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Research papers

Numerical evaluation of community-scale aquifer storage, transfer and recovery technology: A case study from coastal Bangladesh

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ABSTRACT

Aquifer storage, transfer and recovery (ASTR) may be an efficient low cost water supply technology for rural coastal communities that experience seasonal freshwater scarcity. The feasibility of ASTR as a water supply alternative is being evaluated in communities in south-western Bangladesh where the shallow aquifers are naturally brackish and severe seasonal freshwater scarcity is compounded by frequent extreme weather events. A numerical variable-density groundwater model, first evaluated against data from an existing community-scale ASTR system, was applied to identify the influence of hydrogeological as well as design and operational parameters on system performance. For community-scale systems, it is a delicate balance to achieve acceptable water quality at the extraction well whilst maintaining a high recovery efficiency (RE) as dispersive mixing can dominate relative to the small size of the injected freshwater plume. For the existing ASTR system configuration used in Bangladesh where the injection head is controlled and the extraction rate is set based on the community water demand, larger aquifer hydraulic conductivity, aquifer depth and injection head improve the water quality (lower total dissolved solids concentration) in the extracted water because of higher injection rates, but the RE is reduced. To support future ASTR system design in similar coastal settings, an improved system configuration was determined and relevant non-dimensional design criteria were identified. Analyses showed that four injection wells distributed around a central single extraction well leads to high RE provided the distance between the injection wells and extraction well is less than half the theoretical radius of the injected freshwater plume. The theoretical plume radius relative to the aquifer dispersivity is also an important design consideration to ensure adequate system performance. The results presented provide valuable insights into the feasibility and design considerations for community-scale ASTR systems but installation of systems in different hydrogeological contexts (i.e. high regional hydraulic gradient and aquifer TDS concentration) may require re-evaluation of the system design.

1. Introduction

There is an increasing need to develop disaster resilient, low-cost drinking water supply options, with many areas worldwide experiencing more frequent water shortages and natural disasters, combined with rapid population growth (United Nations Development Programme, 2006). Aquifer storage and recovery (ASR), and aquifer storage, transfer and recovery (ASTR) are a subset of managed aquifer recharge (MAR) technologies where surface water is injected directly into the aquifer, creating a water store that is later extracted and used for water supply (Maliva and Missimer, 2010). ASR and ASTR have proven to be promising technologies for addressing various water quantity and quality issues including limiting saltwater intrusion in coastal aquifers, raising groundwater levels, reducing aquifer salinity, and treating wastewater and surface water for reuse (e.g., Almulla et al., 2005; Barry et al., 2010; Berens et al., 2009; Miotliński et al., 2014; Rushton and Phadtare, 1989; Sakthivadivel, N.D.; Shammas, 2008; Vandenbohede et al., 2009). Consequently their implementation continues to expand globally.

ASTR differs from ASR in that injection wells are located some distance from the extraction wells, rather than individual wells switching between injection and extraction cycles. One of the key benefits of ASTR is that due to the physical separation of the injection and extraction wells, the minimum travel distance and thus minimum residence time of the injected water in the aquifer

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is greater for ASTR compared with ASR systems (Miotliński et al., 2014). Longer travel distances and residences times in the aquifer promote removal or inactivation of pathogens in the subsurface, thereby improving the quality of the extracted water (Sidhu et al., 2010). Transport of injected water through the aquifer can also improve water quality via microbially-mediated degradation reactions, mineral dissolution, ion exchange and sorption reactions (Vanderzalm et al., 2010).

ASTR is being tested by UNICEF-Bangladesh, University of Dhaka and Acacia Water (Netherlands) as a potential cost-effective, disaster-resilient water supply alternative for coastal communities in the low-lying Khulna-Satkhira-Bagerhat region in Bangladesh (Fig. 1). These communities are experiencing increasingly severe seasonal freshwater scarcity (Hasan, 2012; Sultana et al., 2015). In the region, groundwater is naturally brackish (total dissolved solids [TDS] >4 g/L) and traditional drinking water sources such as surface ponds are frequently contaminated from overland saltwater flooding associated extreme weather events including cyclones and storm surges (Karim and Mimura, 2008). Similar conditions occur in other vulnerable low-lying coastal areas worldwide. Since 2011, field testing has been carried out at thirteen ASTR sites established in south-western Bangladesh with findings including discussion of operational issues (e.g. well clogging) provided in Sultana et al. (2015). Following the success of this testing, an additional 75 sites have recently been installed in the region with systems now providing water supply to approximately 50,000 people. At these sites, freshwater collected via rooftop rainwater harvesting and surface ponds is injected into shallow aquifers during the monsoon season and stored for extraction that occurs throughout the year (Fig. 2). The average cost of installing a system which serves a community of approximately 300 people and provides 300–1500 m^3 of extracted water per year ranges from \$5000 to \$7000 USD (Sultana et al., 2015).

A main limitation of ASR and ASTR technologies when they are used for water supply is that the injected freshwater mixes with the ambient brackish groundwater resulting in an overall loss in the available freshwater that can be recovered. Appropriate engineering design and operation, and suitable hydrogeological conditions are critical to minimizing this loss and ensuring an acceptable recovery efficiency (RE; Maliva et al., 2006). RE is defined as:

$$RE = \frac{V_{ext}}{V_{inj}} \quad (1)$$

where V_{ext} (m^3) is the annual volume of water extracted from the system at a suitable quality and V_{inj} (m^3) is the annual volume of water injected. In coastal Bangladesh, TDS concentration of the extracted water needs to be below the Bangladesh Drinking Water

Fig. 1. (a) Map of Bangladesh with Satkhira district highlighted in red (U.S. Department of State, 2013) and (b) Satkhira district map showing location of Assasuni (PATH Foundation Bangladesh, 2007). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)