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An approach towards site selection for water banking in unconfined aquifers through artificial recharge

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ABSTRACT

Selection of sites for water banking is very crucial for successful recovery of groundwater at the time of need. Attempts were made earlier to demarcate artificial recharge sites, and several indices were proposed for post-event evaluation of site-efficiency. In the present study a step-by-step method has been proposed for pre-event site selection for groundwater banking, based on meteorological, hydrological, hydraulic and hydrogeological parameters. Further, an index has been developed to evaluate site-efficiency. The proposed Normalized Difference Water Recovery Index (NDWRI) is the normalized ratio of water input and output in terms of recharge and productivity. Greater the value of yield, productivity, and the NDWRI higher is the suitability of the site for subsurface water banking. The index assumes a linear relation between recharge and sustainability of well productivity. In this article, the proposed methodology is explained and the related issues are discussed with a case study in the hard-rock Aravalli terrain of India.

1. Introduction

Continuous failure of monsoon, increasing demand and over-exploitation leads to depletion of groundwater resource and decline of groundwater level in many parts of the world. This has forced scientists and planners to understand, agree, and execute replenishment of groundwater artificially in order to arrest such aggressively falling groundwater tables (Samadder et al., 2012). As a consequence, artificial recharge or managed aquifer-recharge (MAR) for subsurface water banking has become an important aspect of studies and an effective measure to tackle water-scarcity problem all over the world (Barksdae and Debuchanne, 1946; Todd, 1959; Wright and du Toit, 1996; CGWB, 2000; Bouwer, 2002; Asano and Cotruvo, 2004; Ong'or and Long-Cang, 2009). Artificial recharge of aquifers is governed by several factors such as: need and demand, practical feasibility (source water, operation cost, cost-effectiveness, etc.), technical feasibility (site suitability, compatibility between source water and native water, clogging, etc.), and expected outcome (percent of recovery, meeting of target, usability of extracted water, etc.). Water banking through injection wells, also known as aquifer storage and recovery (ASR) is an alternative to surface-water storage. ASR involves injection of fresh water from rivers, lakes or even stored rain-water into an aquifer via single well or a cluster of wells during periods of surplus, and is withdrawn at the time of need from the same well through which it was injected. Re-injection of even one-fourth of extracted water may cause significant increase in recharge (Schaeffer et al., 2001) as it suffers little loss due to evaporation (Bouwer, 2002). In fractured rock aquifers of most arid and semi-arid regions where groundwater is already over-exploited, artificial recharge has potential for banking water and to combat drought (Dillon, 2005). Subsurface water banking has several advantages over surface-water storage such as minimum chance of contamination and evaporation loss, non-occupancy of space over the land and little maintenance cost. However, banking of water in the subsurface formations is a complex method, and has several important issues of concern. Starting from site evaluation and selection to determination of the suitability of the source water and its compatibility with the native groundwater, from clogging of wells/artificial-recharge structures to recovery of injected water, all are crucial for the success of a water-banking project and require due consideration and prior assessment. Water quality is an important aspect of artificial recharge of aquifers. However, unless anomaly between the native water and injected water is extremely high, hydro-chemistry generally imposes no restriction to water banking project. In fact, injection of portable water improves water quality of the concerned wells through dilution or treatment (Gale et al., 2002). From water quality point of view, artificial recharge of aquifers has several specific advantages as listed by Stuyfzand (2001) including a nearly 100% elimination of suspended fine particles, heavy metals, trace

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organic contaminants and pathogens. Due to the high quality of the desalinated water, geochemical compatibility is expected between the native aquifer-water and the injected water. Therefore, banking of desalinized water into aquifers through well injection may be prospective (Mukhopadhyay and Al-Sulaimi, 1998). Clogging is an inherent challenge for subsurface water banking through artificial recharge, and may occur even when recommended guidelines are followed (Timmer et al., 2001). In fact clogging during ASR is a rule rather than an exception (Bouwer, 2002). Issues related to clogging have been discussed in details by many researchers including Olsthoorn (1982), Pérez-Paricio and Carrera (1998) and Pérez-Paricio et al. (2001a,b). All these issues are beyond the scope of exploration and discussion in this article as the present study focuses on evaluation and selection of well sites for subsurface water-banking prior to ASR operations.

Selection of methods and proper sites is very crucial for the success of a subsurface water-banking project. However, selection of sites and techniques for water banking requires prior evaluation of hydro and geological conditions which is more complex in hard rocks, where evaluation of infiltration and recharge is difficult. Water banking through ASR operations gives emphasis on recovery of recharged water. Several indices such as recovery ratio λ (Bear and Jacobs, 1965) and Operational Recovery Efficiency (Sheng et al., 2007) have been proposed for assessment of well-efficiency in terms of percent of recovery of injected water for a recharge-pumping cycle. However, these indices can be used for post-event evaluation of site-efficiency, but are not helpful in pre-event decision-making in site selection for water banking. Site selection for artificial recharge had been attempted also on the basis of surface runoff variation (Anbazhagan et al., 2005). However in reality, low surface runoff can ensure neither higher recharge nor greater productivity. Other attempts were based on hydraulic parameters such as transmissivity and hydraulic gradients (Mukhopadhyay and Fadlelmawala, 2009) or hydro-chemical criteria such as TDS, chloride concentration, isotopes, pH (Sukhija et al., 1997; Pérez-Paricio et al., 2001a,b; Kumar et al., 2009). However, these parameters at different well-sites may be same but recharge, storage, and yield may be different. Therefore, it is most likely that these parameters will assess different recovery percentage. Since subsurface water banking aims maximum possible recovery of injected water during the lean period, the input–output ratio of water seems a more appropriate criterion.

On this consideration, an attempt has been made in the present study to develop an index and a method for site selection for water banking by taking the meteorological (potential rainfall and its probability), hydrological (recharge, drawdown, yield, and productivity), hydraulic (hydraulic conductivity, transmissivity, storativity, and specific yield) and geological (soil type and thickness, drainage density, lineament density, vadose-zone geology, aquifer formation, and thickness of weathered-zone, fracture-zone, saturated-zone) factors into account. The Normalized Difference Water Recovery Index (NDWRI) has been formulated on the basis of hydrological parameters, and is the normalized ratio of well productivity and recharge. The study has been carried out in the composite hard-rock Aravalli terrain of Rajasthan, India. The details of this index including the assumptions and formulation have been discussed in the later section. Although the methodology is proposed here aiming ASR through well injection, the index and the methodology are equally applicable for other techniques of artificial recharge of aquifers.

2. The study area

2.1. Geological setup

The Aravalli Mountain Range (AMR) located in the north-western India is one of the oldest (3500–750 Ma) mountain belts of the world. It stretches itself for a length ~700 km from the northern Gujarat to the central Rajasthan states of India covering ~40,000 km^2 area. The study area (Fig. 1) comprises of the main block of the Aravalli range along with isolated hill of Mount Abu covering ~25,000 km^2 between N23°30′–N26°18′ latitudes and E72°24′–E74°36′ longitudes.

The AMR has a complex evolutionary history and a twisted geological set-up. The Aravalli craton is delineated by the Great Boundary Fault (GBF) of the Himalayas in the north, the Cambay Graben in the southwest, and the Narmada-Son Lineament in the south and southeast. The AMR separates the Ganga River system from the Indus River system. The terrain has a horst-graben structure guided by the NE–SW trending undulations of the AMR, and bound by Eastern Marginal Fault (EMF i.e. the GBF) and Western Marginal Fault (WMF). The basement rock in the AMR is the Banded Gneissic Complex (BGC), which is overlain in succession by the rocks of the Aravalli supergroup and Delhi supergroup. The geological set-up in the Aravalli terrain is extremely complex due to several episodes of folding and faulting, including thrusting and rifting. Successive phases of deformation of the rocks have developed numerous geological lineaments, which include fold axes, joints, fractures, faults, shear zones, and mylonites. Based on lithology, the Aravalli craton can be divided into two parts – east and west of the GBF. The present study area is situated to the west of the GBF and is covered broadly, by five rock types (granite, phyllite, schist, gneiss, and quartzite) with different compositional associations and mineralogical variations.

2.2. Hydrogeology and geohydrology

Various hydrogeological factors such as soil type, soil thickness, drainage density, land-surface slope, fracture density, lithology, weathered-zone thickness, and thickness of subsurface fractured zones influence hydraulic parameters and in turn govern the groundwater regime of the Aravalli terrain in different extent (Bhuiyan et al., 2009c; Bhuiyan, 2010). Water banking in the aquifers and its successful recovery will also be influenced by these hydrogeological factors. In this composite crystalline terrain, primary porosity is insignificant and secondary porosity due to joints and fractures are the chief controller of infiltration, recharge, and productivity of aquifers. Lithological log have revealed that fractures at places terminate at shallow depths within the vadose zone, but at other locations continue at deeper levels in the saturated zone. Greater thickness of both shallow and deep fracture-zones is found in the central, northern and southern parts indicating continuation of fractures in the deeper levels of the aquifers (Fig. 2a). Many places in the western part are devoid of subsurface fractures, whereas in the eastern and central parts, fractures are present only in the saturated zone. The terrain is characterized by high surface runoff due to undulating hilly topography, and low infiltration of rainwater due to crystalline rocks with little primary porosity. Soil types and soil thickness plays crucial role particularly in the infiltration process. In major parts of the Aravalli region the top soil layer is very thin (0–1 m). In the western, central parts and in some eastern and northern parts, soil thickness varies within 3–10 m (Fig. 2b). Thin soils are found in the elevated central and northern parts and also in major eastern and south-western parts with low-relief. Although the eastern part of the region is dominated by pediments and buried pediments and the western part is associated with denudational hills, soil layers are comparatively thicker (10–35 m) in the western part. Weathering thickness influence both recharge and productivity. In two-third area of the AMR, weathered-zone thickness varies in the range of 10–20 m. Greater (21–40 m) weathering thickness is found at the central and western parts, and further higher (>40 m) at several parts all over