Recommendations of Controlling Saltwater Intrusion in an Inland Aquifer for Drinking-Water Supply at a Certain Waterworks Site in Berlin (Germany)

Jialiang Cai · Thomas Taute · Michael Schneider

Abstract Saltwater intrusion is a widespread contamination problem of continuing great practical interest in many coastal and inland aquifers all over the world. Therefore, it is highly desirable to properly manage groundwater resources for drinking-water supply by controlling saltwater intrusion. This paper proposes to provide two recommendations of controlling saltwater intrusion in an inland aquifer for drinking-water supply at a certain waterworks site in Berlin (Germany) on the basis of the validated source of saltwater intrusion as well as pumping optimization, using a density-dependent groundwater flow and solute transport model. In terms of pumping-rate reduction, the optimal pumping rate was validated for eliminating the effect of saltwater intrusion. Without consideration of scenario conditions, its value could be set 1.39×10^{-2} m^3/s (50 m^3/h) or 5.56×10^{-3} m^3/s (20 m^3/h), if the requirement of drinking water palatability were good or excellent, respectively. With regard to pumping-pattern rearrangement, the well construction was modified to access bank filtration for eliminating the effect of saltwater intrusion.

Keywords Saltwater intrusion · Inland aquifer · Density-dependent groundwater flow · Pumping optimization · Saltwater upconing

1 Introduction

Saltwater intrusion is a widespread problem of continuing great practical interest in many coastal and inland aquifers all over the world, which is often described by coupled density-dependent groundwater flow and advection–dispersion equations because of hydrodynamic dispersion and a wide transition zone (Bear 1972; Huyakorn and Pinder 1983; Ségol 1994; Servan-Camas and Tsai 2009; Mastrocicco et al. 2012). It is considered a special category of contamination to make groundwater unsuitable for human, industry and irrigation uses, by reducing freshwater storage and in extreme cases even resulting in abandonment of drinking-water-supply wells if salinity, generally defined as concentration of total dissolved solids (TDS), exceeds acceptable drinking water standard (El Moujabber et al. 2006; Abd-Elhamid

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and Javadi 2011). Therefore, it is highly desirable to properly manage groundwater resources for drinking-water supply by controlling saltwater intrusion.

In coastal aquifers, an enormous amount of studies have been conducted to control saltwater intrusion using various methods, which can be summarized as (1) reduction of pumping rates or rearrangement of pumping pattern, (2) relocation of pumping wells, (3) use of natural or artificial recharge, (4) construction of artificial subsurface barriers, (5) abstraction of saline water, and (6) combination of various techniques (Todd and Mays 2005; Abarca et al. 2006; Abd-Elhamid and Javadi 2011). Despite the fact that these aforementioned methods all have some constraints, the first alternative of pumping optimization has been proven more effective and economic using analytical or numerical models (Finney et al. 1992; Hallaji and Yazicigil 1996; Emch and Yeh 1998; Das and Datta 1999a, b; Cheng et al. 2000; Gordon et al. 2000; Mantoglou 2003; Zhou et al. 2003; Abarca et al. 2006; Singh 2015). In brief, the key issue of pumping optimization is to maintain a balance between pumping demand and quality requirements, it is thus necessary to develop appropriate models as above mentioned for determination of water quantity which can be pumped from aquifers while protecting pumping wells from saltwater intrusion (Mantoglou 2003; Abarca et al. 2006; Singh 2014).

With regard to inland aquifers, to our knowledge, there is greatly limited discussion for controlling saltwater intrusion to date, owing to the fact that the sources of saltwater intrusion are not routinely certain in comparison with coastal aquifers that are in hydraulic connection with the sea (Freeze and Cherry 1979; Mohsen et al. 1990). Saltwater intrusion in inland aquifers may originate from various sources, including (1) seawater that entered aquifers during deposition or during a high stand of the sea in past geologic time (connate water), (2) salt in saline domes, thin beds, or disseminated in the geologic formations, (3) slightly saline water concentrated by evaporation in tidal lagoon, playas, or other enclosed areas, (4) return flows to streams from irrigated lands, and (5) anthropogenic saline wastes (Bobba 1993). Hence, it is important and essential to identify the source(s) of saltwater intrusion before implementing pumping management.

Cai et al. (2014) have pointed out that there is an increasingly significant effect of salinization in most abstraction wells with a great depth of ~ 50 m below the surface in an inland aquifer at the Beelitzhof waterworks (BEEWW) in southwestern Berlin, Germany, which provides approximately 25 % of total drinking-water supply for the city region. So it was assumed that the source of saltwater intrusion would originate from deeper saline groundwater. This assumption is supported by geological conditions in the Northern German Basin, where the upper fresh groundwater bearing Quaternary sediments is separated from deeper saline groundwater by Oligocene clay, whose local name in the area of Berlin is Tertiary Rupelian clay. Deep reaching Quaternary Elsterian glacial erosional channels lead to either more or less thinning of the Oligocene clay up to a complete removal. Noting that a very thin film of saline groundwater (centimeter scale) has been observed in sediments on the top of the Rupelian clay, therefore, it was assumed that Elsterian glacial channels would be in the close vicinity of the site, which results in saltwater upconing owing to pressure release by pumping a large amount of groundwater in drinking-water-production wells. Cai et al. (2014) have tested for two hypotheses about geological conditions leading to pathways for upwelling deep saline groundwater due to pumping, which validated that the hydraulic windows could occur in the clay caused by glacial erosion at the site and their locations under some conditions could significantly cause saltwater intrusion in the pumping well.

The principal aim of this research, consequently, was to provide recommendations of controlling saltwater intrusion in an inland aquifer for drinking-water supply at BEEWW on the basis of the validated source of saltwater intrusion as well as pumping optimization, using a density-dependent groundwater flow and solute transport model. The specific objectives were

to (1) reduce the pumping rate until getting the optimal value and (2) rearrange the pumping pattern by modifying the well construction for eliminating the effect of saltwater intrusion.

2 Methods

2.1 Conceptual Model

According to stratigraphic investigations at BEEWW, the geological profile shows that an aquitard (Holstein) divides the entire fresh groundwater aquifer into an upper aquifer and a lower aquifer (Fig. 1). A well with a depth of 50 m below the surface screened in the lower aquifer would be hydraulically decoupled from the upper aquifer and Lake Wannsee, i.e., no bank filtration from the lake to the well would occur (Cai et al. 2014). Therefore, the conceptual model was accordingly developed in the lower aquifer as a confined unit (Fig. 1).

Cai et al. (2014) have demonstrated there were three scenarios of the deep saline-groundwater pathway for interpreting the validated hypothesis. Scenario 1: the windows A and B were located on the left- and right-hand sides of the well respectively, without consideration of H_A or H_B conditions (Fig. 2a); Scenario 2: the window A was only located
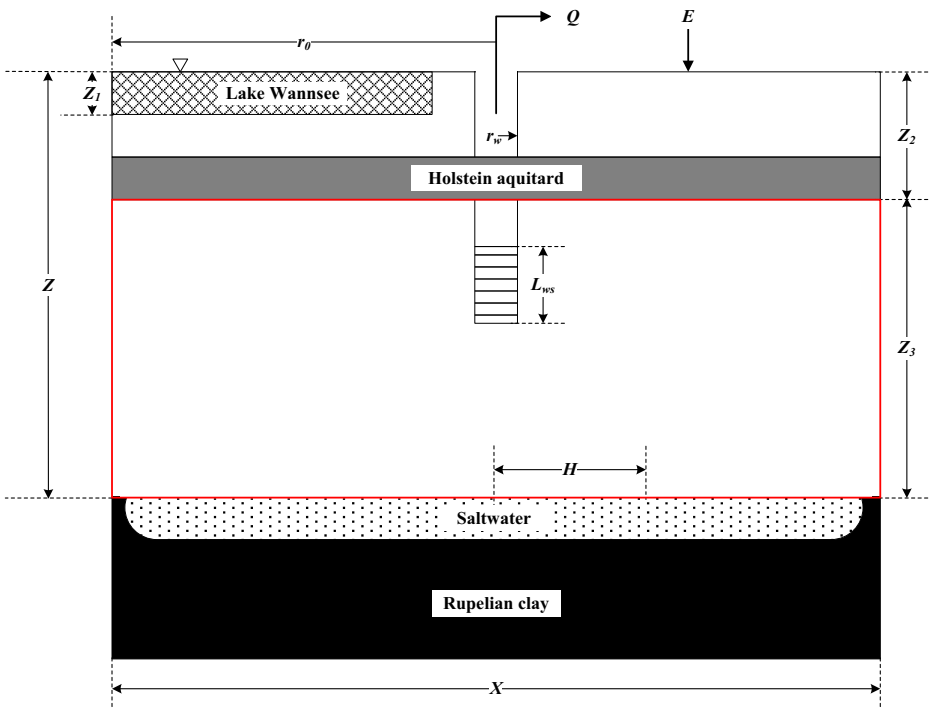

Fig. 1 Schematic vertical cross-section of field situation and conceptual model (*red rectangular area*) (not to scale). Z—thickness of the entire fresh groundwater aquifer, 170 m; Z_1—depth of Lake Wannsee, 9 m; Z_2—thickness of the upper fresh groundwater aquifer, 30 m; r_w—well radius, 0.45 m; L_{ws}—length of well screen, 30 m; r_0—radial distance from well center to constant head boundary condition, 1000 m; E—recharge rate, 3.17×10^{-9} m/s; X—model width, 2000 m; Z_3—thickness of the lower fresh groundwater aquifer (model height), 140 m; H—lateral distance from the well to windows in the Rupelian clay, 0~1000 m; Q—pumping rate, $2.78 \times 10^{-3} \sim 2.78 \times 10^{-2}$ m^3/s

Fig. 2 Schematic horizontal cross-section of three scenarios of the deep saline-groundwater pathway in the X-Y plane (not to scale). **a** Scenario 1: the windows A and B were located on the left- and right-hand sides of the well respectively, without consideration of H_A or H_B conditions; **b** Scenario 2: the window A was only located on one side of the well on condition that $H_B=0$; **c** Scenario 3: the window A was only located on one side of the well on condition that $H_B \rightarrow +\infty$. C_0 and C_1 represent the total dissolved solids (TDS) concentration of fresh groundwater and saline groundwater respectively
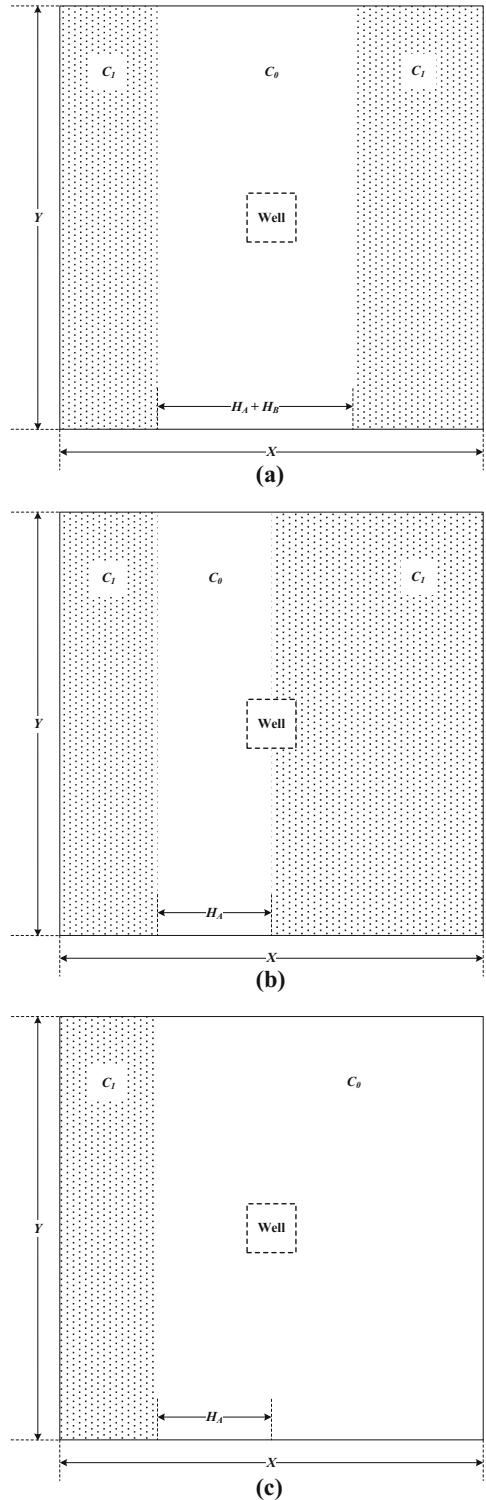
on one side of the well on condition that $H_B=0$ (Fig. 2b); and Scenario 3: the window A was only located on one side of the well on condition that $H_B \rightarrow +\infty$ (Fig. 2c).

Considering recharge rate (E) (Fig. 1), its areal effects on the critical rise were small enough (E/K_v (vertical hydraulic conductivity)$=7.29 \times 10^{-5}$) to be excluded from the analysis (Garabedian, 2013).

2.2 Numerical Model Development

Numerical modeling was performed using SEAWAT-2000 (Langevin et al. 2007). SEAWAT-2000 is a coupling of the MODFLOW groundwater flow code, modified to solve variable-density flow conditions using equivalent freshwater head, with the MT3DMS transport model (Garabedian 2013). The coupling between fluid density and solute concentration is incorporated in the code as a linear relationship. The developed numerical model by Cai et al. (2014) was used in this study, with specified modifications.

2.2.1 Model Discretization

The model in a two-dimensional X-Z environment was spatially discretized to form a nonuniform mesh. The columns (Δx) were variably spaced with 0.45-m horizontal resolution at the well according to the well radius (r_w) of 0.45 m at the site symmetrically expanding to 20-m horizontal resolution at the lateral boundaries (Fig. 1). The layers (Δz) were spaced into two parts: (1) each layer was set to 10 m thick above the well screen (5 layers total); (2) each layer was set to 2 m thick below the well screen (45 layers total) (Fig. 1). In order to minimize numerical dispersion and oscillation, the common criterion mesh Peclet number (Pe) was set to be ≤ 2 with all different Δx values (Zheng and Bennett 2002).

All simulations were performed as transient flow until steady-state conditions were reached, using the TVD advection solver, which is mass conservative, without excessive numerical dispersion and artificial oscillation (Zheng and Bennett 2002). Trial-and-error analysis demonstrated that it took 600 years to reach steady-state conditions with the current model setup, where time steps (Δt) were set to 1 year. Using this small Δt values can ensure that Courant number (Cr) correspondingly remained ≤ 1 with all different Δx values for minimization of numerical dispersion and oscillation (Zheng and Bennett 2002).

2.2.2 Boundary and Initial Conditions

The top of the model was set to no-flow boundaries according to the Holstein aquitard (Fig. 1). The left- and right-hand sides of the model were chosen to be far enough ($r_w/r_0=4.5 \times 10^{-4}$) (Fig. 1) not to be influenced by the pumping activities (Jakovovic et al. 2011; Garabedian 2013) and implemented as 1st order boundary conditions with a constant head ($h_0=30$ m) and concentration ($C_0=0.2$ kg/m^3) respectively. According to the observed thin film of saline groundwater in sediments on the top of the impermeable Rupelian clay, 2nd order boundary conditions were chosen at the bottom of the model.

The simulated concentration was obtained at the bottom of the well screen. The concentration of saline groundwater (C_1) was incorporated as total dissolved solid (TDS) and its value was set to 5.5 kg/m^3 (Cai et al. 2014). The values of the pumping rate (Q) were varying in a range from 2.78×10^{-3} (10) to 2.78×10^{-2} m^3/s (100 m^3/h).

2.2.3 Model Parameters

The model was considered to be homogeneous according to our previous study (Cai et al. 2015), with uniform parameters. The site-specified values of h_0, hydraulic gradient (i), horizontal hydraulic conductivity (K_h), specific storage (S_s) and effective porosity (n_e) were measured (Table 1). The longitudinal (α_L) and transverse dispersivity (α_T) values were estimated to 10 and 1 m respectively (Cai et al. 2014). The hydraulic anisotropy (a) defined as K_h/K_v was determined to 2.3 by an integrated laboratory method called modified constant-head permeameter test (MCHPT) (Cai et al. 2015).

3 Results and Discussion

3.1 Reduction of Pumping Rate

3.1.1 Scenario 1

When $Q = 2.78 \times 10^{-2}$ m^3/s (100 m^3/h), the salinity in the well was estimated to be 1 kg/m^3 when $H_A + H_B = 1100$ m (Fig. 3a), i.e., the well water was classified as brackish water on condition that $0 < H_A + H_B \leq 1100$ m, noting the criteria listed in Cai et al. (2014). Owing to the fact that our recommendations aimed to control saltwater intrusion for drinking-water supply at BEEWW, it was thus essential to consider the impact of TDS concentration on drinking water palatability (DWP) as well. According to the criteria listed in Cai et al. (2014), DWP was

Table 1 Numerical model parameters

Parameter	Symbol	Value	Unit
Flow parameter			
Model width	X	2000	m
Model height	Z_3	140	m
Initial hydraulic head	h_0	30	m
Hydraulic gradient	i	0	–
Horizontal hydraulic conductivity	K_h	1×10^{-4}	m/s
Hydraulic anisotropy	a	2.3	–
Effective porosity	n_e	0.3	–
Well radius	r_w	0.45	m
Length of well screen	L_{ws}	30	m
Pumping rate	Q	2.78×10^{-3}, 1.11×10^{-2}, 1.94×10^{-2}, 2.78×10^{-2}	m^3/s
Transport parameter			
Specific storage	S_s	5×10^{-4}	1/m
Longitudinal dispersivity	α_L	10	m
Transverse dispersivity	α_T	1	m
Effective diffusion coefficient in porous media	D^*	1×10^{-10}	m^2/s
Total dissolved solids (TDS) concentration of fresh groundwater	C_0	0.2	kg/m^3
TDS concentration of saline groundwater	C_1	5.5	kg/m^3
Lateral distance from the well to windows in the Rupelian clay	H	0~1000	m

Fig. 3 Simulations of total dissolved solids (TDS) concentration at steady-state condition in the well with varying pumping rate (Q) by Scenario 1 (**a**), Scenario 2 (**b**), and Scenario 3 (**c**), respectively. The *dashed line* represents the concentration threshold between freshwater and brackish water

(a)

(b)

(c)
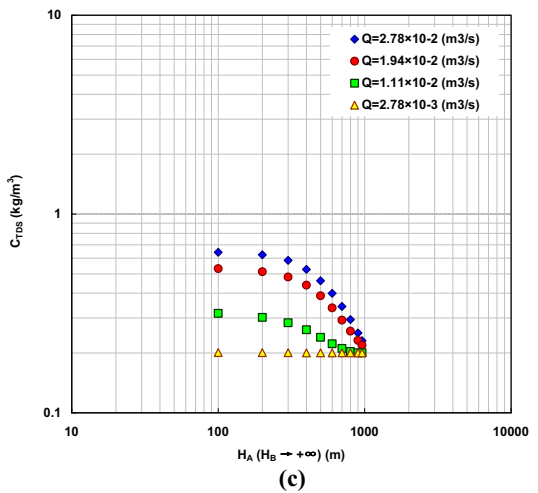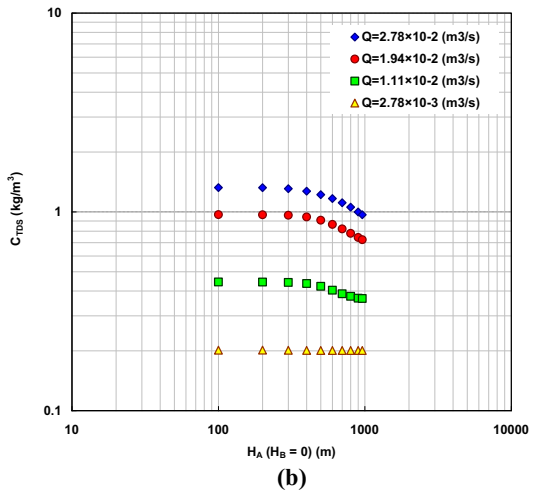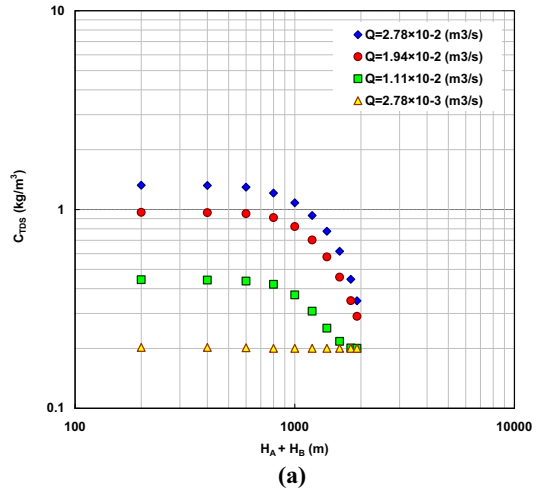
classified as unacceptable on condition that $0<H_A+H_B\leq800$ m, as poor on condition that 800 m$<H_A+H_B\leq1230$ m, as fair on condition that 1230 m$<H_A+H_B\leq1610$ m, and as good on condition that 1610 m$<H_A+H_B\leq1920$ m, respectively. Therefore, when $0<H_A+H_B\leq$ 1100 m, the effect of saltwater intrusion was significant, as the well water was brackish water and DWP was unacceptable to poor; when 1100 m$<H_A+H_B\leq$ 1230 m, the effect was modest, as the well water was freshwater but DWP was poor; when 1230 m$<H_A+H_B\leq1920$ m, there was no or slight effect, as the well water was freshwater and DWP was fair to good.

When $Q=1.94\times10^{-2}$ m^3/s (70 m^3/h), the well water of all simulations was classified as freshwater (Fig. 3a). DWP was classified as poor on condition that $0<H_A+H_B\leq820$ m, as fair on condition that $820<H_A+H_B\leq1360$ m, as good on condition that 1360 m$<H_A+H_B\leq1900$ m, and as excellent on condition that 1900 m$<H_A+H_B\leq1920$ m, respectively. Thus, when 0 m$<$ $H_A+H_B\leq820$ m, the effect of saltwater intrusion was modest; when 820 m$<H_A+H_B\leq1920$ m, there was no or slight effect.

When $Q=1.11\times10^{-2}$ m^3/s (40 m^3/h), the well water of all simulations was classified as freshwater (Fig. 3a). DWP was classified as good on condition that $0<H_A+H_B\leq1220$ m, and as excellent on condition that 1220 m$<H_A+H_B\leq1920$ m, respectively. Therefore, there was no effect of saltwater intrusion.

When $Q=2.78\times10^{-3}$ m^3/s (10 m^3/h), the salinity of all simulations was almost as identical as C_0, so no saltwater upconing occurred (Fig. 3a).

Consequently, according to the correlation of the salinity in the well to Q on condition that $H_A+H_B=200$ m (Fig. 4), it could be estimated in all simulations that there was no effect of saltwater intrusion and DWP was good when $Q=1.39\times10^{-2}$ m^3/s (50 m^3/h) as well as DWP was excellent when $Q=5.56\times10^{-3}$ m^3/s (20 m^3/h).
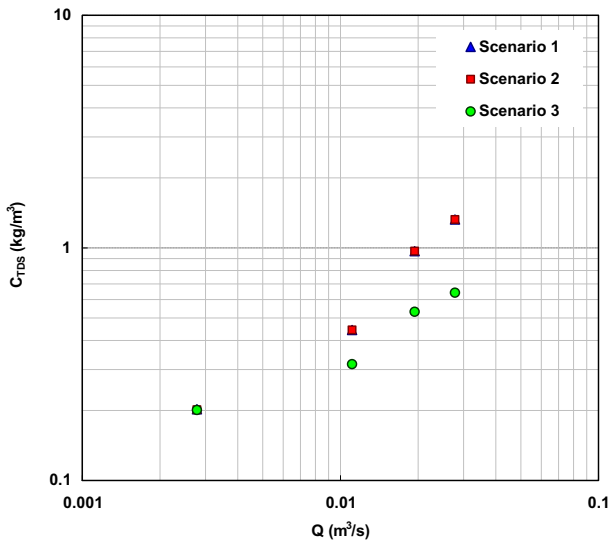

Fig. 4 Correlation of total dissolved solids (TDS) concentration at steady-state condition in the well to pumping rate (Q) in Scenario 1 on condition that $H_A+H_B=200$ m, Scenario 2 on condition that $H_A=100$ m, and Scenario 3 on condition that $H_A=100$ m, respectively. The *dashed line* represents the concentration threshold between freshwater and brackish water

3.1.2 Scenario 2

When $Q=2.78 \times 10^{-2}$ m^3/s (100 m^3/h), the salinity in the well was estimated to be 1 kg/m^3 when $H_A=865$ m (Fig. 3b), i.e., the well water was classified as brackish water on condition that $0<H_A \leq 865$ m. DWP was classified as unacceptable on condition that $0<H_A \leq 530$ m, and as poor on condition that 530 m$<H_A \leq 960$ m, respectively. Thus, when $0<H_A \leq 865$ m, the effect of saltwater intrusion was significant; when 865 m$<H_A \leq 960$ m, the effect was modest.

When $Q=1.94 \times 10^{-2}$ m^3/s (70 m^3/h), the well water of all simulations was classified as freshwater (Fig. 3b). DWP was classified as poor on condition that $0<H_A \leq 520$ m, as fair on condition that 520 m$<H_A \leq 960$ m, respectively. Therefore, when 0 m$<H_A \leq 520$ m, the effect of saltwater intrusion was modest; when 520 m$<H_A \leq 960$ m, the effect was slight.

When $Q=1.11 \times 10^{-2}$ m^3/s (40 m^3/h), the well water of all simulations was classified as freshwater (Fig. 3b). DWP of all simulations was classified as good. Thus, there was no effect of saltwater intrusion.

When $Q=2.78 \times 10^{-3}$ m^3/s (10 m^3/h), the salinity of all simulations was almost as identical as C_0, so no saltwater upconing occurred (Fig. 3b).

Consequently, according to the correlation of the salinity in the well to Q on condition that $H_A=100$ m (Fig. 4), it could be estimated in all simulations that there was no effect of saltwater intrusion and DWP was good when $Q=1.39 \times 10^{-2}$ m^3/s (50 m^3/h) as well as DWP was excellent when $Q=5.56 \times 10^{-3}$ m^3/s (20 m^3/h), the same as Scenario 1.

3.1.3 Scenario 3

When $Q=2.78 \times 10^{-2}$ m^3/s (100 m^3/h), the well water of all simulations was classified as freshwater (Fig. 3c). DWP was classified as fair on condition that $0<H_A \leq 265$ m, as good on condition that 265 m$<H_A \leq 790$ m, and as excellent on condition that 790 m$<H_A \leq 960$ m, respectively. Therefore, there was no or slight effect of saltwater intrusion.

When $Q=1.94 \times 10^{-2}$ m^3/s (70 m^3/h), the well water of all simulations was classified as freshwater (Fig. 3c). DWP was classified as good on condition that $0<H_A \leq 685$ m, as excellent on condition that 685 m$<H_A \leq 960$ m, respectively. Thus, there was no effect of saltwater intrusion.

When $Q=1.11 \times 10^{-2}$ m^3/s (40 m^3/h), the well water of all simulations was classified as freshwater (Fig. 3c). DWP was classified as good on condition that $0<H_A \leq 210$ m, as excellent on condition that 210 m$<H_A \leq 960$ m, respectively. Therefore, there was no effect of saltwater intrusion.

When $Q=2.78 \times 10^{-3}$ m^3/s (10 m^3/h), the salinity of all simulations was as identical as C_0, so no saltwater upconing occurred (Fig. 3c).

Consequently, according to the correlation of the salinity in the well to Q on condition that $H_A=100$ m (Fig. 4), it could be estimated in all simulations that there was no effect of saltwater intrusion and DWP was good when $Q=2.50 \times 10^{-2}$ m^3/s (90 m^3/h) as well as DWP was excellent when $Q=8.34 \times 10^{-3}$ m^3/s (30 m^3/h).

Overall, the optimal Q (Q_{opt}) was validated for eliminating the effect of saltwater intrusion at BEEWW. Without consideration of scenario conditions, its value could be set 1.39×10^{-2} m^3/s (50 m^3/h) or 5.56×10^{-3} m^3/s (20 m^3/h), if the requirement of DWP were good or excellent, respectively.
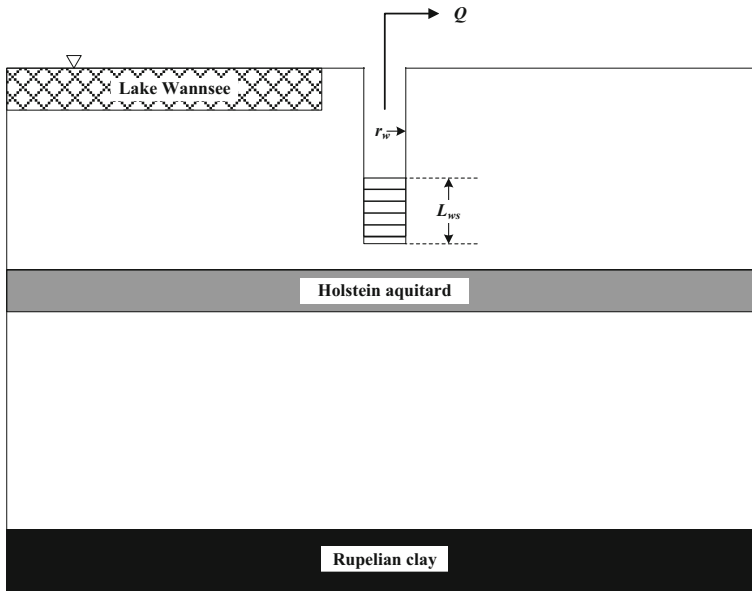
Fig. 5 Schematic vertical cross-section of well-construction modification (not to scale). L_{ws}—length of well screen; r_w—well radius; Q—pumping rate

3.2 Modification of Well Construction

As noted, the key issue of pumping optimization is to maintain a balance between pumping demand and drinking-water quality requirements. However, the aforementioned Q_{opt} with a value of 5.56×10^{-3} m³/s (20 m³/h) would be apparently a low pumping rate, if the requirement of DWP were excellent, which would hardly meet the demand of drinking-water supply for cities like Berlin. Thus, it was necessary to rearrange the pumping pattern by modifying the well construction for controlling saltwater intrusion, while maintaining the present pumping rate, e.g., $Q = 2.78 \times 10^{-2}$ m³/s (100 m³/h).

The Friedrichshagen waterworks (FRIWW) is located in southeastern Berlin, which shares the same geological conditions as BEEWW. However, no effect of saltwater intrusion has been observed in pumping wells with a depth of 50 m below the surface at FRIWW, owing to the fact that there is no aquitard dividing the fresh groundwater aquifer. Therefore, the bank filtration from Lake Müggelsee to pumping wells occurs to play an important role for controlling saltwater intrusion. Hass (2012) showed that there is approximately 70 % bank filtration for total drinking-water supply at FRIWW. Hence, the well screen could be built in the upper aquifer to access bank filtration from Lake Wannsee for eliminating the effect of saltwater intrusion at BEEWW (Fig. 5). Based on the situation at FRIWW, there was no need to conduct further numerical modeling to validate the effect of the well-construction modification.

4 Conclusions

In this research, it is the first time to conduct a theoretical study to provide recommendations of controlling saltwater intrusion in an inland aquifer for drinking-

water supply at a certain waterworks site on the basis of the validated source of saltwater intrusion as well as pumping optimization, using a density-dependent groundwater flow and solute transport model. The key findings could not only enlighten to conduct further modeling studies of real-field situation sharing the same or similar geological conditions, but also provide fundamental knowledge of modeling the pumping interaction between the wells for controlling saltwater intrusion, with two pumping wells, multiple pumping wells, till an entire well gallery.

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