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Quantification of potential groundwater recharge from recharge pond in small watershed

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ABSTRACT

A study was conducted during 2006–08 to estimate the potential groundwater recharge from the recharge ponds in a small watershed of the semi-arid region of Rajasthan. A recharge pond having storage capacity of 0.65 ha m was constructed to harvest the surface runoffs otherwise going the waste from the watershed. The analysis has revealed that the potential recharge rates from the selected recharge pond varied between 0.019 and 0.051 m/day with a mean of 0.024 m/day during the study period. The components of water balance of the pond have been estimated to be, 77% of the stored water as the groundwater recharge to the aquifer underneath the pond, 9% as loss due to water surface evaporation, 13% as the surplus flow from the pond, and 1% as the dead storage in the pond. An exponential recharge regression model depicting relation between daily recharge rate and recharge period has also derived for the study area. This area specific derived relationship will help for determining potential recharge rate for any recharge period.

Key words: Model, Pond, Potential recharge, Semi-arid, Watershed

Quantification of the artificial groundwater recharge (AGR) from the recharge pond is essentially important for evaluating effectiveness of that pond in augmentation of the groundwater resources and also for evolving a sustainable development and management plan based on the augmented resources in a watershed. The AGR is particularly important in many industrialized countries, and the arid and the semi-arid regions of worlds where the groundwater level is depleting very fast due to exploitation/over development, and the natural replenishment of groundwater is slow for the reason that of low and highly erratic nature of rainfall and geological conditions of aquifer. The primary purposes of artificial recharge is to: (i) enhance the sustainable yield of groundwater in areas where over development has depleted the aquifer, (ii) conserve and store monsoon surface runoffs for future requirements, and (iii) maintain or augment the natural groundwater as an economic resource.

A variety of methods have been developed and applied for artificial recharge to an aquifer in various parts of world (Todd 1980, CGWB 1994, de Silva 2004). Common AGR techniques include recharge ponds and basin, deep well injection, aquifer storage and recovery (ASR) and river bank filtration (Bouwer 2002, Herczeg *et al*. 2004). Among those, surface water recharge structures as ponds are largely practiced in many countries including India for surface runoff harvesting and groundwater recharge through people participation with the government economic inputs during the construction phage.

A numerous methods have been developed and used in the past to better understand and estimate the potential recharge rate from recharge structures in many countries of the world as well as in India (Sukhija *et al.* 1997, Lerner *et al.*1990, Sharda *et al*. 2005, Ali 2009). These methods include: (i) empirical, (ii) water budget, (iii) infiltration/flow equation, (iv) tracer techniques, (v) numerical modeling code as MODFLOW, and (vi) measurements. Reconnaissance of the various recharge estimation methods and measurement found that estimation of the artificial groundwater recharge is often crucial, and exhibits high spatial and temporal variability. And there is no single technique yet identified universally, which is capable of estimating accurate artificial groundwater recharge. The increasing use of artificial recharge structure in the watershed development programmes has brought the need of a method for the estimation of potential recharge

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accurately that can be used in design and evaluation of the performance of recharge ponds. The main objective of this study is to demonstrate the application of newly developed holistic recharge estimation model by Ali (2009) for assessing the potential groundwater recharge from a small recharge pond in small watershed.

MATERIALS AND METHODS

An experiment was conducted in a small watershed known as Badakhera watershed located, in the Bundi district of Rajasthan, India between 25^0 36' to 25^0 51' N latitude and 75^0 15' to 75^0 38' E longitude. The area is characterized mainly by dry semi-arid climate of average annual rainfall about 724 mm, 90% of which receives during July through September. The summer (March through June) is characterized by higher temperature, with a mean daily temperature of 35°C. The winter (November through February) normally remains cooler and dryer with a mean daily temperature of about 15°C. A recharge pond of trapezoidal shape having side slope 1V: 0.5H, bottom dimension of 75 m × 45 m and maximum depth of 2.75 m has been constructed. The maximum storage capacity of the pond is 0.65 ha m. The monsoon runoff is the main source of water for the pond. The harvested monsoon runoffs in the pond are normally available for a short period (mid June through December). The inlet of the pond is equipped with a silt retention basin to prevent entry of silt from the catchment to the pond. To let off excess runoff, a rectangular weir has been installed as an outlet device. The runoff contributing area to the recharge pond is 15.32 ha and has different land uses. The soils in the watershed are black in colour of recent alluvial origin. The data collected during the years 2006-08 seasons is used in this study. The season here is defined as the period which there is actually water in the recharge pond. In the selected region, the season started with filling of recharge pond by setting of monsoon and continued till December or January. Monsoon, generally sets in the last week of June or first week of July, and continued till first week of September. The pond level was usually monitored from first filling of recharge till almost the empty pond. The data related to the hydrological characteristics of the pond's catchment, rainfall, pond's geometry, water temperature and water leveling the pond, soil samples below the pond's bed and the underneath aquifer, depth to groundwater level, etc. were collected by devising instrumentations and measurements. For measuring rainfall a Tipping bucket type rain gauge was installed in the vicinity of the experimental pond site. The water temperature of the pond at 10 mm below the water surface was measured by water thermometer. For measurement of time-varying water levels in the recharge pond, a graduated staff gauge (with precision of 0.1 cm) was installed at the centre of the pond. The staff gauge reading was observed manually from time to time. The water level and the water temperature in the pond were monitored for the period since onset of the runoff accumulation and till depth of water in the pond reduced to a minimal height (about 10 to 30 cm) as the dead storage. Meteorological input data sets of the air temperature, relative humidity and actual sunshine duration were obtained from the agricultural meteorological observatory (AMO) site maintained by the Central Soil and Water Conservation Research and Training Institute, Research Centre, Kota about 65 km away from the study site that located in the same climatic region as dry semi-arid zone No-4 of the Country.

The potential recharge from the recharge pond is estimated as suggested by Ali (2009):

$$R_P\left(t\right)=\frac{\left\{\begin{array}{l}H\left(t-1\right)A_{ws}\left(t-1\right)+\psi_f A_{ws}\left(t\right)\\+\left[Q\left(t\right)A_w+P\left(t\right)A_s-E\left(t\right)\overline{A}_{ws}-Q_0\left(t\right)\right]\Delta t\end{array}\right\}}{\left\{\dfrac{\left(\dfrac{K_s t}{C_i\eta}\right)\overline{A}_{ws}R_P\left(t\right)}{\left[\left(\dfrac{1-B_i}{2C_i}\right)^2-\dfrac{A_i}{C_i}\right]R_P^2\left(t\right)-\left[\dfrac{K_s}{2C_i}\right]^2}+\overline{A}_{rs}\,\Delta t\right\}} \quad ...1$$

Where $R_p(t)$ is the rate of potential recharge from the recharge pond [LT^{-1}] at time t; Q(t) is the rate of runoff inflow into pond [LT^{-1}]; P(t) is the rate of rainfall over the pond [LT^{-1}]; E(t) is the rate of evaporation from the water surface of pond [LT^{-1}]; $Q_o(t)$ is the volumetric rate of outflow of surplus water from the pond [LT^{-3}]; H(t-1) is the depth of water in the pond[L] at time t-1; t is the current time; Δ is the time interval; K_s is the saturated hydraulic conductivity of the transmission zone[LT^{-1}]; ψ_f is the suction pressure at wetting front [L]; η is the fillable porosity pond's bed material[dimensionless] and equal to θ_f - θ_i; in which θ_i is the initial volumetric moisture content [dimensionless]; and θ_s is the volumetric moisture content at near saturation [dimensionless]; A_w is the area of the pond's catchment [L^2]; A_s is the surface area of the pond at the top [L^2]; $A_{ws}(t)$ is the water surface area at time t[L^2]; A_{ws} is the average water surface area between t-1 and t [L^2], = 0.5[A_{ws}(t-1)+ A_{ws}(t)]; is the average wetted surface area of the pond between t-1 and t [L^2] = 0.5[A_{rs}(t-1)+ A_{rs}(t)]; and A_i, B_i and C_i are the coefficients of the models whose value depend on the length of advancement of wetting front [dimensionless].

In Eq.(1), the variable, $R_p(t)$, which is to be determined, is also appeared both in the L.H.S and R.H.S. To determine R_p at the current time step t, H at the previous time step (t-1) and its related components are to be known. Thus, for determining $R_p(t)$; Eq.(1) was solved in succession of daily time step t.

The runoff (Q) is estimated by an equation derived by Ali *et al.* (2010) as:

$$Q = \frac{P\left(b\,P+c\,NAPI-a\right)}{\left[\left(b\,P+c\,NAPI-a\right)+1\right]} \quad ...2$$

where Q is the daily runoff (mm); P is the daily rainfall over the recharge pond's catchment; NAPI is the daily normalized precipitation index (dimension less); a, b and c are the model parameters.

The NAPI is calculated as suggested by Heggen (2001). The model parameters are calibrated as 0.0046, 0.0169 and –0.1625 for b, c and a, respectively for the study area (Ali *et al.* 2010). The estimated runoff yields from the pond's catchment vary between 10% and 42% of the corresponding rainfall events with a mean of 20%. The total monsoon rainfall during the years 2006-08, ranged from 362 and 611 mm with a mean of 493 mm.

Evaporation from the recharge pond is often the large percentage component of recharge model, so its accurate determination is crucial for a reasonable estimate of potential groundwater recharge. The Bowen ratio energy balance 'BREB' method has been found suitable for the daily evaporation estimation under semi-arid climate of India (Ali *et al.* 2008). Considering the advected energy and the heat exchange by conduction between a recharge pond and the under laying sediment are negligible. The Bowen ratio energy balance approach can be written as:

$$E = \frac{R_n - G}{\lambda\,(1 + \beta)} \qquad \text{...3}$$

where E is the evaporation rate (mm/day); R_n is the net radiation (incoming radiation minus reflected radiation) on the water surface(MJ m^{-2}/day); G is the heat gained or lost by the upper layer of water body (MJm^{-2}/day); λ is the latent heat of evaporation of water (= 2.45 MJ/kg); and β is the Bowen ratio (dimensionless).

Net radiation is estimated empirically as (Ali *et al.* 2008):

$$R_n = (1-\alpha_w)\, R_s - \lfloor \varepsilon_w \varepsilon_a\, \sigma\, (Ta + 273.15)^4 - \varepsilon_w\, \sigma\, (Ta + 273.15)^4 \rfloor \qquad \text{...4}$$

where α_w is the albedo or reflection coefficient of water surface (dimensionless); R_s is the incoming solar or short wave radiation (MJm -2); ε_w (=0.97) is the emissivity of the water surface (dimensionless); ε_a is the emissivity of the atmosphere (dimensionless); α is the Stefan-Boltzmann constant = 4.903 × 10^{-9} MJM^{-2} K^{-4}; and T_a is the air temperature above the pond surface (°C).

The α_w is a time dependent function of solar position and mean cloudiness, and is determined using the relation given by Henderson-seller (1986). The short wave radiation, R_s is estimated as given by Allen *et al.* (1998). The heat stored or lost by water 'G', is calculated from the change in mean water temperature using the expression:

$$G = 4.186\ d\ \frac{T_w(t) - T_w(t-1)}{\Delta t} \qquad \text{...5}$$

where T_w(t) is the water temperature at time, t (°C); T_w(t-1) is the water temperature at time, t-1 (^{0}C).

The Bowen ratio, β (Henderson-Sellers 1986) is calculated as:

$$\beta = 6.665 \times 10^{-3}\, P \left(\frac{T_w - T_a}{e_s - e_a} \right) \qquad \text{...6}$$

where P is the atmospheric pressure (kpa); T_a is the air temperature above the pond surface (°C); e_s is the saturated vapour pressure at water temperature (kpa); and e_a is the actual vapour pressure at air temperature (kpa).

The atmospheric pressure, P is calculated using the equation proposed by Allen *et al.* (1998). The saturated vapour pressure (e_s) is as given by Magnus-Tetens formula and the actual vapour pressure (e_a) is computed using the expression suggested by Allen *et al.* (1998). The values of R_n and G computed from the daily data series are found to be from 1.93 to 16.03 MJ m^{-2}/day and 0.01 to 1.81 MJ m^{-2}/day, respectively while β is estimated to be between 0.06 and 0.08. The surface evaporation rates are estimated to be varied from 1.2 mm/day to 5.7 mm/day with a mean of 3.2 mm/day.

Surplus flow from the recharge pond (Q_o) was estimated using the formula of rectangular weir as; $q = 1.71 L_c H_f^{3/2}$, in which q is the rate of overflow over the crest of weir [m^3/s]; L_c is the length of crest[m]; and H_f is the depth of flow over the crest[m]. Volume of surplus flow is obtained by multiplying q with the time of flow of the surplus water. H_f was measured manually in the field for each of the event, which exceeded the storage capacity of the pond. During 2006–08, the pond had surplus flow in 7 and 5 times in 2007 and 2008 respectively, while there was no overflow during 2006.

To determine the saturated hydraulic conductivity, K_s of the bed material of the pond, infiltration tests were conducted at five places in the pond, one at the center of the pond and other four at the four middle edges of the pond. The saturated hydraulic conductivity, K_s is estimated utilizing the data of the infiltration tests in the Green-Ampt equation. The estimated K_s varied from 0.79 to 0.94 mm/hr with a mean of 0.85 mm/day.

For determining the physical properties of the bed material below the pond such as; total porosity, initial moisture content and bulk density, undisturbed soil cores, each of 6 cm in diameter and 7.6 cm in length collected from the upper soil layer (0-15 cm) were analyzed in the laboratory. The bulk density was ascertained from the ratio of air-dried soil core mass to the core volume of that soil, while the initial moisture content was determined by the gravitational method. The volumetric moisture content at near saturation, q_s is determined from the total porosity and found to be 45.36 (cm^3 cm^{-3}) for the year 2006 and 46.21 (cm^3 cm^{-3}) for 2007 and 2008. The initial moisture content for the all study years was almost same of about 20 (cm^3 cm^{-3}). The suction head, ψ_f was determined from the standard table describing representative value of ψ_f for different classes of soil textures, the value of ψ_f was determined as 0.34 m.

RESULTS AND DISCUSSION

Potential recharge rate

Making the use of the estimated values of the runoff (Eq. 2), evaporation (Eq. 3), saturated hydraulic conductivity, fillable porosity and other requirements input parameters of the recharge model, daily potential recharge rates have been computed using the Eq. 1. Time series of the daily potential recharge rate for the respective period during 2006–08 are given in Fig 1 (a, b, c). It is apparent from the curves for the periods 2006–08 that daily potential recharge rates is high in the beginning of the recharge process and reduced gradually with time. These are because, at the beginning of recharge process, there is high hydraulic head between the recharge pond's bottom and groundwater table results in a higher recharge rate. After some time, less hydraulic head are developed due to the mounding effect underneath the pond bottom and small water head on the pond. Result in, slower seepage rate. It can further be seen that the recharge rates fluctuated during the monsoon period. It is because of variation of inflows into the pond that in turn, changed the depth of water. These characteristics are in the expected line. The statistical properties, viz. range, mean, coefficient of variation and skewness of individual data years as well as combined data series have also been analyzed for 2006-08 and given in Table 1. It indicated that the potential recharge rates varied between 0.019 and 0.051 m/day with a mean of 0.024 m/day. It is recorded that both the initial and final potential rate decreases from 2006 to 2008 during the study periods. This is attributed to accumulation of silt in the pond with the passes of time even pond has had silt retention basin. For maintaining the recharge efficiency of a recharge pond, the inflow of sediment laden runoff and pond banks erosion must be avoided. The management techniques (Bouwer 2002) developed in past to minimize the clogging effect such as surface cleaning, natural drying and cracking of the bottom of recharge pond and removal of dried and sediment layers on the bed of the pond is the techniques for maintaining the recharge efficiency of the recharge ponds.

Table 1 Statistical values of the recharge rate computed for the experimental pond during 2006–08

Year	Simulation period (days)	Statistical parameters			
		Range (m/day)	Mean±Std, (m/day)	Cv (%)	Skewness
2006	147	0.020–0.051	0.025±0.003	13	4.3
2007	182	0.019–0.049	0.025±0.003	14	3.2
2008	203	0.019–0.045	0.023±0.003	14	2.8
Pool dataset	532	0.019–0.051	0.024±0.003	14	3.0

Std., Standard deviation; Cv, coefficient of variation

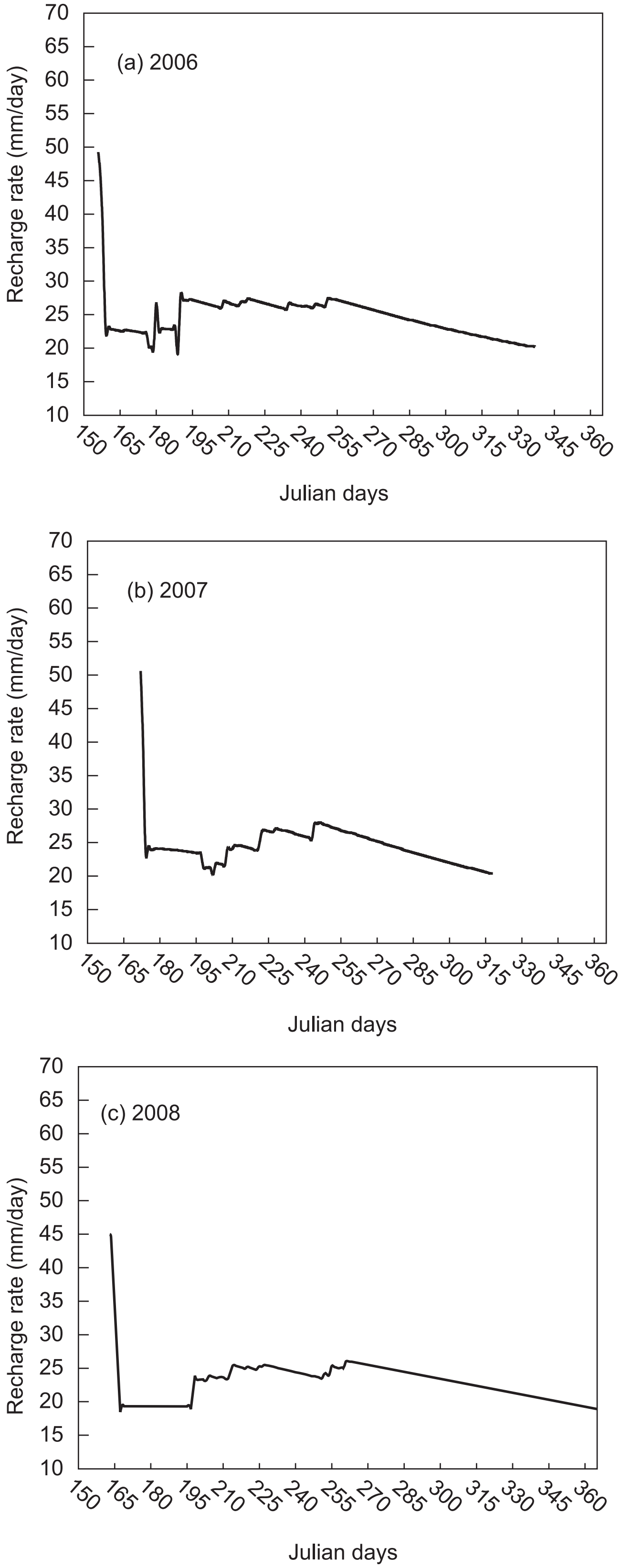

Fig 1 Variation of computed recharge rates of the experimental recharge pond during 2006–08

The coefficient of variation (C_v) for potential recharge rate is varies between 13 and 14% that is expected in recharge process. This is obviously because of decreasing trend of recharge rate during recharge process. A similar trend is also seen in the skewness of the daily recharge data series.

An effort was also made to develop a regression model using the recorded recharge period and their corresponding potential recharge rates. An exponential equation, i e $R_p = \varpi \exp(-\gamma t)$ was found to be best fitted to the potential recharge rates for the pooled data series during the years 2006–08. Two goodness-fit measures as coefficient of determination (R^2) and index of agreement (D), and two error measures as root mean square error (RMSE) and percent bias (PB) have been used to evaluate the performance of fitted regression model. Analysis showed that 2-parameters exponential decay model had fitted well as had better correction correlation factor; $R^2 = 0.60$ and $D = 0.61$, and the least RMSE = 2.06 mm/day PB = 1.44% values between the observed and simulated potential recharge rates during the study periods. Further, it was observed that exponential decay model overestimated the potential recharge rate for data sets (as $PB > 0$). In mathematical notation, the 2-parameter exponential decay model fitted to combine data set is given by:

$$R_p = 26.24 \exp(-0.0011\, t) \qquad \ldots 7$$

where R_p and t are the potential recharge rate [mm/day] and recharge period [day], respectively.

Water balance partitioning factors

The cumulative of the volumetric runoff into the pond Q_c, the rainfall over the pond P_c, the evaporation from the pond, E_c, the outflow from the pond Q_{oc} and the recharge through the pond's wetted surface, R_c are estimated from the volumetric rate of each component for each time interval. The cumulative potential groundwater recharge volume for the year 2006, 2007 and 2008 are estimated to be 11 885, 15 542 and 16 742 m³, respectively (Table 2) that gives a total of 44 168 m³ of water with an average of 14 723 m³/year recharged artificially from the pond to the underneath aquifer during 2006–08. The total loss of water from the recharge pond during the years 2006–08 by the evaporation varied between 1 454 and 1 861 m³ with a mean of 1 723 m³.

Table 2 Estimated water balance components of the recharge pond during 2006-08

Year	Simulation period (days)	Water balance components					
		Q_t (m³)	P_t (m³)	E_t (m³)	Qot (m³)	Rt (m³)	Storage (St)(m³)
2006	147	12 209	1 205	1 454	0	11 885	+74
2007	182	19 934	1 679	1 861	4 096	15 542	+113
2008	203	22 072	2 054	1 855	4 965	16 742	+565
Mean	177	18 072	1 646	1 723	3 020	14 723	+251

Table 3 Partition factors of the water balance components of the experimental recharge pond during 2006–08

Year	Water balance partition factors (%)			
	$\frac{R_t}{Q_t + P_t}$	$\frac{E_t}{Q_t + P_t}$	$\frac{Q_{ot}}{Q_t + P_t}$	$\frac{S_t}{Q_t + P_t}$
2006	88.60	10.84		0.56
2007	71.91	8.61	18.95	0.52
2008	69.39	7.69	20.58	2.34
Mean	76.63	9.05	13.18	1.14

The average dead storage in the recharge pond is estimated to be 251 m³ at the end of the simulation period.

The dimensionless water balance partitioning factors, namely; the ratio of total volume of water recharged into the aquifer Rt to the total volume of inflows, which include: the volume of runoff into the pond and the volume of rainfall over the pond, (Qt + Pt), i e ($R_t/(Q_t + P_t)$); the ratio of total volume of water loss by evaporation to the total volume of inflows, ($E_t/(Q_t + P_t)$); the ratio of total volume of outflows from the pond to the total volume of inflows ($Q_{ot}/(Q_t + P_t)$); and the ratio of total volume of water remained as storage in pond at the end of the simulation period to the total volume of inflows ($S_t/(Q_t + P_t)$) are estimated and given in Table 3. It can be seen from Table 3 that a large fraction of the accumulated runoffs into the pond that varied between 69 and 89% with a mean of 77% during the periods 2006–08 has been recharged into the underneath aquifer, while the fraction of evaporation losses is found to be varied between 8 and 11% with a mean of 9%. The mean fractions of outflows from the recharge pond and the storage in the pond are of 13 and 1% of the total inflows, respectively.

The responses of the integrated process based potential recharge model in simulation of the potential recharge rates are found most promising. This process based models can be extended to other areas for quantifying the recharge component for similar or other types of recharge structures.

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