

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

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Online Supplementary Material (SM)**Mitigation of saltwater intrusion by ‘integrated fresh-keeper’ wells combined with high recovery reverse osmosis**Wisam M. Khadra<sup>1,2</sup>, Pieter J. Stuyfzand<sup>1,3</sup>, Ibrahim M. Khadra<sup>4</sup><sup>1</sup>*Delft University of Technology, Dept. of Geoscience and Engineering, section Geo-environmental Engineering, P.O. Box 5048, 2600 GA Delft, Netherlands.*<sup>2</sup>*American University of Beirut, Dept. of Geology, P.O. Box 11-0236, 1107 2020 Riad El-Solh Beirut, Lebanon.*<sup>3</sup>*KWR Watercycle Research Institute, P.O. Box 1072, 3430 BB Nieuwegein, Netherlands.*<sup>4</sup>*Northcentral University, Engineering and Technology Management, 10000 University Dr, Prescott Valley, AZ 86314, USA.***Table S1**

Chemistry of groundwater extracted at well D5 (Damour aquifer – Lebanon) for both wet and dry seasons. The well is cased to 83 m below groundwater level (BGL), slotted between 13 and 74 m BGL, and pump installed at 34 m BGL. Fresh top water is selected based on samples collected in the very close vicinity at 4 m BGL. Reliable observations deeper than 35 m BGL are not available.

	Season (mg/L)		Freshwater on top (mg/L)
	Wet	Dry	
TDS	1094	1587	792
Cl	373	700	209
SO <sub>4</sub>	58	84	66
HCO <sub>3</sub>	307	260	261
NO <sub>3</sub>	4.3	5.5	6.3
PO <sub>4</sub>	0.1	0.1	0.1
Na	156	340	93
K	5.6	5.9	4.1
Ca	101	128	86
Mg	57	65	34
Fe	0.007	0.008	0.005
Mn	0.003	0.003	0.001
NH <sub>4</sub>	0.065	0.065	0.065
SiO <sub>2</sub>	9.0	10.9	8.9
Barium	0.032	0.032	0.027
Boron	0.107	0.176	0.061
Strontium	0.207	0.207	0.174
pH	7.2	7.5	7.18

**Table S2**

Rainfall data in the Damour area over a 10-year period, variable on monthly basis for the first year (based on year 2009 available data) and annually averaged for the remaining 9 years.

Rate (mm/yr)	Start Time (day)	Stop Time (day)
660	0	31
852	31	58
660	58	89
84	89	119
72	119	150
0	150	180
0	180	211
0	211	242
504	242	272

312	272	303
1176	303	333
1272	333	365
825	365	720
825	720	3650

**Table S3**

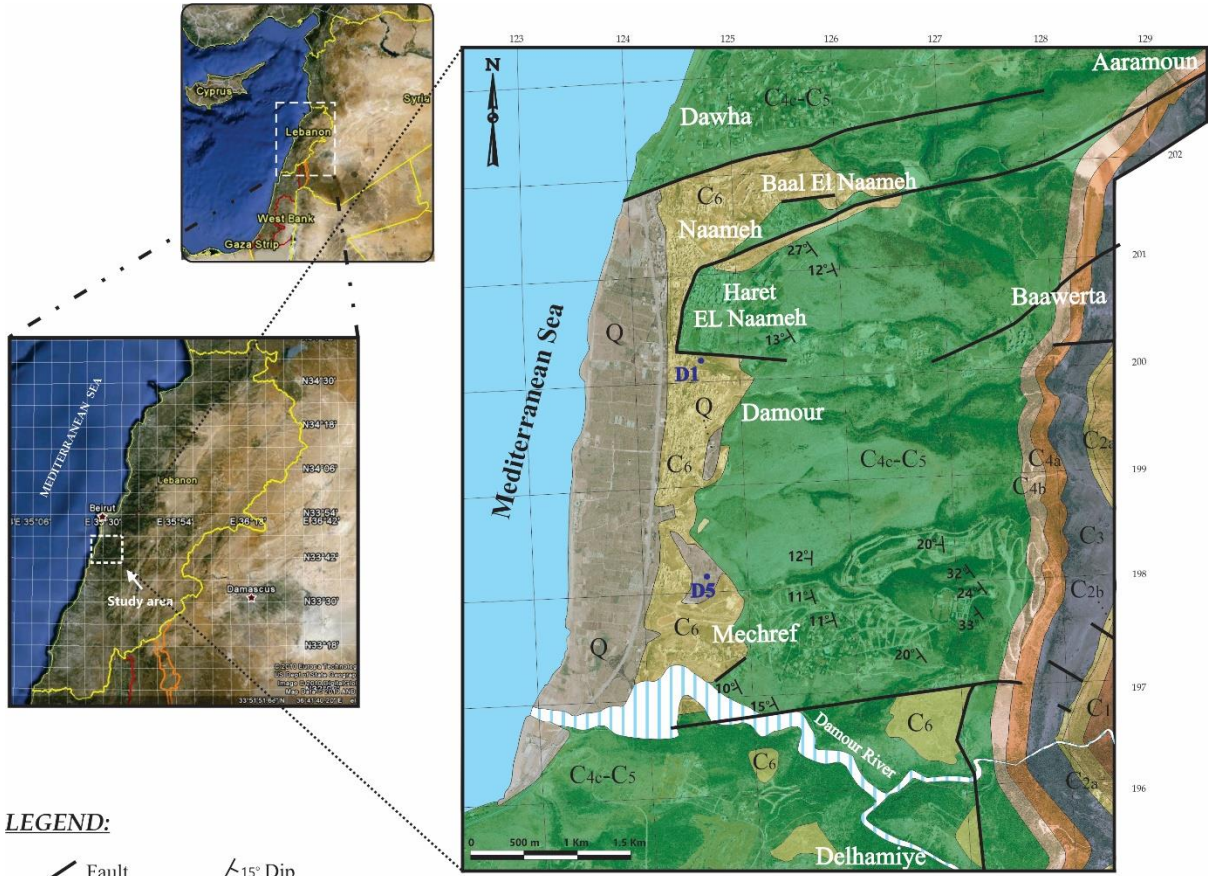
Detailed cost analysis of a HR-RO tandem plant for a total capacity of 400 m<sup>3</sup>/d. Expansion of the system to higher volumes requires a series of the proposed skid design where the total cost is multiplied by the number of units involved.

Primary RO – Pass 1		Secondary RO – Pass 2		RO Tandem	
	m <sup>3</sup> -m <sup>3</sup> /h-bar		m <sup>3</sup> -m <sup>3</sup> /h-bar		m <sup>3</sup> -m <sup>3</sup> /h-bar
Unit set for economic evaluation		Unit set for economic evaluation		Unit set for economic evaluation	
System water production (m <sup>3</sup> /h)	11.8	System water production (m <sup>3</sup> /h)	3.5	System water production (m <sup>3</sup> /h)	15.3
System recovery (%)	71	System recovery (%)	72	System recovery (%)	92
<b>Project Economic Variables</b>		<b>Project Economic Variables</b>		<b>Project Economic Variables</b>	
Project Life (years)	10	Project Life (years)	10	Project Life (years)	10
Interest rate (%)	8	Interest rate (%)	8	Interest rate (%)	8
Power cost (\$/kWh)	0.17	Power cost (\$/kWh)	0.17	Power cost (\$/kWh)	0.17
<b>Projection Results</b>		<b>Projection Results</b>		<b>Projection Results</b>	
Pass 1 permeate production (m <sup>3</sup> /h)	11.8	Pass 2 permeate production (m <sup>3</sup> /h)	3.5	Tandem permeate production (m <sup>3</sup> /h)	15.3
Pass 1 feed pressure (bar)	17.2	Pass 2 feed pressure (bar)	17.2	Tandem feed pressure (bar)	17.3
Pass 1 concentrate pressure (bar)	12.2	Pass 2 concentrate pressure (bar)	13.5	Tandem concentrate pressure (bar)	12.6
Pass 1 recovery (%)	15.0	Pass 2 recovery (%)	15.0	Tandem recovery (%)	15.0
Pass 1 energy recovery efficiency (%)	50.0%	Pass 2 energy recovery efficiency (%)	50.0%	Tandem energy recovery efficiency (%)	50.0%
<b>Capital Expense</b>		<b>Capital Expense</b>		<b>Capital Expense</b>	
Pass 1 pressure vessels	5	Pass 2 pressure vessels	6	Tandem pressure vessels	11
Pressure vessel cost (\$/vessel)	20,000	Pressure vessel cost (\$/vessel)	20,000	Pressure vessel cost (\$/vessel)	20,000
Pass 1 capital for pressure vessels	\$100,000	Pass 2 capital for pressure vessels	\$120,000	Tandem capital for pressure vessels	\$220,000
Product	HSRO-390-FF	Product	LC LE-4040	Product	HSRO-390-FF + LC LE-4040
Pass 1 total elements	15	Pass 2 total elements	18	Tandem total elements	33
Element cost (\$/element)	\$10,000	Element cost (\$/element)	\$10,000	Element cost (\$/element)	\$10,000
Pass 1 capital for elements (\$)	\$150,000	Pass 2 capital for elements (\$)	\$180,000	Tandem capital for elements (\$)	\$330,000
Capital for pre-treatment (\$)	\$200,000			Pre-treatment capital	\$200,000
Pass 1 capital (\$)	\$250,000	Pass 2 capital (\$)	\$300,000	Land acquisition <sup>a</sup> (\$)	\$0
Pass 1 capital(\$/m <sup>3</sup> )	\$0.24	Pass 2 capital(\$/m <sup>3</sup> )	\$0.98	Disposal pipelines (\$)	\$10,000
				Construction works (\$)	\$30,000
				HR-RO Tandem capital (\$)	\$790,000
				HR-RO Tandem capital(\$/m <sup>3</sup> )	\$0.59
<b>Operating Expense</b>		<b>Operating Expense</b>		<b>Operating Expense</b>	
<b>Power</b>		<b>Power</b>		<b>Power</b>	
Pass 1 pumping power (kW)	11.9	Pass 2 pumping power (kW)	2.9	Tandem pumping power (kW)	9.2
Pass 1 pump specific energy (kWh/m <sup>3</sup> )	1.01	Pass 2 pump specific energy (kWh/m <sup>3</sup> )	0.83	Tandem pump specific energy (kWh/m <sup>3</sup> )	0.96
Brine energy recovery (kWh/m <sup>3</sup> )	-26.8	Brine energy recovery (kWh/m <sup>3</sup> )	-26.8	Brine energy recovery (kWh/m <sup>3</sup> )	-26.8
Pass 1 net energy consumption (KWh/m <sup>3</sup> )	1.01	Pass 2 net energy consumption (KWh/m <sup>3</sup> )	0.83	Tandem net energy consumption (KWh/m <sup>3</sup> )	0.96
Pass 1 net energy cost (\$/year)	\$1,063	Pass 2 net energy cost (\$/year)	\$259	Tandem net energy cost (\$/year)	\$1310














Energy expense NPV (\$)	\$7,133	Energy expense NPV (\$)	\$1,740	Energy expense NPV (\$)	\$8,792
Pass 1 energy expense (\$/m <sup>3</sup> )	\$0.17	Pass 2 energy expense (\$/m <sup>3</sup> )	\$0.14	Tandem energy expense (\$/m <sup>3</sup> )	\$0.16
<b>Membrane cleaning</b>		<b>Membrane cleaning</b>		<b>Membrane cleaning</b>	
Pass 1 cleaning frequency (cycle/year)	2	Pass 2 cleaning frequency (cycle/year)	4	Tandem cleaning frequency (cycle/year)	6
Pass 1 Cleaning expense (\$/cycle)	\$5,000	Pass 2 Cleaning expense (\$/cycle)	\$5,000	Tandem Cleaning expense (\$/cycle)	\$5,000
Pass 1 cleaning expense (\$/year)	\$10,000	Pass 1 cleaning expense (\$/year)	\$20,000	Tandem cleaning expense (\$/year)	\$30,500
Pass 1 cleaning expense NPV (\$)	\$67,101	Pass 2 cleaning expense NPV (\$)	\$134,201	Tandem cleaning expense NPV (\$)	\$204,657
Pass 1 cleaning expense (\$/m <sup>3</sup> )	\$0.01	Pass 2 cleaning expense (\$/m <sup>3</sup> )	\$0.07	Tandem cleaning expense (\$/m <sup>3</sup> )	\$0.02
<b>Labor (for both passes 1 and 2)</b>				<b>Labor</b>	
Full time employee (FTE)	1			Full time employee (FTE)	1
Salary for each FTE (\$/year)	\$7,200			Salary for each FTE (\$/year)	\$7,200
Total labor (\$/year)	\$7200			Total labor (\$/year)	\$7,200
Total labor NPV (\$)	\$48,313			Total labor NPV (\$)	\$48,313
Labor expense (\$/m <sup>3</sup> )	\$0.02			Labor expense (\$/m <sup>3</sup> )	\$0.01
<b>Membrane replacement cost</b>		<b>Membrane replacement cost</b>		<b>Membrane replacement cost</b>	
Pass 1 replacement rate (%/year)	10	Pass 2 replacement rate (%/year)	10	Tandem replacement rate (%/year)	10
Replacement price (\$/element)	\$10,000	Replacement price (\$/element)	\$10,000	Replacement price (\$/element)	\$10,000
Pass 1 replacement cost for elements (\$/year)	\$15,000	Pass 2 replacement cost for elements (\$/year)	\$18,000	Tandem replacement cost for elements (\$/year)	\$33,000
Pass 1 replacement membrane NPV (\$)	\$100,651	Pass 2 replacement membrane NPV (\$)	\$120,781	Tandem replacement membrane NPV (\$)	\$221,432
Pass 1 membrane replacement expense (\$/m <sup>3</sup> )	\$0.15	Pass 2 membrane replacement expense (\$/m <sup>3</sup> )	\$0.59	Tandem membrane replacement expense (\$/m <sup>3</sup> )	\$0.25
<b>Pre-treatment elements replacement cost (for both passes 1 and 2)</b>				<b>Pre-treatment elements replacement cost</b>	
Replacement cost (\$/year)	\$20,000			Replacement cost (\$/year)	\$20,000
Replacement cost NPV (\$)	\$134,202			Replacement cost NPV (\$)	\$134,202
Pre-treatment replacement expense (\$/m <sup>3</sup> )	\$0.19			Pre-treatment replacement expense (\$/m <sup>3</sup> )	\$0.15
				<b>Water quality monitoring cost</b>	
				Lab capital cost (\$)	\$5,000
				Full time employee (FTE) salary (\$/year)	\$7,200
				Consumable items (\$/year)	\$10,00
				Total monitoring (\$/year)	\$8,200
				Total monitoring NPV (\$)	\$60,023
				Water quality monitoring expense	\$0.01
<b>Operating expense subtotal</b>		<b>Operating expense subtotal</b>		<b>Operating expense subtotal</b>	
Pass 1 operating expense NPV (\$)	\$223,197	Pass 2 operating expense NPV (\$)	\$256,723	Tandem operating expense NPV (\$)	\$539,862
Pass 1 operating expense per m <sup>3</sup>	\$0.54	Pass 2 operating expense per m <sup>3</sup>	\$0.79	Tandem operating expense per m <sup>3</sup>	\$0.59
<b>Pass 1 Total</b>		<b>Pass 2 Total</b>		<b>Tandem Total</b>	
Pass 1 cost NPV (\$)	\$373,197	Pass 2 cost NPV (\$)	\$436,723	Tandem cost NPV (\$)	\$869,862
Life Cycle Cost (\$/m <sup>3</sup> )	\$0.36	Life Cycle Cost (\$/m <sup>3</sup> )	\$1.43	Life Cycle Cost (\$/m <sup>3</sup> )	\$0.65
<b>Total System</b>		<b>Total System</b>		<b>Total System</b>	
Capital	\$250,000	Capital	\$300,000	Capital	\$790,000
Operating expense NPV (\$)	\$223,197	Operating expense NPV (\$)	\$256,723	Operating expense NPV (\$)	\$539,862
Cost of water NPV (\$/m <sup>3</sup> )	\$0.59	Cost of water NPV (\$/m <sup>3</sup> )	\$1.82	Cost of water NPV (\$/m <sup>3</sup> )	\$0.99

PV: The present value (PV) is the total amount that a series of future payments is worth now.

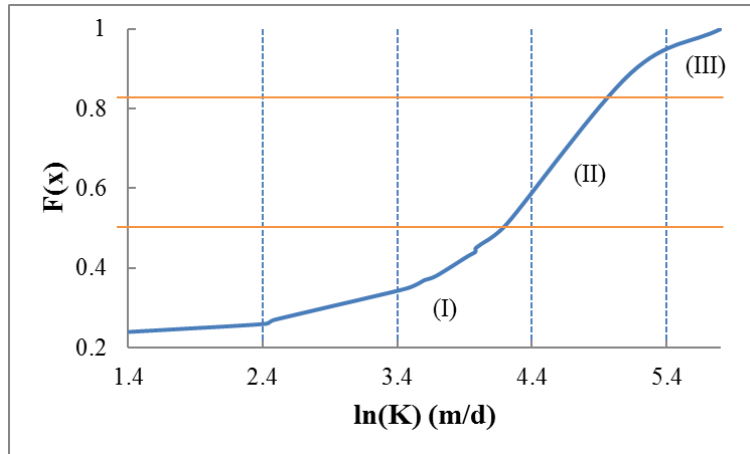
<sup>a</sup> Land acquisition is zero because the selected well (well D5 in the Damour aquifer – Lebanon) already owns enough space as part of its local territory.



**LEGEND:**

-  Fault
-  15° Dip
-  Quaternary Deposits: Sand, gravel and clay with spatial variation.
-  Alluvium
-  C<sub>6</sub> Chekka Formation: Greyish white jointed and fissured chalky to marly limestone alternating with marl beds.
-  C<sub>4c-C5</sub> Upper Sannine-Maameltain Formations: jointed and fissured dolomitic limestone with chalky limestone and micritic limestone. Micritic nodules are apparent.
-  C<sub>4b</sub> Sannine Formation: Jointed and fissured marly limestone. Middle Subunit.
-  C<sub>4a</sub> Sannine Formation: Dolomite, fissured and jointed, interbedded with dolomitic limestone and marly limestone. Lower Subunit.
-  C<sub>3</sub> Hammana Formation: Alternation of brownish green marl and marly limestone, more marl are found in lower middle part and yellowish green marly limestone at the top.
-  C<sub>2b</sub> Mdairej Formation: Grey micritic and cliff forming limestone, fissured and jointed.
-  C<sub>2a</sub> Abeih Formation: Brown green variable unit of marly limestone interbedded with thin beds of marl and yellow brown clayey sandstone at the bottom.
-  C<sub>1</sub> Chouf Formation: Ferruginous brown sandstone, coarse to fine, compact to slightly compact, clay and lignite lenses in the lower part.
-  Targeted salinizing wells (D1 and D5).

**Fig. S1.** Geological map of the Damour area (Khadra and Stuyfzand 2014).



**Fig. S2.** Cumulative distribution function (CDF) of the Gaussian  $\ln(K)$  distribution generated using a variance and mean of 85 m/d and 65 m/d, respectively. Values are sorted then discriminated into three zones (I, II and III), which are subsequently attributed to the corresponding lithofacies (higher values to more permeable lithofacies).