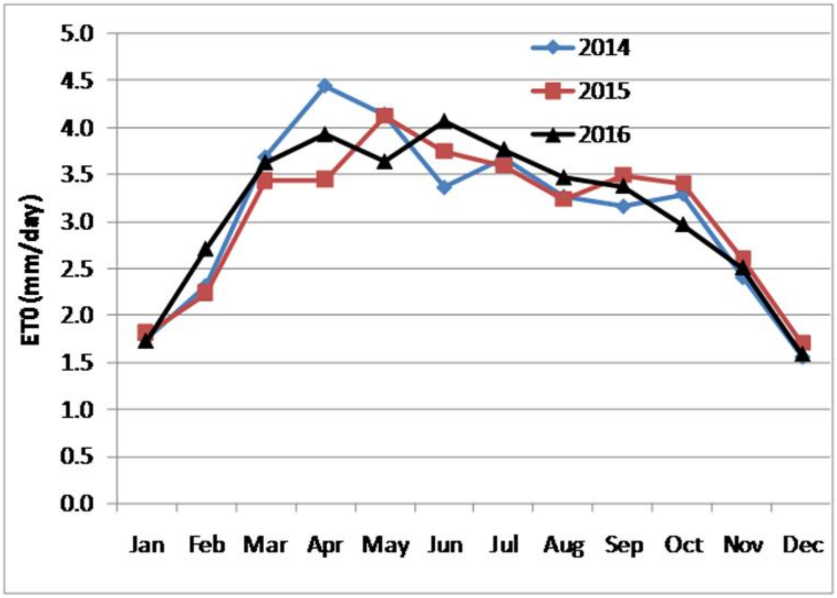

Fig. 3. Daily average ET_0 pattern throughout the months during the study years

Table 1. Rainfall and recharge (by tracer technique) at Mymensingh, Bangladesh

Year	Rainfall, mm	Recharge, mm	Recharge, % of rainfall
2014	1916	196	10.2
2015	2068	257	12.4
2016	1934	233	11

2.3 Modification/Adjustment of Different Empirical Equations

The empirical equations were modified by equating the recharge (R) of the equation to the standard (obtained by tracer method). The coefficient value was then determined from the equation by putting the respective year's rainfall value. This was done for each year of 2014, 2015, and 2015. Then the average value of the coefficient was determined, which was taken as modified coefficient value. An example is given below for Chaturvedi formula.

Chaturvedi (1973) [24] formula is:

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

where R and P in inches.

For the year 2014, recharge (R) value (standard) is 7.72 inch (196 mm), rainfall (P) is 75.43 inch (1916 mm). Putting the values of R and P in above equation,

$$7.72 = C\ (75.43 - 15)^{0.4}$$

or, C= 1.38

Similarly, for the year 2015 and 2016, the coefficient values are 1.75 and 1.63, respectively. The average value of the coefficient is 1.59, which is the adjusted/modified value of the coefficient.

2.4 Evaluation of Performance of Modified Equations

The recharge was estimated by the modified equation using the rainfall value. The deviations from the recharge by tracer method were determined, and Percent Mean Relative Absolute Error (PMRAE) (Ali and Abustan [40]) were determined for evaluation.

$$PMARE(\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{Abs(O_i - P_i)}{O_i} \quad (16)$$

Where, "*Abs*' indicates 'absolute value' (of the difference between observed and estimated value), O_i is the observed or measured value, and P_i is the estimated or predicted value.

According to Ali and Abustan (2014), the PMRAE gives unambiguous result compared to other indicators (under diverse data sets), and it is logical, straight-forward, and interpretable; thus was used here for evaluating performance of the equations.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Recharge estimation by various empirical methods and deviation from tracer method

The features and characteristics of various equations used in this study are summarized in Table 2. The recharge values estimated by various equations and the deviations of estimated recharge from tracer value are summarized in Table 3.

It is observed that, Chaturvedi Formula, Modified Chaturvedi Formula, and Sehgal formula under-estimated recharge; while other formulas over-estimated. The Chaturvedi Formula under-estimated most, while the Maxey-Eakin method over-estimated the most. The Kirchner et al. [27] formula [for Alluvial cover, which is the case for our study area] estimated very close value (average 3% variation).

3.1.2 Modified/adjusted equations based on tracer data

Based on recharge value obtained by tracer method, modification/adjustment of various equations were performed, and summarized in Table 4. These equations can be used for similar climatic and physiographic conditions, and may be useful for estimating recharge.

3.1.3 Evaluation of the modified equations

Deviation of recharge values estimated by modified equations and the 'Percent Mean Relative Absolute Error' value are summarized in Table 5. It is revealed that the modified equation of Sehgal, Krishna Rao, Kirchner et al., and Maxey-Eakin performed very good (<10% error), Chaturvedi Formula and Modified Chaturvedi formula are also good (~11%). The Bredenkamp et al formula predicted a bit higher error value, about 17%. Overall, the modified equations predicted the recharge with good accuracy, and can be used to estimate groundwater recharge in similar climatological areas.

Table 2. The features of various equations used in the study

Sl no.	Formula name	Equation(s)	Definition of Parameter, and coefficient value range	Parameter/ coefficient value used in this study
1	Chaturvedi Formula (in inch)	$R = 2.0\ (P - 15)^{0.4}$	P = Yearly rainfall	As it is.
2	Modified Chaturvedi Formula	$R = 1.35\ (P-14)^{0.5}$	P = Yearly rainfall	As it is.
3	Sehgal formula (in inch)	$R = 2.5\ (P - 0.6)^{0.5}$	P = Yearly rainfall	As it is.
4	Relationship of Krishna Rao (mm)	$R = 0.35\ (P - 600)$ $P > 2000$ mm $R = 0.25\ (P - 400)$ $600 < P < 1000$ mm	P = Yearly rainfall	As it is.
5	Kirchner et al. (1991) formula for Alluvial cover: [mm]	$R = 0.12\ (MAP – 20)$	MAP = Mean annual rainfall	MAP = Annual rainfall
6	The Maxey-Eakin (1949) method	$R = P*a$	P = Yearly rainfall a = 0 - 25%	a = 20%
7	Bredenkamp et al. (1995) formula [mm]	$R = 0.32\ (MAP – 360)$	MAP = Mean annual rainfall	MAP = Annual rainfall

Table 3. Recharge estimates and deviations by various empirical methods compared to tracer method

Year	Recharge (mm) under formula no. (as of Table 2)							Tracer (mm)
	1	2	3	4	5	6	7	
2014	71.9	74.1	174.3	460	228	498	383	196
2015	74.1	97.8	181.1	514	246	547	414	257
2016	72.1	181.1	175.1	467	230	504	387	233
Mean deviation from tracer (%)	-68	-58	-22	112	3	128	74	-

Table 4. Modified forms of different equations for estimating recharge for Mymensingh region of Bangladesh

Sl no.	Formula	Original Eqn.	Adjusted/ Modified eqn.
1	Chaturvedi Formula (in inch)	$R = 2.0\ (P - 15)^{0.4}$	$R = 1.59\ (P - 15)^{0.4}$
2	Modified Chaturvedi Formula	$R = 1.35\ (P-14)^{0.5}$	$R = 1.03\ (P-14)^{0.5}$
3	Sehgal formula (in inch)	$R = 2.5\ (P - 0.6)^{0.5}$	$R = 1.02\ (P - 0.6)^{0.5}$
4	Relationship of Krishna Rao (mm)	R = 0.35 (P - 600) P> 2000 mm R = 0.25 (P - 400) 600<P< 1000 mm	R = 0.17 (P - 600), 1500>P> 2000 mm
5	Kirchner et al. (1991) formula, For Alluvial cover [mm]	R = 0.12 (MAP – 20)	R = 0.12 (P – 20), P = annual rainfall
6	The Maxey-Eakin (1949) method	ME = P*a (a = 20%)	ME = P*a, a = 0.12
7	Bredenkamp et al (1995) formula [mm]	R = 0.32 (MAP – 360)	R = 0.116 (P – 360), P = annual rainfall

Table 5. Deviation of recharge estimated by modified equation and the percent mean relative absolute error (PMRAE)

Sl no.	Modified formula	Full Equation	% deviation by modified formula			PMRAE
			2014	2015	2016	
1	Chaturvedi Formula (in inch)	$R = 1.59\ (P - 15)^{0.4}$	+6.3	-15.8	-10.2	11.07
2	Modified Chaturvedi Formula	$R = 1.03\ (P-14)^{0.5}$	+4.6	-16.4	-11.5	11.00
3	Sehgal formula (in inch)	$R = 1.02\ (P - 0.6)^{0.5}$	+14.6	-9.2	-3.6	8.82
4	Relationship of Krishna Rao (mm)	R = 0.17 (P - 600), 1500>P> 2000 mm	+14.14	-2.89	-2.67	6.56
5	Kirchner et al. (1991) formula, For Alluvial cover [mm]	R = 0.12 (P – 20), P = annual rainfall	+16.1	-4.4	-1.4	7.28
6	The Maxey-Eakin (1949) method (a = 20%)	ME = P*a, a = 0.12	+17.3	-3.4	-0.4	7.04
7	Bredenkamp et al (1995) formula [mm]	R = 0.116 (P – 360), P = annual rainfall	+7.9	+22.9	+21.6	17.49

3.2 Discussion

In general, groundwater recharge in a particular area (having fixed hydro-geological situation) is dependent on rainfall – increases with rainfall, unless potential recharge occurs. In this study, parameter/coefficient of empirical equations was adjusted/modified with the recharge value determined by tracer technique – which is a reliable method for recharge estimation.

Saghravani et al. [22] estimated groundwater recharge using empirical method in a tropical zone, Selangor, Malaysia. They used a modified version of Chaturvedi [24]. They found that the recharge coefficient (ratio of recharge to effective rainfall) was 18% for the study area. In our study area, the recharge estimates by tracer technique was about 10~12% of total rainfall, depending on rainfall and climatic evaporative demand (ET_0). The yearly total rainfall in Malaysia is higher (about 175 to 1000 mm, average value is about 600 mm higher) than the rainfall in our study area. Thus, a higher rate of recharge can be expected. Further, they did not verify the recharge rate with a direct measurement.

The application of the modified empirical equations developed in this study for estimating groundwater recharge can help to quickly estimate recharge in an un-parameterized/ new area having similar rainfall areas.

4. CONCLUSION

Various empirical equations for estimating groundwater recharge were evaluated in this study. The Kirchner et al. (1991) formula performed well under the study condition. Modification/adjustment of various equations was performed. The modified equations predicted the recharge with good accuracy (mostly <11% relative error). These equations can be used for similar climatic and physiographic conditions, and may be useful for estimating recharge.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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