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Effectiveness of check dam and percolation pond with percolation wells for artificial groundwater recharge using groundwater models

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ABSTRACT

Population growth and higher living standards have resulted in ever-increasing demand for water. For the present study natural recharge was computed from a water balance model and daily water level fluctuations were measured to study the increase in water level due to artificial recharge. Numerical models were developed using MODFLOW to analyze the feasibility of different artificial recharge arrangements such as check dam and percolation pond with percolation wells individually and in combination and evaluate the effectiveness of the structures in recharging the aquifer. The maximum increase in water level was found to be 3.46 m, 2.54 m and 4.7 m respectively for the check dam, percolation pond with three percolation wells and combined structure arrangement after 2 years of artificial recharge. The zone of influence was obtained as 400 m, 600 m and 500 m respectively for the check dam, percolation pond and combined structure system. Water level fluctuations also proved the same. Water level increase obtained from the natural recharge study was only of the order of 0.2 m. Artificial recharge is found to be very effective for sustainable development of water resources and the percolation pond was found to be the most appropriate structure for groundwater recharge for the study area.

Key words | artificial recharge, check dam, climatic change, groundwater, numerical model, percolation pond

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INTRODUCTION

Urbanization, industrialization and agriculture needs continue to compete, environmental requirements will be stressed and groundwater quality is declining. Artificial groundwater recharge is essential for sustainable development of water resources for countries where large variations exist in rainfall distribution. Changing precipitation patterns together with increased evapotranspiration linked to increased temperatures can affect groundwater recharge rates. Maintaining groundwater levels would minimize carbon footprint and maximize agrarian resilience to hydro-climatic change as groundwater can act as a buffer source during the vagaries of climate. A depleted aquifer means higher emission of greenhouse gases for pumping groundwater from deeper layers during periods of drought. Groundwater resources are over-exploited in 45% of Tamil Nadu's area and demarcated as black areas.

Artificial recharge is defined as the process of replenishing the aquifer by augmenting the natural infiltration process through various methods designed depending on the topographic, lithologic, and soil conditions. Artificial recharge is expected to become increasingly necessary in the future as urbanization is taking place at a faster pace and the growing population requires more water, which can be provided by storing water in times of surplus in the underground reservoir. Recharge systems can be used to clean water of poor quality, as soil acts as a natural filter. Recharge is

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also a good option to control sea water ingress in coastal areas (Singh 2014; Lal & Datta 2018).

The water level fluctuation method gives superior results compared with other estimation methods but continuous monitoring of groundwater levels is required (Dandekar *et al.* 2018). The most commonly used method for natural recharge estimation is the mass balance approach (Edmunds *et al.* 2002; Khazaei *et al.* 2003; Mahmood & Hubbard 2003; Xu & Chen 2005; Rushton *et al.* 2006; Naranjo *et al.* 2015). Neuman *et al.* (2004) conducted a recharge study using the water balance of reservoirs and found that 96% of the water was recharged and 4% was evaporated in the most favourable case and 45% was recharged and 55% was evaporated for the worst scenario. Water balance study has been carried out using the Natural Resources Conservation Service (NRCS) curve number method which is widely accepted and has been proven effective for runoff estimation by several authors (Mishra *et al.* 2008; Thakuriah & Saikia 2014; Santhanam & Abraham 2018).

Athavale *et al.* (1992) found that in India, about 5% to 10% of the rainfall is recharged in the peninsular hard rock regions and 15% to 20% in the alluvial areas. Mohan & Abraham (2010) estimated natural recharge as 19% of rainfall for Neyveli basin in Tamilnadu. Jothiprakash *et al.* (2002) studied the response of two percolation ponds in Tamil Nadu, India and observed that wells located within 400 m from the ponds were strongly influenced and wells located between 400 m to 800 m from the ponds were moderately influenced.

A groundwater model is a mathematical description of a groundwater flow system which helps in effective management of the resource. Numerical models have been developed by various researchers worldwide to simulate the response of aquifers under different hydrogeological scenarios using MODFLOW (Lubczynski & Gurwin 2005; Aish & de Smedt 2006; Szucs *et al.* 2009; Chenini *et al.* 2010; Chitsazan & Movahedian 2015; Ghouili *et al.* 2017). MODFLOW can be used to simulate groundwater recharge in semi-arid regions (Dandekar *et al.* 2018). Many researchers have integrated MODFLOW with geographic information system for groundwater resource management (Khadri & Pande 2016; Sudhakar *et al.* 2016).

The present study is aimed at computing natural recharge, developing a tool for studying the spatial and temporal replenishment patterns of artificial recharge structures, namely check dams, a percolation pond with percolation wells, and a combined structure and verifying the same with actual groundwater level fluctuations.

METHODS

Study area and database

The study area is in Cuddalore groundwater basin between sub-basins of Vellar river and Gadilam river at Nadiyapattu village in Tamil Nadu, India, between latitudes 11°39′ 36″ to 11°45′ 00″N and longitudes 79° 24′ 12″to 79° 24′ 48″E. The basin is heavily pumped for agricultural, industrial, domestic, and mining purposes. Locations favourable for artificial recharge structures were identified on the basis of geological sections interpreted from data obtained through electrical resistivity surveys (Mohan 2003).

Recharge structures, namely check dam and percolation pond along with percolation wells, were constructed in the study area. Wells having a diameter of 45 cm penetrating to 75 m and filled with gravel and pebbles to allow free flow of filtered water were used as percolation wells. A recharge well had a diameter of 15 cm and depth of 75 m with a slotted length of 24 m. Observation wells extending to 75 m had a diameter of 10 cm and a slotted length of 24 m. Water levels from 15 observation wells constructed were monitored and recorded at 8:00 am and 2:30 pm every day for 30 months. The location map, recharge arrangements, and observation wells are given in Figure 1.

Water level fluctuations

Daily rainfall and water level for observation wells near the check dam area (CS5), percolation pond area (PO1) and combined structure area (CS2) are shown in Figure 2. The maximum increase in groundwater level observed in the representative observation wells after 2 years of artificial recharge are 3.81 m, 2.48 m, and 3.95 m respectively for the check dam area, percolation pond area and combined structure area.

Water balance model

Natural recharge was estimated by a water balance model as a prerequisite for the artificial recharge study. The

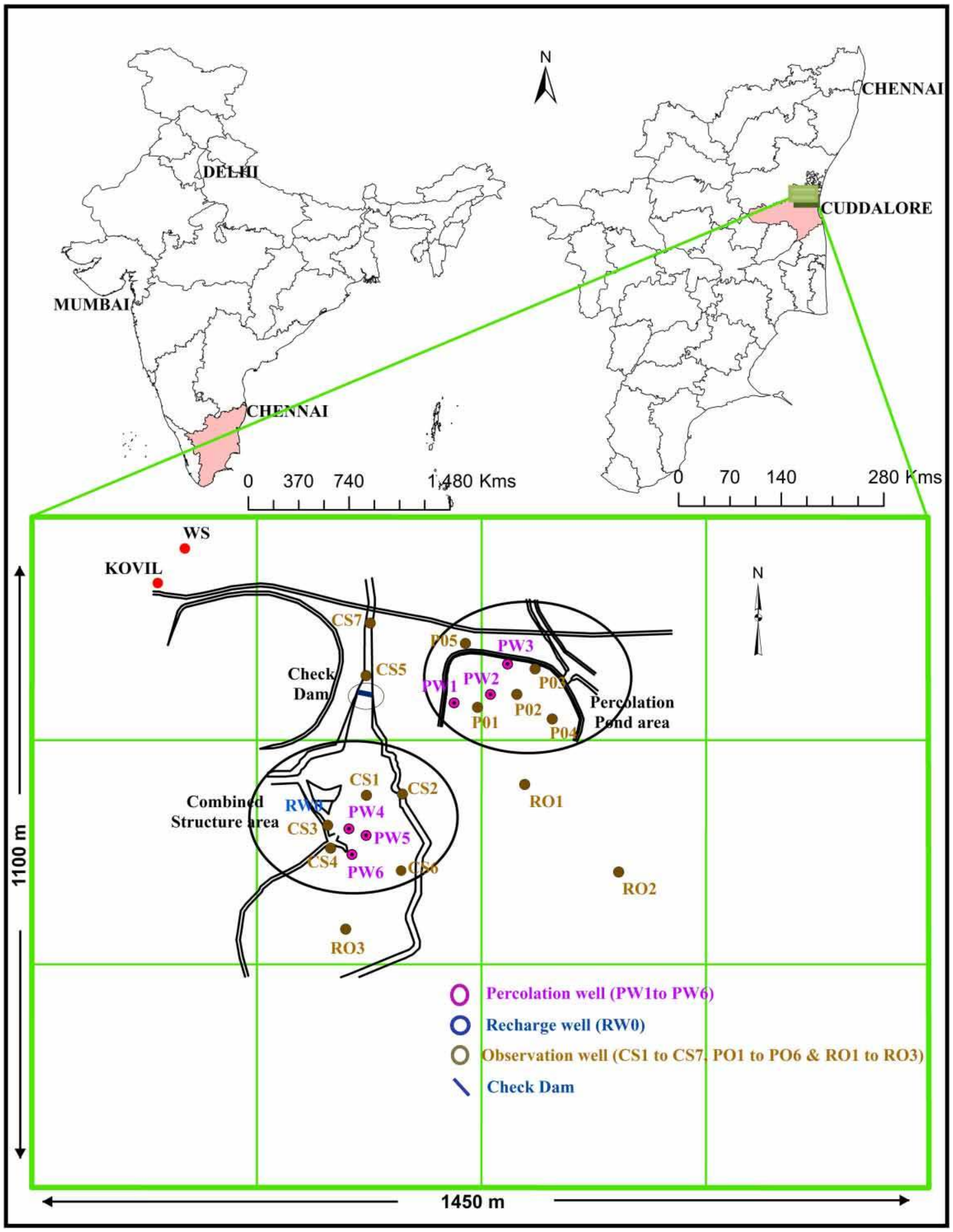

Figure 1 | The location map, recharge arrangements and observation wells in the study area.

components of the water balance model were independently evaluated on a daily basis and substituted in the mass balance equation to estimate natural recharge as given below:

$$R_e = P - R - I_a - ET_a \pm \Delta S \quad (1)$$

where

R_e = recharge (mm)
P = precipitation (mm)
R = runoff (mm)
I_a = initial abstraction (mm)

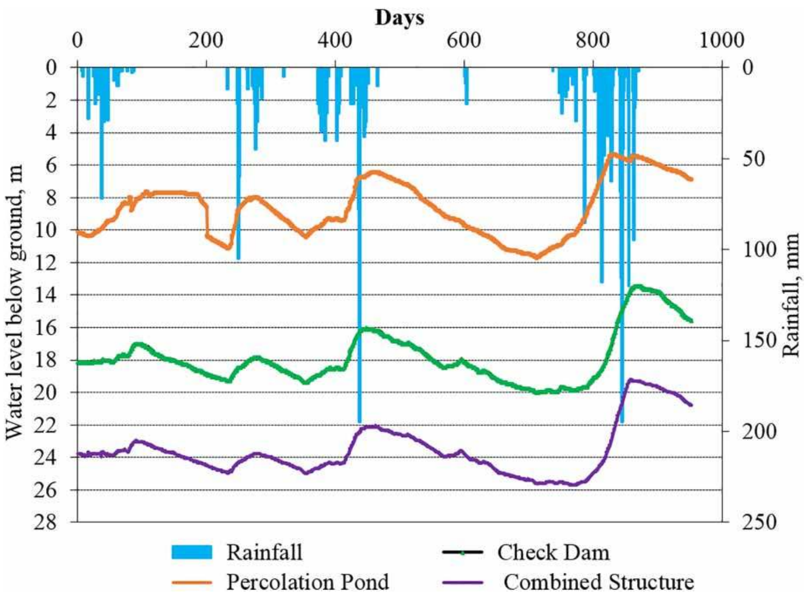

Figure 2 | Daily water level variation in the study area due to artificial recharge structures.

ET_a = actual evapotranspiration (mm)
ΔS = change in soil water storage (mm).

As the balance is carried out annually, the change in soil moisture storage can be neglected (de Silva 1999).

Runoff was calculated using the NRCS model with daily rainfall and curve numbers based on land use and hydrologic soil group (Chow *et al.* 1988).

Initial Abstraction was taken as $0.2\,S$ where S is maximum retention.

Evapotransipiration was computed using the Penman–Monteith model, which is the standard model recognized by the Food and Agricultural Organization (FAO) (Allen *et al.* 1998).

Numerical models

Numerical models are capable of solving complex equations that describe multi-dimensional groundwater flow. Numerical solution techniques for the governing flow equation offer less restrictive assumptions, thus allowing the model to more accurately fit the natural conditions to quantify the impact on the groundwater system due to pumping or recharge stresses. The modular three-dimensional finite difference groundwater flow model (MODFLOW) developed by Harbaugh *et al.* (2000) with the Groundwater Modeling System (GMS) (EMRL 2002) as graphical user interface was used to simulate flow. The model is based on the governing equation as given below:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-w = S_s\frac{\partial h}{\partial t} \tag{2}$$

where

h = hydraulic head in the aquifer [L]
w = volumetric flux per unit volume [1/T] – source or sink term
K_{xx}, K_{yy}, and K_{zz} = hydraulic conductivities in x, y, and z directions [L/t]
S_s = specific storage [1/L].

The computer program uses finite difference techniques and a block-centered formulation to solve the groundwater flow equations for three-dimensional flow in the anisotropic, heterogeneous, porous media. Creating numerical groundwater models of field problems requires careful attention while describing the problem domain, selecting boundary conditions, assigning model parameters, and calibrating the model. Model construction consists of three steps: design of the conceptual model, creation of 3D finite difference grids and running the MODFLOW simulation.

In order to use a finite difference approximation, a grid was superimposed over the study area, and the aquifer's hydraulic parameters necessary to solve the flow equations were averaged over the area of a cell. The basic differential flow equation for each cell was replaced by an algebraic equation so that the entire flow field was represented by as many equations as the number of cells. The system of algebraic equations was solved numerically, through an iterative process. Finite differences computed the average head value for a cell at the node. In the block-centered formulation, the nodes for which water levels were simulated were located at the center of the grid cells. These cells were the smallest volumetric units over which the hydraulic properties were assumed constant.

RESULTS AND DISCUSSION

Natural recharge by water balance model

Daily rainfall data were collected and water balance was calculated on a daily basis for each rainfall event for 7 years. From the daily recharge values from the water balance model, monthly and annual recharges were calculated. Annual recharge was studied for the 7-year period and the values varied between 127.8 mm and 286.6 mm with an average recharge value of 218.1 mm. The distribution of rainfall played an important role in the quantum of recharge and heavy spells of rainfall in short duration were going as runoff rather than effectively recharging the aquifer. The average annual recharge for the study area was found to be 19.23% of rainfall during the study period.

Artificial recharge estimation by numerical model

Artificial recharge due to different structures, namely check dams, percolation pond with percolation wells and combined structure (check dam with recharge well and percolation pond with percolation wells) were studied using a numerical model study. Numerical models were developed to study the individual as well as combined effectiveness of various artificial recharge arrangements and their effects on spatial and temporal scale.

A finite difference grid superimposed over the study area was designed and constructed based on the simplification of a conceptual model representing the physical properties of the groundwater system. The study area spread over 1.6 km^2 was divided into 1,400 cells comprising 36 rows and 39 columns. To represent the study region a single model layer extending vertically from 80 m above mean sea level to 45 m below mean sea level was considered. The finite difference model was developed by incorporating geological data and measured and inferred hydrological data. Block-centered formulation was used, in which water levels were simulated at the center of the grids. The solver selected was the Pre-conditioned Conjugate Gradient procedure.

Data input

A contour map of the potentiometric surfaces of the aquifer was developed and was based on the interpolation and extrapolation of heads from measured points. Boundaries were given as Dirichlet boundaries. Input parameters to the model included hydraulic conductivity, hydraulic head, aquifer thickness, rainfall, estimated recharge values and estimated evapotranspiration values. Hydraulic properties were assigned based on an infiltration study conducted at the site and hydrogeological investigations. The vertical conductivity was set as 10% of the horizontal hydraulic conductivity. The saturated hydraulic conductivities in the x, y and z directions were taken as 10 m/day, 10 m/day and 1 m/day respectively. The specific yield was assumed as 0.2. Natural recharge for the study area was obtained from a water balance study. Evapotranspiration is a key factor controlling recharge (Dandekar *et al.* 2018) and the values were computed from a Penman–Monteith model (Allen *et al.* 1998). Monthly time-step was used in the model and average monthly water levels were computed from the daily water level observations.

Calibration

Calibration was carried out with 16 months of water level data and validation with 14 months of water level data. During the calibration process, hydraulic conductivity values were adjusted within reasonable limits until field water level approximated the numerical model. The hydraulic conductivity was found to be 12 m/day. The recharge rate of the wells was fixed as 500 m^3/day by a trial-and-error method.

Recharge estimation and effectiveness of recharge structures

The distribution of hydraulic head was simulated using a numerical model for transient state and the recharge pattern was found for different time periods. Simulated head contours for the study area can be viewed from the numerical model developed (Figure 3). Figure 4 shows that the observed and simulated heads match well.

Recharge was found to vary considerably with time and location. The calibrated model was used to find the spatial and temporal variation in head in the study area. The radius of influence of each structural arrangement was obtained from the model. The maximum increase in mound height and the radius of influence for each structure are given in Table 1. This is in agreement with the analytical and numerical study results of Aish & de Smedt (2006). The maximum area of influence was obtained for the percolation pond with percolation well arrangement. The zone of influence was around 400 m, 600 m and 500 m respectively for check dam, percolation pond with percolation well arrangement and combined structure from the center point of the structure, which coincides with the findings of Jothiprakash *et al.* (2002). From the model study, the maximum increase in water level was found to be 3.46 m, 2.54 m and 4.7 m respectively for check dam, percolation pond along with three percolation wells and combined structure arrangement after 2 years of artificial recharge.

CONCLUSIONS

Artificial recharge has become more prevalent in recent years because it can be used to buffer against climatic variability and associated floods and droughts. To evaluate the long-term effectiveness of individual and various combinations of artificial recharge arrangements, a field experimental setup was established and a comprehensive groundwater flow model was developed using MODFLOW. Simulated head contours could infer the spatial and temporal recharge pattern of the various structures studied. The model study indicated that due to artificial recharge there was an increase in water level between 2 m and 4 m with an influence zone of around 500 m. The same was verified by a water level fluctuation method. Natural recharge

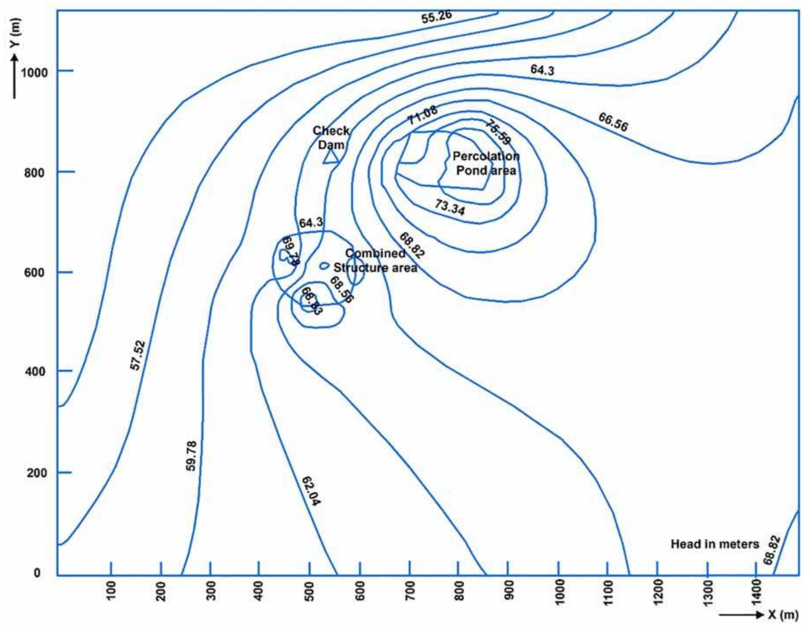

Figure 3 | Simulated head contours after 2 years of artificial recharge.

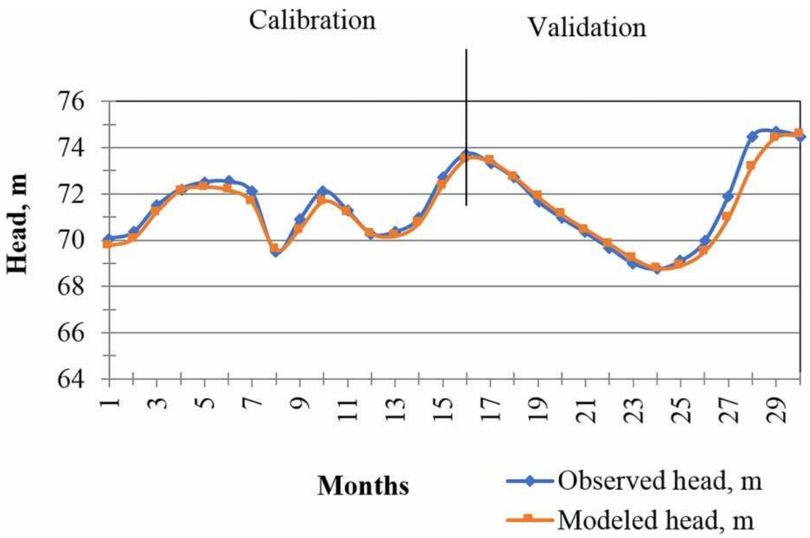

Figure 4 | Comparison of observed and simulated heads near the percolation pond area.

Table 1 | Evaluation of artificial recharge structures from the numerical model study

Recharge arrangement	Time/ponding area	Maximum increase in head	Zone of influence
Check dam	Base data	0 m	
	After 1 year 1,300 m^2	0.93 m	350 m down gradient and 300 m up gradient
	After 2 years 1,300 m^2	3.46 m	450 m down gradient and 300 m up gradient
Percolation pond with 3 percolation wells	Base data	0 m	
	After 1 year 15,000 m^2	1.63 m	600 m down gradient and 500 m up gradient
	After 2 years 15,000 m^2	2.54 m	650 m down gradient and 600 m up gradient
Combined structure	Base data	0 m	
	After 1 year 2,800 m^2	1.27 m	350 m down gradient and 300 m up gradient
	After 2 years 15,000 m^2	4.7 m	500 m down gradient and 450 m up gradient

estimates from the water balance study showed only an increase in water level of around 0.2 m. The percolation pond with percolation wells arrangement was found to be more effective in recharging the aquifer compared with the other structures studied. The simulated head is useful in determining the recharge pattern and may serve as a guidance tool in planning artificial recharge projects for sustainable development of water resources. Aquifer recharge is imperative in the groundwater management plan in areas where over-development has depleted the aquifer and deteriorated the quality of groundwater.

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REFERENCES

Aish, A. & de Smedt, F. 2006 Modeling of a groundwater mound resulting from artificial recharge in the Gaza Strip, Palestine. *Water for Life in the Middle East* **2**, 779–787.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. Irrigation and Drainage Paper No. 56, Food and Agricultural Organization of the United Nations, Rome, Italy.

Athavale, R. N., Rangarajan, R. & Muralidharan, D. 1992 Measurement of natural recharge in India. *Journal of Geological Society of India* **39** (3), 235–244.

Chenini, I., Mammou, A. B. & El May, M. 2010 Groundwater recharge zone mapping using GIS-based multi-criteria analysis: a case study in Central Tunisia (Maknassy Basin). *Water Resources Management* **24** (5), 921–939.

Chitsazan, M. & Movahedian, A. 2015 Evaluation of artificial recharge on groundwater using MODFLOW model (case study: Gotvand Plain-Iran). *Journal of Geoscience and Environment Protection* **3** (5), 122–132.

Chow, V. T., Maidment, D. R. & Mays, L. W. 1988 *Applied Hydrology*. McGraw-Hill, New York, USA.

Dandekar, A. T., Singh, D. K., Sarangi, A. & Singh, A. K. 2018 Modelling vadose zone processes for assessing groundwater recharge in semi-arid region. *Current Sciences* **114** (3), 608–618.

de Silva, R. P. 1999 Estimating groundwater recharge in the dry zone of Sri Lanka using weekly, 10-daily or monthly evapotranspiration. *Journal of Environmental Hydrology* **7**, 4.

Edmunds, W. M., Fellman, E., Goni, I. & Prudhomme, C. 2002 Spatial and temporal distribution of groundwater recharge in northern Nigeria. *Hydrology Journal* **10**, 205–215.

Environmental Modeling Research Laboratory (EMRL) 2002 *Groundwater Modeling System (GMS) Version 4.0 Tutorial Documents, Volumes 1–4*. Environmental Modeling Research Laboratory, Brigham Young University, Provo, UT, USA.

Ghouili, N., Horriche, F. J., Zammouri, M., Benabdallah, S. & Farhat, B. 2017 Coupling WetSpass and MODFLOW for groundwater recharge assessment: case study of the Takelsa multilayer aquifer, northeastern Tunisia. *Geosciences Journal* **21** (5), 791–805.

Harbaugh, A. W., Banta, E. R., Hill, M. C. & McDonald, M. G. 2000 *MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process*. Open-File Report 00-92, US Geological Survey, Reston, VA, USA.

Jothiprakash, V., Mohan, S. & Elango, K. 2002 Artificial recharge through percolation ponds. In: *International Conference on Sustainable Development and Management of Groundwater Resources in Semi-Arid Regions with Special Reference to Hard Rock*. Oxford & IBH Publishing Co. Pvt Ltd, New Delhi, India, pp. 193–197.

Khadri, S. F. R. & Pande, C. 2016 Ground water flow modeling for calibrating steady state using MODFLOW software: a case study of Mahesh River basin, India. *Modeling Earth System and Environment* **2**, 39.

Khazaei, E., Spink, A. E. F. & Warner, J. W. 2003 A catchment water balance model for estimating groundwater recharge in arid and semiarid regions of south-east Iran. *Hydrogeology Journal* **11**, 333–342.

Lal, A. & Datta, B. 2018 Modelling saltwater intrusion processes and development of a multi-objective strategy for management of coastal aquifers utilizing planned artificial freshwater recharge. *Modeling Earth Systems and Environment* **4** (1), 111–126.

Lubczynski, M. W. & Gurwin, J. 2005 Integration of various data sources for transient groundwater modeling with spatio-temporally variable fluxes – Sardon study case, Spain. *Journal of Hydrology* **306** (1–4), 71–96.

Mahmood, R. & Hubbard, K. G. 2003 Simulating sensitivity of soil moisture and evapotranspiration under heterogeneous soils and land uses. *Journal of Hydrology* **280** (1–4), 72–90.

Mishra, S. K., Jain, M. K., Suresh Babu, P., Venugopal, K. & Kaliappan, S. 2008 Comparison of AMC-dependent CN-conversion formulae. *Water Resources Management* **22** (10), 1409–1420.

Mohan, S. 2003 *Study on Enhancement of Recharge Potential in the Recharge Area of the Neyveli Deep Seated Aquifers*. Interim Report submitted to Neyveli Lignite Corporation, Neyveli, Tamil Nadu, India.

Mohan, S. & Abraham, M. 2010 Derivations of simple site-specific recharge–precipitation relationships: a case study from the Cuddalore Basin, India. *Environmental Geosciences* **17** (1), 37–44.

Naranjo, G., Cruz-Fuentes, T., Cabrera, M. C. & Custodio, E. 2015 Estimating natural recharge by means of chloride mass balance in a volcanic aquifer: northeastern Gran Canaria (Canary Islands, Spain). *Water* **7** (6), 2555–2574.

Neuman, I., Barker, J., MacDonald, D. & Gale, I. 2004 *Numerical Approaches for Approximating Technical Effectiveness of Artificial Recharge Structures*. Groundwater Systems and Water Quality Programme Commissioned Report CR/04/265N, British Geological Survey, Nottingham, UK.

Rushton, K. R., Eilers, V. H. M. & Carter, R. C. 2006 Improved soil moisture balance methodology for recharge estimation. *Journal of Hydrology* **318** (1–4), 379–399.

Santhanam, K. & Abraham, M. 2018 Assessment of surface water potential and groundwater recharge in ungauged watersheds: a case study in Tamil Nadu, India. *Environmental Earth Sciences* **77**, 788.

Singh, A. 2014 Optimization modelling for seawater intrusion management. *Journal of Hydrology* **508**, 43–52.

Sudhakar, S., Verma, M. K. & Soumya, S. 2016 Application of GIS and MODFLOW to ground water hydrology – a review. *International Journal of Engineering Research and Applications* **6** (1), 36–42.

Szucs, P., Madarasz, T. & Civan, F. 2009 Remediating over-produced and contaminated aquifers by artificial recharge from surface waters. *Environmental Modeling & Assessment* **14** (4), 511–520.

Thakuriah, G. & Saikia, R. 2014 Estimation of surface runoff using NRCS curve number procedure in Buriganga Watershed, Assam, India – a geospatial approach. *International Research Journal of Earth Sciences* **2** (5), 1–7.

Xu, C. Y. & Chen, D. 2005 Comparison of seven models for estimation of evapotranspiration and groundwater recharge using lysimeter measurement data in Germany. *Hydrological Processes* **19**, 3717–3734.

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