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Mitigation of saltwater intrusion by 'integrated fresh-keeper' wells combined with high recovery reverse osmosis

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Abstract

Most countermeasures to mitigate saltwater intrusion in coastal, karstic or fractured aquifers are hindered by anisotropy, high transmissivities and complex dynamics. A coupled strategy is introduced here as a localized remedy to protect shallow freshwater reserves while utilizing the deeper intercepted brackish water. It is a double sourcing application where fresh-keeper wells are installed at the bottom of a deepened borehole of selected salinized wells, and then supported by high recovery RO desalination. The RO design has < 1 kWh/m^3 energy consumption, and up to 96% recovery in addition to low scaling propensity without use of any anti-scalant. A feasibility study is presented as an example for a salinizing, brackish well (TDS ~1600 mg/L) in the Damour coastal aquifer in Lebanon. The concept is expected to produce ca. 1000 m^3/d of freshwater from this well by pumping 250 m^3/d of fresh groundwater from the top well screen and 800 m^3/d of brackish groundwater (to be later desalinized) from the fresh-keeper well screen below. Cost analysis shows that the capital cost could be returned back in 1 to 4 years depending on the choice of produced water (bottled or tap) and available market. As an alternative, water from the RO plant could be blended with lower quality water, for instance untreated brackish groundwater (if unpolluted), to supply 3 more volumes for domestic use. The usage of brackish groundwater from integrated fresh-keeper wells thus serves 3 purposes: production of high quality drinking water, financial gain and mitigation of water stress by overpumping.

Keywords: High recovery RO. Groundwater deterioration. Non-conventional water resources. Urban water system. Lebanon

1. Introduction

Planning of coastal aquifers requires special attention due to proximity and direct interaction with seawater. Wells close to the shoreline often encounter a rapid increase in salinity deteriorating water quality and making it of less suitability. Many sources of saltwater exist (Stuyfzand and Stuurman 2008; Bobba 2007), such as: (1) direct seawater encroachment, (2) connate seawater from the past geologic time, (3) saltwater concentrated in enclosed areas like tidal lagoons and playas, (4) return flow from irrigation, (5) halite dissolution, and (6) anthropogenic salty wastes. The first source is the most dominant and imminent, due to steeply increasing water demands and ineffective management strategies (Datta et al. 2009). The situation worsens where alternative water resources are scarce or absent, leading to rapid exhaustion of groundwater reserves.

In many instances groundwater extraction cannot be reduced, which necessitates strategies to simultaneously prevent saltwater intrusion and provide other resources. These have been considered as major challenges to coastal hydrologists. Replenishment of already deteriorated water is expensive and sometimes ineffective, and prevention is hampered by the need to provide enough substitutes of chemically suitable water. Therefore, this issue has attracted much attention over the last decades, and several countermeasures have been proposed: (1) reducing pumping (Sherif et al. 2012), (2) changing extraction arrays (Cai et al. 2015), (3) enhanced natural and/or artificial recharge (Sophiya and Syed 2013), (4) direct reuse of treated wastewater or via artificial recharge (Ouelhazi et al. 2014), (5) water transfer from other regions, (6) building subsurface physical barriers (Sugio et al. 1987), (7) installing hydraulic barriers with/without injection wells (Hendizadeh et al. 2016) which are sometimes supported by desalination plants (Payal 2014; Javadi et al. 2015), (8) integrated fresh-keeper (IFK) wells (Grakist et al. 2002; Kooiman et al. 2004; Stuyfzand and Raat 2010; Zuurbier et al. 2016), or (9) stand-alone BWRO or seawater reverse osmosis (SWRO) plants; the former with better feedwater quality has several advantages over SWRO leading to lower operational costs and less environmental problems (Stein et al. 2016). Nevertheless, most of these actions are hampered by specific limitations reducing their wide applicability. So none has revealed overall applicability, and each has demonstrated some pros and cons (Table 1).

This paper formulates a coupled strategy of 'Integrated Fresh-Keeper' (IFK) wells, and a high recovery (HR) brackish water reverse osmosis (BWRO) system. An IFK well is installed at some vertical distance below the fresh water pumping well to be secured, within the same borehole. It creates a vertical hydraulic barrier that intercepts upconing brackish water below the upper well screen before it reaches the overlying fresh water body. This concept was first introduced by KWR Watercycle Research Institute (The Netherlands) as a remedy to salinizing well fields (Grakist et al. 2002; Kooiman et al. 2004; Stuyfzand and Raat 2010). Abandoned or intentionally drilled saline wells could be exploited to provide new volumes of freshwater; this is achieved by (a) protecting freshwater at shallower depths (i.e. keeping it fresh) where additional amounts may be safely extracted, and (b) desalting pumped saltwater. Collected water is then distributed as high quality potable water or lower quality for domestic use. This in lieu delivery of groundwater can also aid efforts to reduce pumping rates at heavily exploited spots which subsequently reduces saltwater encroachment. Nevertheless, waste disposal has created an environmental problem against wider adoption of the desalting process, which encouraged efforts towards higher recoveries. The HR-BWRO design introduced here follows a modified Type A Zero Liquid Discharge (ZLD) scheme (Pérez-González et al. 2012) characterized by a very low percentage of reject, sometimes reaching 4% during normal operation. It is also characterized by reduced energy consumption and low propensity of membrane fouling by precipitates making it superior to other widespread commercial designs.

The proposed strategy is tested here as an example to utilize brackish water extracted from a salinizing well at the Damour coastal aquifer (Lebanon). This aquifer is one of the major water resources of Beirut city (the Lebanese capital) and its suburbs, and has been facing saltwater intrusion since the 1960s. Masciopinto (2013) proposed the use of well barriers via artificial recharge along the Damour coastline to reduce seawater intrusion. The IFK approach is another management option with a more localized remedy. It is presumably more convenient than creating larger scale hydraulic barriers, especially in settings where a precise understanding of system dynamics is not possible, as in karstic or fractured aquifers.

Table 1
Main saltwater intrusion countermeasures with their pros and cons.

Mitigation	Description	Pros	Cons
Well field reorganization	Redesign well field by optimizing their withdrawal rates and/or distributing them landward	- Reduction of withdrawal is easy and direct without expenses - Decreases the chance of upconing at local scale	- Temporary solution - Not reliable when demand exceeds supply - Relocation of wells is costly
Aquifer recharge (AR)	Water artificially infiltrated into the underground, stored and then extracted	- Increases available storage and reduces seawater intrusion - Polluted water may suit as a recharge source	- Problematic in karst aquifers - If using basins, large areas may be needed, i.e. not always economically feasible - Clogging
Subsurface barriers (SB)	Artificial dams built underground	- Prevent seawater intrusion physically	- Feasibility limited to few meters in unconsolidated thin layers
Positive hydraulic barriers (PHB)	Artificial recharge wells	- Raise water level and push saltwater backwards	- Lack of chemically suitable recharge water
Negative hydraulic barriers (NHB)	Single or multi-pumping wells to intercept saltwater	- Protect freshwater wells from salinization - Good choice when raising water level is not possible - May be coupled with desalination plants	- Sensitive to pumping rates - Needs accurate understanding of aquifer dynamics - Requires a network of wells to form a complete barrier - May salinize freshwater reserves if not implemented properly
Desalination	Desalting of brackish or salt groundwater	- Provides alternative water resource - Reduces the stress on groundwater	- Problem of reject disposal - Operation and maintenance costs - Extraction of brackish groundwater may accelerate salt water intrusion
Integrated fresh-keeper wells (IFK)	Create a stable fresh-brackish interface by vertical interception of upconing brackish water within individual wells	- More feasible than negative hydraulic barriers - Suitable in complex dynamic settings - Local remedy and can be individually implemented - May be coupled with desalination plants	- Not applicable if aquifer is fully salinized to the water table - heterogeneous macroporosity (typical in karstified rock, and faulted rock)

2. Methods

2.1. Selection of proper vertical barrier

The decision on the proper depths and simultaneous fresh/brackish pumping rates at an individual site is a critical step in planning for IFK wells. Local scale numerical modeling is needed to define the proper layout of wells and warrant a stable saltwater interface with suitable feed volume and quality. For this purpose, two alternatives exist: (a) 3-D models with fine discretization around wells of interest (Anderson and Woessner 1992), or (b) axisymmetric (radial) profile models (Langevin 2008). The finite-difference code SEAWAT (Guo and Langevin 2002) could do the job; however, 3-D formulations require lengthy runtimes and computational costs. Hence, faster radial axisymmetric 2-D simulation is desirable provided that some input parameters are adjusted and the proper weighting scheme is chosen (Langevin 2008; Louwyck et al. 2012). Parameter scaling seems to be sometimes awkward, but it is a worth effort because the axially symmetric models require significantly less execution times and are capable of producing reliable solutions to complex problems involving reactive or nonreactive transport (Wallis et al. 2013).

2.2. Design of high recovery RO system

After deciding on location and flux of the IFK wells or the vertical negative barrier, the RO system specifications and the fate of membrane concentrate should be considered. RO recovery usually varies between 35% and 85% depending on feedwater, scaling propensity and reject quality (Greenlee 2009). This paper aims at introducing a high recovery BWRO system at up to 96% recovery during normal operation. The proposed design is illustrated in Fig. 1 and Table 2; it is a HR-RO tandem following modified Type A Zero Liquid Discharge (ZLD) scheme (Pérez-González et al. 2012), where main foulants and scalants are reduced in a pre-treatment multi-stage facilitating more efficient desalination with higher recovery (Henthorne and Boysen 2015). Such tandem designs have been recently introduced by several authors as promising options aiming at high recoveries and reduced effluents (e.g. Ning and Troyer 2009; Rahardianto et al. 2010), in addition to their successful application at different sites, for instance, El Paso (Texas), Kifan (Kuwait), Ehime (Japan), Mas Palomas (Spain) and Laayoune (Morocco).

Feedwater initially enters a pre-treatment phase where: (a) chlorine injection at the beginning keeps microorganisms down, (b) multimedia filter with dual parallel units minimizes instantaneous water flow and drain requirements, and removes particles >25μm (further elimination is usually not needed in BWRO due to low turbidity in groundwater), (c) filtered water is then supplied to downstream dual series softeners (primary and polisher) to strongly reduce the hardness of feedwater after which (d) non-back washable carbon filter (CF) removes impurities, chlorine (introduced in the beginning because it should not go through the ROs) and some contaminants notably humic acids to avoid potential organic foulants, then (e) water enters a 5 micron filter to catch any particles that fall off the carbon filter before (f) it is exposed to 254 nm UV light (germicidal light) to disinfect any possible microbial growth (carbon beds may be a breeding ground for bacteria, and uncontrollable microbial growth would ultimately affect the RO membranes by forming thin biofilms). The water subsequently goes through a heat exchanger to regulate its temperature at the RO inlet (best is 19-20ºC).

Pre-treated water then enters a primary RO of several units. The system re-circulates part of the membrane reject through the same configuration, which improves recovery without significant increase in energy consumption. The reject is then sent to a secondary RO system to provide higher recoveries. Two booster pumps (centrifugal pumps) are needed to allow for acceptable flow rates through the CF and RO. High recovery reject goes to drain during operations, and when there is no demand on the system (i.e. no request to make water) the reject follows a recirculation operational mode. It goes back to the break tank to repeat the loop via carbon filter, 5 micron, 254 nm UV, primary and secondary RO (Fig. 1). This mode achieves nearly 100% recovery; it is advantageous to avoid halting the system during no demand because stagnant water creates unwanted effects such as micro-contamination and clogging. Another purpose of the heat exchanger and the recirculation loop is Hot Water Sanitization (HWS). From a maintenance perspective, HWS is an essential step done once or twice a month in order to kill any microbial growth in the entire system (including the CF and the ROs). It is a temporary mode (30-60 minutes) where production of water is stopped, a small volume is alternatively heated to 80-85ºC, and then allowed to go through the circulation loop back to the break tank and consequently via the RO membranes (Fig. 1).

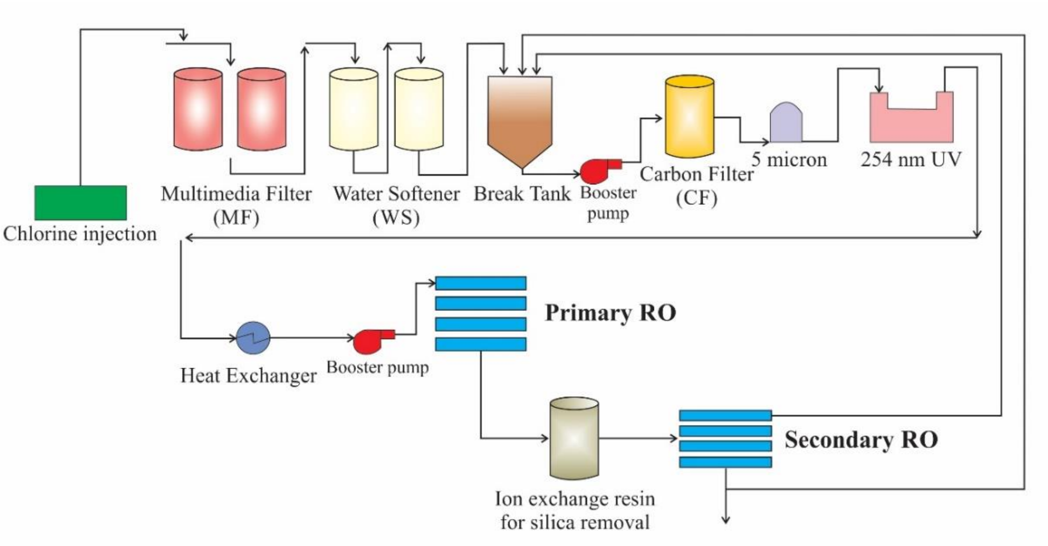

Fig. 1. Process flow diagram of the proposed treatment system design. The intermediate treatment stage (silica removal ion exchange resin) is optional depending on SiO_2 concentration.

Table 2
RO tandem design and implementation (example for 400 m^3/d).

Multimedia filter
Back-wash and rinse based upon ΔP
Dual / Parallel units to minimize instantaneous water flow and drain requirement
Always filtered water supplied to downstream softeners
Water softener
Dual Series Softeners (Primary / Polisher)
Regenerate based on total hardness
Final (fast) rinse controlled by conductivity (compare inlet to outlet)
Optimized chemical cost
Reduced service water
Reduced waste stream
High water quality
Carbon filter
Non – back-washable carbon
Replace carbon every 6 months to 1 year (manual valves provided to facilitate change out)
Continuous circulation over bed
Sanitized twice a month (No need for carbon regeneration in case of CF annual replacement)
5 micron
Cartridge filter
Natural or synthetic yards
Disposable and replaced when clogged
254 nm UV
UV lamp is replaced every 1 year
Primary RO configuration
Membrane Material: Polyamide Composite
Membrane Configuration: Full Fit / Loose –wrap
Membrane Size: 8’’ diameter x 40’’ Length
Membrane Manufacturer: FILMTEC™
Design Membrane Flux: 34 m^3/d
Secondary RO configuration
Membrane Material: Polyamide Composite
Membrane Configuration: Full Fit/ Loose –wrap
Membrane Size: 4’’ diameter x 40’’ Length
Membrane Manufacturer: FILMTEC™
Design Membrane Flux: 9.5 m^3/d

The system could be improved further by adding membrane pre-treatment to replace conventional pre-treatment. This may further improve feedwater quality and avoid fluctuations in notably turbidity and TDS. Economically, this option is more expensive; however, costs are counteracted by the expected reduced costs of the RO system and life extension when operating under better quality feedwater. In case of potential SiO_2 precipitation, an intermediate treatment stage (Fig. 1) with ion exchange resins for silica removal could be installed between the primary and secondary ROs.

Designing the RO system with proper configuration of membranes could rely on different commercial softwares. Reverse Osmosis System Analysis (ROSA) from Dow Water and Process Solutions (www.dowwaterandprocess.com) is one famous alternative using DOW FILMTEC™

elements. ROSA is capable of defining system configuration and chemistry of permeate/concentrate once feedwater composition is selected, and its results have been proven to be of high reliability and in agreement with experimental tests at different sites (e.g. Moudjeber et al. 2014).

3. Application to the Damour aquifer - Lebanon

The Damour aquifer is a major coastal aquifer in Lebanon lying south of the capital Beirut (Fig. S1, *Supplementary Material*). It is a main source of water providing one third of Beirut and its suburbs demands, and has been extensively pumped since 1991 with a total abstraction rate of about 13.5 Mm^3/year. A description of the hydrogeological setting of this area is available from Khadra and Stuyfzand (2014). Upconing was recorded at different spots. The increase of population and water demands forced water authorities to continue pumping at the expense of water quality. One major governmental well, known as D1 to the water authorities (Fig. S1), previously pumping at 2880 m^3/d in Naameh village was shut down in 2009 due to high salinity (Cl > 1000 mg/L). Salinization is foreseen to slowly progress in the coming decades, and hence water authorities are expected to lose other wells close to the shoreline if no further action is taken.

Another governmental well, known as D5, located between the villages of Damour and Mechref at a distance of 1370 m from the shoreline (Fig. S1) was chosen here as an example site for possible IFK installation. It has been pumping continuously since 1991 at a constant rate of 1680 m^3/d. It taps the current saltwater mixing zone, and it is anticipated that continued pumping at shallower depths will result in more deterioration of water quality due to upconing of saltwater. Its groundwater chemistry is presented in Table S1 (*Supplementary Material*) for wet and dry seasons.

4. Results and discussion

4.1. IFK pumping layout

For the purpose of choosing the proper pumping layout of the vertical barrier, a radial axisymmetric numerical model was built using SEAWAT (Guo and Langevin, 2002). A radius of 100 m was chosen to represent the well domain for one year, which was assumed a safe assumption with no flow interference based on the following formula:

$$r = \sqrt{\frac{Qt}{\pi bn}} \qquad (1)$$

where r is the radial distance [m]; Q is discharge rate [m^3/d]; t is the time [d]; b is the thickness of flow domain [m] based on borehole logs; n is the porosity [-].

A radially symmetric 2-D model approach was adopted following Langevin (2008). Logarithmic mean was assigned for interblock conductivity calculation (option 2 in the LPF package of SEAWAT). The negative vertical barrier was located at one edge of the model (left side in Fig. 2), and cells representing the borehole were assigned high vertical hydraulic conductivity. Parameters at each cell were adjusted to account for the increase in aquifer volume away from it. As a function of radial distance, each parameter on cell to cell basis became:

$$X_i^* = r_i 2\pi X_i \qquad (2)$$

where X_i^* is the adjusted input parameter at the i^{th} column (hydraulic conductivity, specific storage, porosity and recharge); r_i is the radial distance from model edge to center of cell of the i^{th} column; X_i is the measured parameter at the i^{th} column,

A 1 m horizontal discretization was assigned in the first 25 m surrounding the well, and then allowed to increase at 1.5 factor reaching a maximum of 2.5 m at the edge. Vertical discretization was set at 5 m to a total depth of 170 m from ground level (Fig. 2). Local vertical hydrostratigraphy relied on well-logs (Fig. 3), but lateral heterogeneities were ignored. The sub-layers were given different hydraulic conductivities (K), which were generated using a stochastic approach (Kerrou et al. 2013). Vertical lithological variation was sorted into 3 main lithotypes: limestone with marl and/or marly limestone, partially fractured limestone, and highly fractured limestone (Fig. 3). Lithotypes were then converted into different hydraulic conductivities assuming log-normal distribution. Fifteen values estimated from pump tests in the studied aquifer (Khadra 2003) were utilized for this purpose. Their cumulative distribution function CDF was plotted against *ln(K)* in order to sort the samples into different groups (Fig. S2, *Supplementary Material*), which were represented by their geometric means. The smaller (20 m/d), intermediate (105 m/d) and larger (235 m/d) values were later assigned to the three aforementioned facies, respectively (Fig. 3).

A constant-head boundary (-90.5 m) was assigned to one edge of the model (right side in Fig. 2) in agreement with hydraulic head values in the well's vicinity. The constant-head over the simulation period was justified by minor water level fluctuations recorded in most pumping tests due to high transmissivity of the aquifer (Khadra 2003). The topmost layer had recharge boundary assigned to upper active cells (Fig. 2). Recharge to the aquifer was variable on monthly basis according to rainfall data (Table S2, *Supplementary Material*) (Meteorological Service 2010) with a 40% infiltration coefficient; chloride concentration of recharge water was assigned a constant value of 30 mg/L as deduced from average chloride in rainfall (11 mg/L) and average evapo-concentration factor in the study area (Khadra and Stuyfzand 2014). Noteworthy that SEAWAT sets the recharge to the upper-most active (wet) layer. So no need to account for water flow in the unsaturated zone including the soil moisture characteristics. A constant-concentration (1000 mgCl/L) was assigned to the layer directly overlying the no-flow boundary at the bottom. Its value was deduced after several trials to maintain a good match between observed and simulated salinity values, including seasonal variations, recorded over a one year period in 2009 (Fig. 4). The constant boundary assumption is also justified by stable conditions revealed from chloride time-series collected over the last decade during continuous prolonged pumping at a rate higher than the intended by the IFK installation.

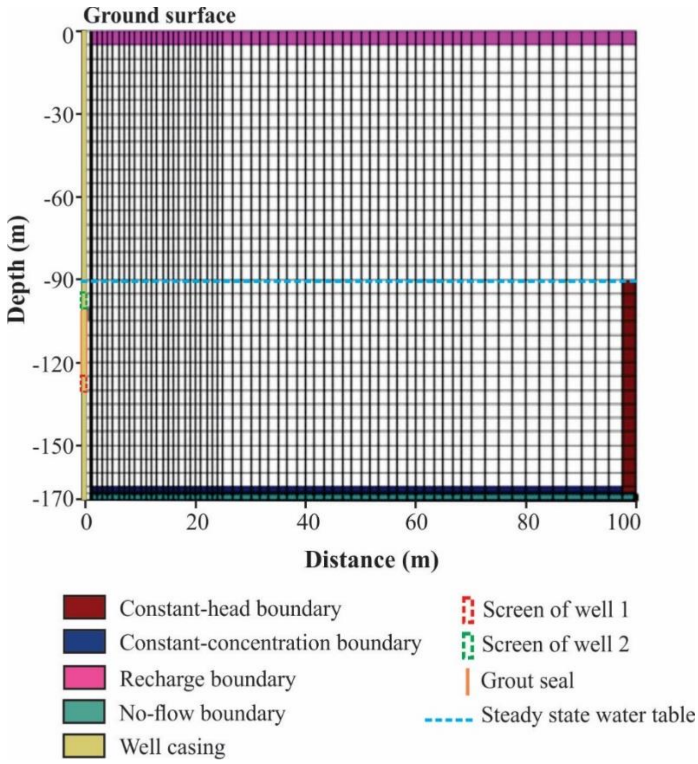

Fig. 2. Discretization mesh of the 2-D radial axisymmetric model. X-axis represents distance (in meters) from well D5 located at the left corner; y-axis represents depth (in meters) from land surface; vertical dimension was suppressed to 50%. Initial salt concentration = 200-400 mg/L.

After the 1-year period satisfactory representation (Fig. 4), another shallower well was added (Fig. 3), and the pumping of the main well was reduced from 1680 m^3/d to 800 m^3/d. A second simulation was then run for different scenarios using both wells in order to choose the proper pumping rates to obtain a stable vertical fresh-saltwater interface. This was assessed based on the breakthrough of chloride in the shallower well. Results showed that pumping 800 m^3/d at the fresh-keeper (main) well for 10 years could warrant a salinity of ca. 200 mg Cl/L in the shallower well (Fig. 5), which was allowed to pump at 250 m^3/d. This way the IFK installation provided local protection against saltwater upconing and simultaneously supplied additional freshwater reserves. Theoretically, the behavior of the new array might differ from the historical attitude over the last decade due to separation of flow via a shallow and a deep well. Therefore, the response was checked for both arrangements (one and two screens). Numerical results showed that the deeper screen will not be stressed more than before especially when the pumping rate is lower (800 m^3/d vs. 1680 m^3/d).

The diminution of the extraction rate will increase the total fresh groundwater outflow at the shoreline by 680 m^3/d (i.e. 3.4 $m^3/d/m$ assuming that well domain is represented by a radius of 100 m), which may subsequently push back the seawater/freshwater interface position by about 70 m. This estimate contains some uncertainty, and hence should be later corroborated by the outcome of numerical models. It assumes Dupuit and Ghyben-Herzberg approximations according to the following formula (Masciopinto 2006, 2013),

$$L = K \frac{B^2 - H^2}{2\delta \times Q} \qquad (3)$$

where L is the distance between the shoreline and the seawater/freshwater interface toe [m]; Q is the freshwater discharge into the sea per unit of coast length [$m^3/d/m$], estimated at 40 $m^3/d/m$ as deduced from hydraulic heads in the vicinity but raised later by 3.4 $m^3/d/m$; K is the hydraulic conductivity [m/d], 20 m/d; B is aquifer saturated thickness [m], 370 m; H is the depth of the interface at the outflow section [m], assumed here to be at shoreline; δ is freshwater/seawater specific ratio [-], assigned a value of 39.

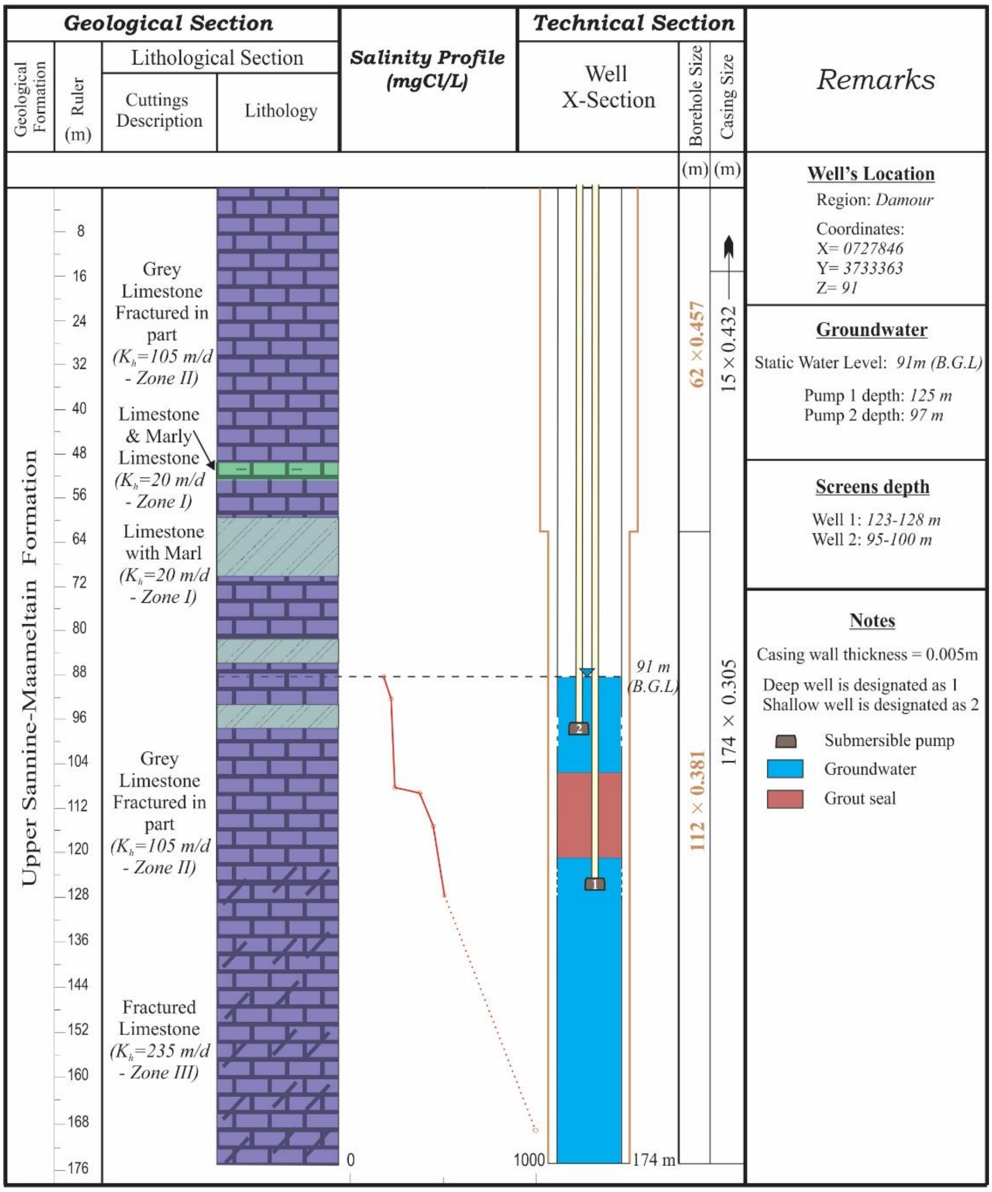

Fig. 3. Geological and technical cross-section of well D5 in the Damour area (south of Beirut, Lebanon) modified for IFK installation. Salinity profile relied on data collected in 2011 at different depths in the same well and the close vicinity. The dotted line is extrapolated from modeling outcome. Zones (I, II and III) of K_h are generated in Fig. S2 (*Supplementary Material*).

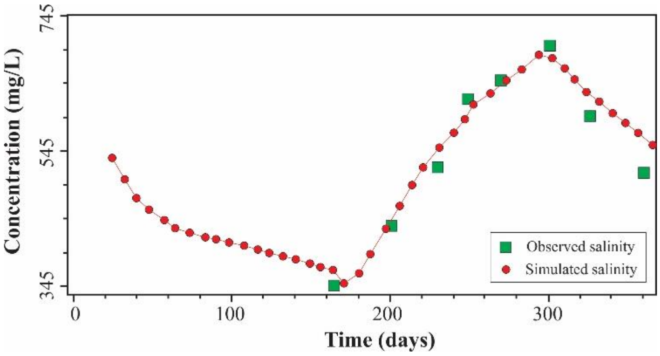

Fig. 4. Observed and simulated salinity concentration versus time at well D5 utilizing a time-series over a 1-year period in 2009. After 300 days salinity drops as a result of recharge increase in the Fall season.

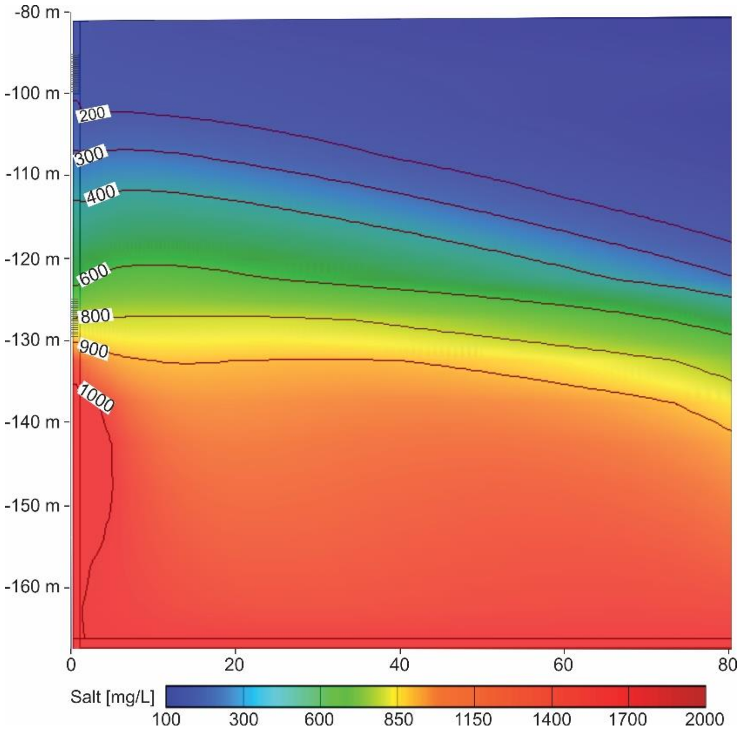

Fig. 5. Predicted chloride distribution of the IFK installation after 10 years of continuous pumping at well D5.

4.2. Design of the HR-RO system

The proposed multi-stage HR-RO tandem design is preceded by different pre-treatment steps as displayed in Fig. 1 improving the overall quality of feedwater. An overview of the HR-RO design is explained in Fig. 6 and Table 3. The first pass utilizes HSRO-390-FF membranes from FILMTEC^{TM} 8 inches in diameter and 40 inches long. It has 4 stages with 2 pressure vessels in the first stage and 1 vessel in the three others; each having 3 elements per vessel. This array is favored because equal membrane elements reduce production between vessel inlet and outlet (Fritzmann et al. 2007). About 40% of reject is re-circulated (path 4 in Fig. 6a) for further treatment and higher recovery. The second pass utilizes LC HR-4040 4 inch diameter × 40 inches long membranes with same number of stages; the first two have two vessels whereas the others have one (Table 3). A booster interstage pump is added before the first stage to counteract for reduced driving force on the feed side induced by higher concentration and pressure loss. pH is adjusted using ion exchange softening to maintain neutral conditions.

The quality and quantity of permeate water rely solely on ROSA calculations. It is assessed for two feedwaters anticipated during wet and dry seasons (Table S1). For the dry season, pass 1 has 71% recovery whereas pass 2 has 72% summing to a cumulative recovery of 92% (Table 4). The evolution of water quality from raw conditions via primary and secondary ROs to final permeate and concentrate quality is summarized in Table 5. When utilizing wet season groundwater chemistry the total recovery reaches 96%. The system produces a total feed flow of 367 and 33 m^3/d for permeate and concentrate, respectively in the dry period. The permeate has a TDS of 39 mg/L collected from first pass (70%) and second pass (30%) (Table 4). The concentrate (33 m^3/d) is brackish-salt with TDS of 19584 mg/L including 2930 mg/L HCO_3, 7022 mg/L Na, 8211 mg/L Cl and 1007 mg/L SO_4. This overall process leads to a total power consumption of 0.96 kWh/m^3. However, in the wet season, the system consumes 0.89 kWh/m^3 to produce 384 m^3/d of permeate and 16 m^3/d of concentrate with 18 mg/L and 24791 mg/L TDS, respectively.

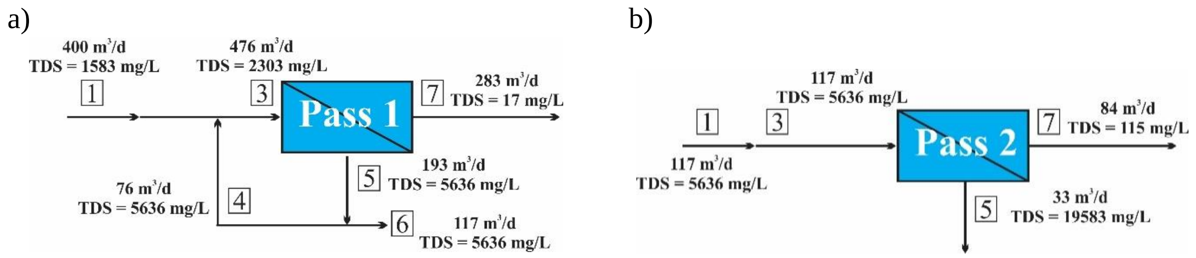

Fig. 6 (**a**) Primary (pass 1) and (**b**) secondary (pass 2) RO tandem system configuration. Numbers and associated conditions are for the dry season; they are explained in Table 4. Stream 1 in pass 2 comes from stream 6 in pass 1. Streams 2, 4 and 6 are not displayed in case of no recirculation.

Table 3
Technical specifications of primary (pass 1) and secondary (pass 2) HR-RO tandem system operated for a groundwater sample representing the dry conditions of well D5 in the Damour aquifer, Lebanon. The flux unit *lmh* is liter/m^2/h.

Pass #		**Pass 1**				**Pass 2**		
Stage #	1	2	3	4	1	2	3	4
Element Type		HSRO-390-FF				LC LE-4040		
Pressure Vessels per Stage	2	1	1	1	2	2	1	1
Elements per Pressure Vessel	3	3	3	3	3	3	3	3
Total Number of Elements	6	3	3	3	6	6	3	3
Pass Average Flux		21.67 lmh				22.24 lmh		
Stage Average Flux	27.54 lmh	22.80 lmh	17.58 lmh	12.92 lmh	37.54 lmh	21.51 lmh	10.52 lmh	4.83 lmh
Permeate Back Pressure	4.14 bar	4.14 bar	4.14 bar	4.14 bar	0.00 bar	0.00 bar	0.00 bar	0.00 bar
Booster Pressure	17.24 bar	0.00 bar	0.00 bar	0.00 bar	17.24 bar	0.00 bar	0.00 bar	0.00 bar
Chemical Dose		-				-		
Energy Consumption		**1.01 kWh/m³**				**0.83 kWh/m³**		

Table 4
HR-RO tandem system results for a groundwater sample at well D5 representing the dry season conditions.

	Stream #	Flow (m^3/d)	Pressure (bar)	TDS (mg/L)	Permeate TDS (mg/L)	Permeate Volume (m^3/d)	Concentrate TDS (mg/L)	Concentrate Volume (m^3/d)	Recovery (%)
Pass 1	1	400.00	0.00	1583.12	17	283	5636	117	71
	3	476.31	17.24	2303.25					
	4	76.31	12.18	5636.38					
	5	193.63	12.18	5636.38					
	6	117.31	12.18	5636.38					
	7	282.69	-	16.59	**39**	**367**	**19583**	**33**	**92**
Pass 2	1	117.00	0.00	5635.94	115	84	19583	33	72
	3	117.00	17.24	5635.94					
	5	33.10	13.47	19583.82					
	7	83.90	-	115.09					

Table 5
Evolution of water quality from raw conditions at well D5 via primary RO (pass 1) and secondary RO (pass 2) to final permeate and concentrate quality. Results represent the dry season conditions.

	Feedwater (mg/L)	**Pass 1**		**Pass 2**	**Final Outcome**	
		Permeate (mg/L)	***Concentrate (mg/L)***	***Permeate (mg/L)***	***Concentrate (mg/L)***	***Permeate (mg/L)***
TDS	1594	17	5636	115	19584	39
Cl	700	56	2005	41	8211	14
SO_4	84.0	0.5	286.9	2.8	1007.3	1.0
HCO_3	260.0	2.5	872.8	25.4	2930.4	7.8
NO_3	18.0	1.9	57.0	5.3	188.1	2.7
Na	330	5	2015	40	7023	13
K	1.9	0.2	6.2	0.3	21.1	0.2
Ca	124.3	< 0.1	0.3	< 0.1	0.3	< 0.1
Mg	62.9	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
SiO_2	10.9	0.1	37.0	0.2	130.3	0.2
B	0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Ba	0.03	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Sr	0.19	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
pH	7.50	5.61	7.8	6.4	7.8	5.8

4.3. Assessment of permeate/concentrate quality and volume

There is usually a call for trade-off between low recovery producing small freshwater volumes with moderately brackish concentrate and high recovery producing more fresh water but more saline concentrate, eventually with higher chance of membrane fouling and more difficult disposal (due to legislative restrictions or well clogging). Scale precipitation in the concentrate stream of some minerals, for instance calcite, gypsum, barite and SiO_2 limits recovery rates. It is a major limitation in high recovery applications, which reduces the mass transfer coefficient of membranes (Wolthek at al. 2013). The pre-treatment process is capable of reducing the fouling propensity and thereby minimizes membrane scaling; however, in this study it was not quantified and thereby scaling estimates demonstrated here represent the worst case scenario by skipping pre-treatment stage, i.e. it is kept as a safety margin.

The proposed design was advantageous in its efficient performance with low scaling propensity under high recovery conditions. The thermodynamic ion association model PHREEQC-2 (Parkhurst and Appelo 1999) was used to calculate the *Saturation Index* (SI) of the relevant minerals.

$$SI = \log (IAP/K_S) \qquad (4)$$

where IAP = the ion activity product, K_S = the solubility product of the mineral.

SIs of different susceptible minerals thus showed a scaling potential for SiO_2 only (Table 6). Other potential mineral like $CaSO_4$, $BaSO_4$ and $SrSO_4$ had no risk of scaling, because Ca was removed in the hardness reduction step, while Ba and Sr were already nearly absent in the source water. Silica removal is usually problematic due to the lack of reliable anti-scalants although there is a chance for scaling not to occur at all because crystallization is slow. Anyway, it is customary to try limiting SiO_2 content to about 120-220 mg/L to ensure a proper operation of the RO desalination system (Fritzmann et al. 2007). In addition, the design could be modified by adding an intermediate treatment between primary and secondary ROs (Fig. 1) in case of problematic performance of the system.

Boron was also checked since it is a very critical component in RO systems. The feedwater extracted at well D5 in the Damour aquifer had ca. 0.18 mg/L, which is lower than drinking water limits. So no threat is posed by its presence in the permeate water, but in case of higher values (> 1.0 mg/L) further modifications to the RO design become essential. One alternative is to back up the RO system with boron-specific ion exchange (Jacob 2007) although the cost may rise significantly especially due to frequent replacement of exhausted ion exchange bottles. Another alternative is to use ultra-filters (UF) in the pre-treatment phase. In addition, some special FILMTEC™ membranes currently exist for boron removal (e.g. BW30-380, BW30-400, BW30LE-400); however, they have overall lower recovery rates.

Table 6
Scaling propensity of concentrate water produced by the proposed HR-RO tandem system. Higher concentration of wet season reject is due to higher recovery.

		Wet season	Dry season
	pH	7.75	7.81
	Langelier Saturation Index	-0.66	-1.09
	TDS (mg/L)	24791	19584
	HCO_3 (mg/L)	6324	2930
	SiO_2 (mg/L)	224	130
		PHREEQC-2	
Saturation Index	Calcium carbonate ($CaCO_3$)	-0.91	-1.25
	Gypsum ($CaSO_4$)	-3.71	-3.85
	Barium sulfate ($BaSO_4$)	-0.29	-0.29
	Strontium carbonate ($SrCO_3$)	-0.86	-1.04
	Strontium sulfate ($SrSO_4$)	-2.39	-2.37
	Silica amorphous (SiO_2)	0.36	0.09

4.4. Options of concentrate disposal

A major environmental dilemma in any RO system is the disposal of concentrate, which is usually included in the feasibility assessment of the treatment facility. In the Damour area a wastewater treatment plant or disposal aquifers do not exist. Therefore, the reject water (or at least part of it) could be dumped directly to the sea as one viable choice. The Mediterranean Sea is ca. 1350 m away with seaward natural gradient, which reduces expenses of transport. Alternatively, the option of disposal to the Damour River (1 km away) (Fig. S1) was assessed here. This river has a surface water discharge between 6×10^3 m^3/d and 215×10^4 m^3/d with 34 and 18 mg/L background chloride concentration, respectively. This results in a chloride load of 138 kg/d and 39×10^3 kg/d during low and high discharge periods. Assuming a reject chloride concentration of 8200 mg/L as released by the RO tandem system and 10% as the maximum permissible increase of chloride in the river (Nederlof and Hoogendoorn 2005), then the allowed disposal is, respectively, 2.5 m^3/d and 470 m^3/d in the lowest and highest discharge seasons, which holds for other chemical constituents as well. This makes the Damour River a suitable alternative for safe disposal of reject water during wet season. A disposal outlet may be selected close to the estuary or at a spot with no downstream water uses in order to avoid any ecological objections. In the remaining period of the year, the reject is either disposed to the sea or held in collection tanks (though more expensive option) to be released later during higher discharge.

4.5. Economic assessment

A cost analysis of the HR-RO tandem desalination plant was executed to evaluate the economic feasibility of the proposed strategy. It included the initial capital cost, operation and maintenance costs, pipelines for reject disposal in addition to a comparison to selling prices of potable and domestic water in Lebanon. The capital costs of the two RO passes were estimated at 550,000 US$ hosting 11 pressure vessels and 33 membrane elements. This is for a 400 m^3/d capacity plant, i.e. it is multiplied by two when a series of two plants is required (800 m^3/d). 200,000 US$ were separately added for the pre-treatment multi-stage components. Operation included energy consumption, labor, cleaning/replacement of system components (membrane and pre-treatment filters), and water quality monitoring. The detailed description is provided in Table S3 (*Supplementary Material*).

The proposed design revealed low energetic demand of < 1 kWh/m^3. In Lebanon, the cost of each kWh electricity cannot be accurately estimated. This country has been facing electricity shortages since the civil war in the 1970s. Reliance is on the official electricity provider, Électricité du Liban, and local generation facilities. The former has lower prices, but since electricity outages are unpredictable the energy costs required for desalination remain dynamic. In this study, the assessment assumed 50% local electricity generation. Each 1 kWh worth maximum 0.17 US$, which is equivalent to 0.16 US$/$m^3$ assuming a 0.96 kWh/m^3 in the dry season. Maintenance costs included cleaning of primary and secondary ROs every 6 and 4 months, respectively, which was estimated annually at 30,500 US$ (Table S3). This also includes 500 US$ as the annual cost of energy consumption (0.02 kWh/m^3) required to run HWS (Hot Water Sanitization) twice a month. It is recommended that cleaning of membranes from fouling takes place on regular basis or when rejection of the system increases by 10% (FilmTec's Technical Manual 2014). All membranes are then replaced every 5 years.

Moreover, the operation costs accounted for labor; one full time employee (operator) would suffice to support the plant 5 days a week (8 hours per day), and the rest of the time automation and remote access to monitor the system could do the job in addition to a second employee for water quality monitoring.

Therefore, the total cost of the HR-RO tandem system over a 10-year life span was estimated at 0.99 US$/$m^3$. This value included 0.59 US$/$m^3$ for operation and maintenance. Accounting for the total intended freshwater production of the system (735 m^3/d), post-treatment, bottling and marketing, and then comparing it to the commercial selling prices of potable and domestic water in Lebanon reveals an annual profit of 4.3 and 0.3 million US$, respectively (Table 7). This means that the capital cost could be returned back in 1-4 years if proper marketing plans are implemented. It is noteworthy that the price of water in Lebanon is relatively high due to improper management. The average price of untreated tap water is ca. 10 US$/$m^3$ whereas the certified drinking water costs 105-210 US$/$m^3$. The viability of the project is partly dictated by the high price of domestic water in Lebanon when intention is to sell tap water only. The price is comparable to that in water scarce countries, e.g. 15 US$/$m^3$ in Somali and 10 US$/$m^3$ in Nigeria. Failure on the market may always pose a financial risk to the profitability of the project.

It may be argued that aquifer storage and hydraulic barriers are generally less expensive options than the proposed IFK installation (e.g. 0.3-0.6 US$/$m^3$ for AR (Maliva 2014), and 0.16-0.2 US$/$m^3$ for PHB (Ortuño et al. 2012)); however, they are only feasible under specific local hydrologic conditions usually not met in karstic aquifers due to complex dynamics and most often the lack of proper recharge and/or storage basins (see cons of "*hydraulic barriers*" in Table 1). Therefore, despite relatively higher costs, IFK still appeals as a main alternative in karstic media in comparison to other countermeasures.

Table 7
Cost of water production by the proposed HR-RO tandem design and the selling prices of water in Lebanon. This assessment is for a series of two units of the skid design (i.e. 800 m^3/day capacity).

		Selling price in Lebanon	
	HR-RO tandem (US$)	**Potable bottled water[a] (US$)**	**Domestic tap water (US$)**
Cost of water ($/$m^3$)	0.99	100	10
Post-treatment[b] ($/$m^3$)	0.10		
Total price (RO plant/day)	800	73,500	7,350
Bottling/distribution[c] ($/year)		0.1 million	--
Marketing and promotion ($/year)		1 million	0.2 million
Profits (RO plant/year assuming 25% selling)[d]		4.3 million	0.3 million[e]

[a] This price is the least provided for certified potable water in the Lebanese market; it exceeds 180$/$m^3$ for some distinguished trademarks.
[b] The desalted brackish groundwater should be polished to some extent in order to gain some buffer capacity against pH fluctuations. This could be done by admixing a small portion of brackish or fresh groundwater.
[c] It includes bottle washing, packaging, distribution and consumable items.
[d] This estimate assumes 300 working (business) days per year.
[e] This estimation assumes that oligohaline water (Cl < 30 mg/L) is sold for domestic use, but blending it with brackish water (maximum TDS of ca. 1500 mg/L) could supply 3 more volumes of water tripling the value of estimated profits.

5. Conclusions

A major challenge in managing water resources is to control saltwater intrusion in coastal aquifers. This is done by testing specific scenarios to select the best scheme. One option consists of a planned pumping strategy through hydraulic controls applying negative barriers via a row of vertical wells between sea and freshwater wells. However, the efficiency of this system depends on among others anisotropy and thickness of the aquifer, which may render it unreliable. This applies in particular to karstic and fractured aquifers, where simulation results carry more uncertainty about salt transport and location of the transition zone. In areas where relatively small volumes of water (extracted by 2-3 wells) would suffice to bridge the gap in water demand, Integrated Fresh-Keeper (IFK) wells form a more secure option than larger scale barriers. IFKs are less complicated, cheaper, and more effective with a lower chance of failure.

This paper proposes a coupled strategy of IFK and high recovery (HR) Reverse Osmosis (RO). The IFK will sustainably produce 2 water types via its 2 separated well screens within the same borehole: freshwater from the shallow screen and brackish or slightly brackish water from the deeper one. The brackish water is treated to demineralized bottled water by utilizing a HR-RO tandem desalination plant. The RO design provides high recovery with low scaling propensity without use of anti-scalants.

Application of the aforementioned strategy to a single pilot well in the Damour aquifer (south of Beirut, Lebanon) provides ca. 250 m^3/d of freshwater by vertical hydraulic interception. In addition, a desalination plant composed of a series (two units) of the proposed skid design could be adequate to treat the extracted brackish water of a pilot well (known as D5) at a capacity of 800 m^3/d. Consequently, the IFK installation coupled with the HR-RO system may supply in a sustainable way a total of about 985 m^3/d of freshwater. This reduces future salinization risks when fresh groundwater abstraction would continue. About 735 m^3/d of this water is suitable for drinking purposes after a slight post-treatment to meet drinking standards, e.g. liming or blending with small portion of brackish or fresh groundwater to stabilize the water and increase its alkalinity and TDS. The other 250 m^3/d of fresh water is good enough to supply as domestic water or to polish up the RO-permeate. The total expense of the desalting process was estimated at 0.99 US$/$m^3$ for a 10-year period life span, which could return back the plant capital cost in the first 1 to 4 years depending on the choice of selling bottled or tap water.

Brackish water has large compositional variation depending on mixing ratios and chemical reactions (e.g. cation exchange, dissolution and precipitation). Under prolonged pumping, there is a chance that salinity in the deeper well might rise. However, (1) the recommended pumping rate is half the current rate which is expected to relieve part of the ongoing stress on the system, and (2) the numerical simulations of the proposed IFK installation conforms to suitable conditions over the 10-year period (salinity may rise by about 20% only). Hence, this strategy necessitates installing a monitoring system to control water levels and groundwater quality from both well screens. A combined pressure and electrical conductivity (EC) sensor could do the job, while the EC can also be used to keep water quality constant for the HR-RO unit by adding more or less fresh water from the shallow well screen. Anyway, the proposed system could safely handle 100% salinity increase (temporal or over long time), which may lower the total RO recovery by 9% and the profits by 11 % only. At this rate, the system maintains its profitability paying back in maximum 5 years when selling tap water.

Installing IFKs opens the door for re-exploiting some abandoned brackish wells, and thereby reduces pumping rates of other wells yielding an optimized scheme. For instance, some wells in the

Damour aquifer currently abandoned due to high salinity may be re-operated after IFK installation, and the extracted brackish water, or at least part of it, could be blended with permeate water of the primary HR-RO system without need for further desalination. This could provide significant volumes of tap water. The strategy formulated here can be extrapolated to other sites, and the proposed treatment system could be used for similar feedwater conditions or be adapted after minor modification for more brackish waters. It is efficient, feasible, easy, profitable and thereby economically attractive in addition to a further potential benefit anticipated, namely the reduction of seawater intrusion lateral extent due to diminution of extraction rates.

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Supplementary data

Supplementary Material related to this article is available online.

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