Journal of Hydrology 476 (2013) 370–383

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

The effect of cutoff walls on saltwater intrusion and groundwater extraction in coastal aquifers

Vassilios K. Kaleris *, Alexandros I. Ziogas

University of Patras, Department of Civil Engineering, University Campus, 26500 Patras, Greece

ARTICLE INFO

Article history:
Received 25 August 2011
Received in revised form 28 May 2012
Accepted 2 November 2012
Available online 10 November 2012

This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Harald Kunstmann, Associate Editor

Keywords:
Saltwater intrusion
Cutoff wall
Groundwater extraction
Numerical simulation
SUTRA
Analytical approximation

SUMMARY

We use numerical simulations to study the effect of cutoff walls on saltwater intrusion and assess their protective effect on groundwater extractions near the coast. Results are presented in terms of dimensionless variables with ranges suitable for field applications. We find that, in the absence of groundwater extractions, the effectiveness of cutoff walls is determined by the wall depth, its distance from the coast, the velocity ratio, the intensity of mixing, the conductivity anisotropy and the relative conductivity of the wall. To assess the effectiveness of cutoff walls in practical applications, we present graphs and empirical equations. Also, we assess the protective effect of cutoff walls on groundwater extractions by means of drains and single wells. We do so by calculating the maximum safe extraction rate before and after the construction of a cutoff wall; i.e. the maximum rate of groundwater extraction for which the maximum salt concentration entering the drain or the well is below a certain threshold. We find that the protective effect of cutoff walls is stronger for single wells rather than drains and for cases when the extractions are located at relative small distances from the coast, relative large depths, and in aquifers with small velocity ratio, weak mixing and high anisotropy. To facilitate the design of safe extractions, we use numerical results to develop analytical approximations for the influence of cutoff walls.

1. Introduction

Deterioration of fresh groundwater due to saltwater intrusion occurs in many coastal and deltaic areas around the globe, where intense human activity takes place. Changes of the climate could intensify saltwater intrusion due to the probable rise of the sea level, the reduction of the natural recharge of groundwater and the increase of water demand. In cases where the reduction of pumping rates is restrained by the water demand, several corrective measures can be applied, such as hydraulic barriers, inland artificial recharge and/or pumping of seawater in the intrusion area (Abarca et al., 2006; Luyun et al., 2009; Pool and Carrera, 2010). Artificial recharge is usually conducted through infiltration from spreading basins at the land surface, or by means of recharge wells. However, the method is applicable only in cases when the geological structure of the aquifer is appropriate and the required water resources are available. In many cases these conditions are not satisfied and the only alternative countermeasure to saltwater intrusion is the development of subsurface barriers.

In the literature three types of barriers have been proposed: (a) the Semi-Pervious Subsurface Barrier (SPSB) extending from the top of the aquifer to the impervious aquifer bottom; (b) the subsurface dam, which has very low permeability and rests on the impervious bottom of the aquifer, blocking only the lower part of the aquifer cross-section; and (c) the cutoff wall, which has very low permeability and penetrates the aquifer to a certain depth, blocking only the upper part of the aquifer.

The protective effect of SPSBs on groundwater extractions in coastal areas has been studied by Mahesha (2009) and Sugio et al. (1987). Based on numerical simulations of aquifers with SPSBs, Mahesha (2009) identified the nearest possible locations to the seacoast for safe freshwater extraction and Sugio et al. (1987) showed that SPSBs can delay seawater intrusion under critical conditions of drought and continuous pumping. An important effect of SPSBs, however, is the rise of the groundwater level during wet years, or when pumping is reduced. In both cases the land use near the coast may be affected.

The rise of the groundwater level is milder if a sufficient space above or below the barrier is left open, as it is the case for subsurface dams and cutoff walls. This is an important advantage of partially penetrating barriers compared to SPSBs. On the other hand, the opening reduces the stemming effect of the cutoff wall on saltwater intrusion. Clearly, effective design of subsurface dams and cutoff walls should counterbalance saltwater intrusion and the rise of groundwater level.

* Corresponding author. Tel.: +30 2610996517; fax: +30 2610996572.
E-mail address: kaleris@upatras.gr (V.K. Kaleris).

0022-1694/$ - see front matter
http://dx.doi.org/10.1016/j.jhydrol.2012.11.007

Subsurface dams have been widely applied in Japan during the 1990s (Japan Green Resources Agency, 2004). According to Luyun et al. (2009), there are about 15 subsurface dams, seven of which have been specifically constructed to prevent saltwater intrusion into coastal aquifers. The construction techniques are described in Japan Green Resources Agency (2004, pp. 196–220). In the latter reference (pp. 186–195) as well as in Osuga (1997), basic design criteria are described based on general principles of groundwater hydraulics and on field experience. A more systematic, laboratory-scale, investigation of subsurface dams has been presented by Luyun et al. (2009). The authors focused on the removal of the saltwater trapped in the storage area of the aquifer upon installation of the dam. They also provided a methodology to determine the height of the dam.

An investigation of the effect of cutoff walls on saltwater dynamics has been presented by Anwar (1983). Using the sharp interface approach, Anwar (1983) developed an analytical relationship to determine the location of the interface under the influence of an impermeable cutoff wall. The values of the coefficients in the relationship were estimated from laboratory-scale experiments. The study, also presented experimental results concerning the effect of a line-sink located at the interface between saltwater and fresh groundwater. While these results provide a thorough insight into the effect of cutoff walls on saltwater intrusion, they are not directly applicable since the values of the estimated coefficients depend on experimental conditions. In a recent study, Luyun et al. (2011) presented laboratory-scale investigations on how the effectiveness of cutoff walls varies with their depth and their distance from the coast. The investigation showed that when a cutoff wall is located in an area of saltwater intrusion, its protective effect increases with decreasing distance from the coast and increasing penetration depth.

The study of Luyun et al. (2011) provides useful insight on how certain geometric parameters of the wall (such as its depth and its distance from the coast) influence its effectiveness. However, when assessing the overall effect of cutoff walls on saltwater intrusion, one should incorporate, in addition to geometric considerations, information related to the characteristics of the aquifer. The latter include the aquifer hydraulic conductivity, anisotropy, mixing intensity due to hydrodynamic dispersion, groundwater discharge to the sea and the impact of groundwater extractions upstream of the wall. In addition, the hydraulic conductivity of the material of the wall plays an important role on its overall effectiveness.

In this study we focus on cutoff walls in confined aquifers. Our objectives are to investigate (1) the effect of cutoff walls on saltwater dynamics for different parameter combinations that characterize the geometry of the cutoff wall, and the hydraulic characteristics of both the aquifer and the wall; and (2) the effectiveness of cutoff walls in protecting groundwater extractions near the coast. All investigations are performed by means of numerical simulations using the SUTRA code (Voss and Provost, 2003) and are based on a systematic sensitivity analysis, where all influential variables are varied within suitable ranges. From the investigation, graphs and approximate analytical relationships are derived that allow direct assessment of the importance of each parameter varied, as well as selection of the design variables for cutoff walls.

It should be noted that (a) preliminary comparisons between simulation results obtained for confined and unconfined aquifers did not show significant differences concerning the effect of the cutoff walls on saltwater intrusion. However, a systematic comparison of the effects of cutoff walls in confined and unconfined aquifers is beyond the aims of this study. (b) In our analysis we do not include the case of subsurface dams (i.e. partially penetrating walls founded at the bottom of the aquifer; see above). We consider them as less suitable than cutoff walls, since the required excavation depths and construction costs are much larger.

2. Investigated configuration

Fig. 1a shows the geometry of the aquifer used in this study. L_{aq} denotes the length of the aquifer, Y_{aq} its width, and H its thickness. In all cases, the length of the cutoff wall is set equal to the width of the aquifer. The seaside boundary is assumed to be vertical with flow-boundary condition described by a hydrostatic pressure distribution; see Fig. 1a. For the parts of the seaside boundary, where saltwater intrusion and groundwater outflow take place, salt mass transport is calculated using the salt concentration of the inflowing seawater and the salt concentration of the outflowing groundwater, respectively (Voss and Provost, 2003). The landside boundary of the aquifer is taken as an inflow boundary with uniform mass flux of fresh groundwater towards the sea. The lateral boundaries are assumed to be no-flow boundaries.

In the first step of our investigations, in which we assume that there is no water extraction within the modeled area, saltwater intrusion is 2-dimensional and can be investigated using the vertical cross section in Fig. 1b. The geometric variables characterizing the cutoff wall are the distance of the wall from the sea boundary L_w, the depth of the wall Z_w and its thickness d_w; see Fig. 1a and b.

In the second step of our investigations, in which we consider groundwater extraction upstream of the cutoff wall, we investigate two limiting cases:

(a) The extraction takes place over the whole width of the aquifer by means of a horizontal drain (Fig. 1a). This type of extraction approximates the flow conditions for pumping through a series of wells located parallel to the coast. The geometric variables characterizing the extraction are the distance L_{ex} of the wells from the coast, the depth Z_{ex} of the midpoint of the drain, and the width and height of the

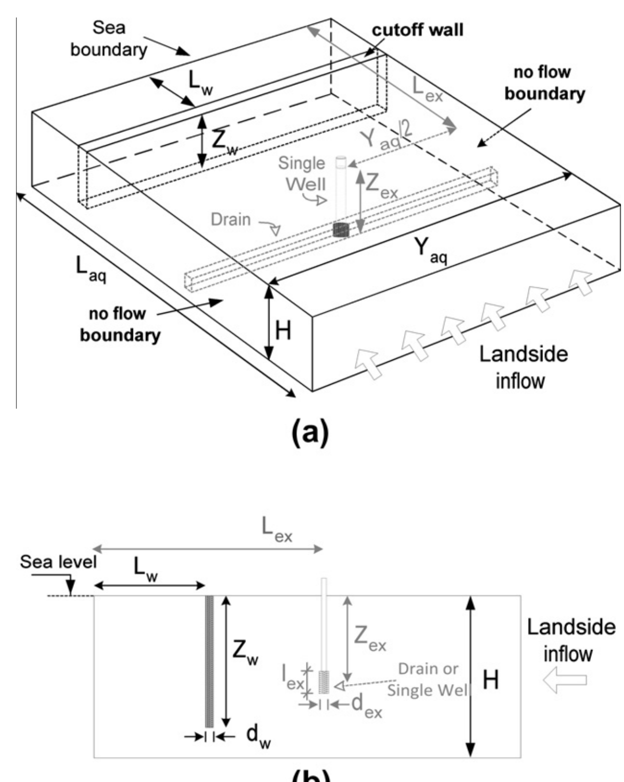

Fig. 1. Investigated configurations: (a) three dimensional aquifer with a cutoff wall and groundwater extraction by means of a drain or a single well; (b) vertical cross section at the symmetry plane of the aquifer.