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Estimation of groundwater recharge from water storage structures in a semi-arid climate of India

V.N. Sharda [a,*], R.S. Kurothe [b], D.R. Sena [b], V.C. Pande [b], S.P. Tiwari [b]

[a] *Central Soil and Water Conservation Research and Training Institute, 218, Kaulagarh Road, Dehradun 248195, Uttaranchal, India*
[b] *Central Soil and Water Conservation Research and Training Institute, Research Centre, Vasad 388306, Anand District, Gujarat, India*

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Summary Groundwater recharge from water storage structures under semi-arid conditions of western India has been estimated by employing water table fluctuation (WTF) and chloride mass balance (CMB) methods. Groundwater recharge was estimated as 7.3% and 9.7% of the annual rainfall by WTF method for the years 2003 and 2004, respectively while the two years average recharge was estimated as 7.5% using CMB method. A Recharge function depicting the relationship between potential recharge from storage structures and successive day averaged storage depths was better exhibited by a power function. A diagnostic relationship correlating the rainfall to the potential recharge from water storage structures has been developed to explain the characteristics of the storage structures for a given geographical location. The study has revealed that a minimum of 104.3 mm cumulative rainfall is required to generate 1 mm of recharge from the water storage structures. It was also inferred that the storage structures have limited capacity to induce maximum recharge irrespective of the amount of rainfall and maximum recharge to rainfall ratio is achieved at a lower rainfall than the average annual rainfall of the area. An empirical linear relationship was found to reasonably correlate the changes in chloride concentration with water table rise or fall in the study area.

Introduction

Groundwater is an important source of irrigation in India accounting for more than half of the net irrigated area in the country (Deb Roy and Shah, 2002). It is estimated that 70–80% of the total production from irrigated areas in India may ultimately depend on groundwater utilization (Dains and Pawar, 1987). According to the World Bank (1998) and

* Corresponding author. Tel.: +91 135 2758564; fax: +91 135 2754213.
E-mail addresses: vnsharda1@rediffmail.com, vnsharda@stpd.soft.net (V.N. Sharda), soiltrg_ad1@sancharnet.in (R.S. Kurothe).

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Nomenclature

a,b,c	arbitrary constants in regression analysis (.)
A_s	average planar area of submergence (L^2)
A_w	area of the watershed (L^2)
Cl_d	Dry deposition rate of chloride (ML^{-3})
Cl_{gw}	chloride concentrations of groundwater (ML^{-3})
Cl_p	chloride concentrations of the rainfall (ML^{-3})
CN	curve number (.)
ET_a	actual evapotranspiration (L)
EV	evaporation (L)
h_{av}	average of consecutive days storage depths (L)
h_t	absolute depth of water impounding (m) on tth day (L)
I	interception of rainfall by vegetation (L)
O_f	outflow (L^3)
P	rainfall (L)
P_{year}	annual average rainfall (L)
R_e	cumulative potential recharge (L)
$R_{e(WB)}$	recharge component in the water balance equation (L)
R_{ep}	potential recharge (L^3)
R_{gw}	actual groundwater recharge (L, L^3)
R_{max}	maximum cumulative potential recharge (L)
RO	runoff (L)
S	storativity (.)
S_T	maximum potential storage of the watershed (L)
Δh	change in depth in water level in the structure (L)
ΔCl	change in chloride concentration in groundwater (ML^{-3})
ΔWT	change in water table (L)
$\Delta\theta$	change in soil moisture storage (L)
N	Number of data pairs (.)

Ministry of Water Resources, Government of India estimates (1998) the contribution of groundwater to India's GDP is about 9%. The great significance of groundwater in the agrarian economy of India is ascribed to the fact that crop yields are generally high in areas irrigated with groundwater than irrigated from other sources (Dhawan, 1995).

On an average, about 32% of the annual utilizable groundwater potential of 452.2 km^3 has been actually exploited in India, out of which 8% of the groundwater resource has been exploited beyond 85% of its potential. In the state of Gujarat, where this study has been undertaken, 25% of the groundwater sources have been exploited by more than 85% of their potential resulting in sharp decline of water table. In Gujarat, water table in over 90% of the wells monitored by Central Groundwater Board has dropped by 0.5 m to as high as 9.5 m in the recent past (Bose et al., 1998).

Water storage structures play a vital role in augmenting the groundwater recharge as they constitute one of the major interventions in the massive watershed development programmes undertaken in the country. It calls for studying the interaction between surface and groundwater (SW–GW) resource systems which include surface water storage structures, artificial recharge systems and addressing the concerns about the quantity and quality of the water being recharged to the aquifer. The concepts of hydrology, geology and ecology need to be combined for comprehensive conceptualization of SW–GW interactions related with groundwater recharge (Sophocleous, 2002).

Estimation of recharge has been a daunting task for the researchers, due to the complexity of the geohydrological settings and the uncertainty associated with the meteorological data of a given location. The groundwater recharge is quantified by employing surface water, unsaturated, and saturated-zone techniques. Identification of an appropriate technique in a given location partly depends on the recharge rate (Scanlon et al., 2002). However, limitations and uncertainty associated with each of the methods sometimes warrants application of multiple methods to authenticate the estimation.

Analysis of water table fluctuations (WTF) is a useful tool for determining the magnitude of both short- and long-term changes in groundwater recharge and has been widely applied under varying climatic conditions (Gerhart, 1986; Hall and Risser, 1993; Healy and Cook, 2002). Groundwater Estimation Committee (India) constituted in 1982 to improve the existing methodologies for estimation of groundwater resource potential has also recommended this method for estimation of groundwater recharge. However, in areas, where groundwater level monitoring is not carried out regularly, or where adequate data about groundwater level fluctuations is not available, ad hoc norms of rainfall infiltration have been recommended. As per guidelines, recharge in hard rock areas with geological formation predominantly representing basaltic rocks varies from 3% to 15% (Kumar, 1996).

In the process of estimating ground-water recharge of fresh-water lenses, it has been observed that the chloride ion can be considered as a tracer for estimating recharge which is concentrated by the processes of evapotranspiration (Vacher and Ayers, 1980; Ayers, 1981). This method is independent of the fact whether the recharge is focused or diffused and integrates spatial data over the watershed. The chloride mass balance method with certain conditions and assumptions has been found to provide reasonable estimates of groundwater recharge in semi-arid areas well comparable to those obtained by physically based methods (Wood and Sanford, 1995).

The estimation of recharge related to surface-water bodies depends on the extent of connectivity between surface water and groundwater systems (Sophocleous, 2002). The impact of water storage structures on groundwater recharge in different agro-ecological situations has not been properly understood except through crude methods based upon fluctuations in water level in the surrounding open or tube wells. No generalized approach or solution is available to decide the location and size of the water storage structure in a micro-watershed and its efficacy in augmenting groundwater table in a quantifiable manner. Arid or semi-arid regions are generally characterized by the lack of