Urban Planning Design to Supply Freshwater By ASR Technique Operations

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***Abstract*—** Artificial recharge has been applied in Kuwait in different groundwater fields since the 1980s. The available surface storage capacity of 11.7 Mm^3 freshwater is sufficient to meet demand for about 7 days. So, aquifer storage and recovery (ASR) can be used to store the water in aquifers instead of surface storage. ASR entails storing water in aquifers during wet times and recovering the water from the same well during drought times. Artificial recharge in Kuwait has used the concept of injection and recovery of water in one cycle, while here it will be applied in a multi-cycle concept to avoid increasing the piezometric head and clogging the porous media. The injected water will be treated wastewater with a TDS content of less than 500 ppm and the TDS of recovered water in each well will be less than 1500 ppm. The success of ASR depends on the recovery efficiency (RE) of each cycle which increases with a decrease in time between the stopping of injection and the starting of the recovery operation. Numerical modeling is used to demonstrate the concept of the process of ASR including the volume and time for injection and recovery of water in multi-cycles.

***Keywords*—** Artificial recharge, Aquifer, ASR, Groundwater, Multi-cycles, Recovery efficiency.

I. Introduction

THE provision of water supply, transport network, sewage network and electricity infrastructure play key roles in the development of sustainable cities. A significant increase is expected in water demand during the next few decades based on the population growth all over the world and increasing environmental pollution will contribute to poor quality of available water resources. These will push decision makers to find alternative solutions for water supply in normal and critical times. Kuwait has limited water resources represented by small reserves of fresh groundwater and has to rely on several artificial water resources to secure its water requirement, either potable or non-potable water, from desalination plants and wastewater plants. The surface storage in Kuwait can provide freshwater for about 7 days (11.7 Mm^3) which is not sufficient to meet the demand for almost one week, especially given the more than one year it takes to bring the desalination plants back online in the event of an outage. In addition, the surface storage is easy to sabotage, which keeps the country without water security in such an emergency condition. Kuwait needs a dual purpose source to meet the demand when non-conventional water resources production are less than the demand or out of service and to improve the natural water resource. Aquifer storage and recovery technique (ASR) is increasingly recognized as a cost-effective and environmentally desirable tool for sustainable water resources management where water is added (injected) to a groundwater body to make it available for later use during times of need or emergency conditions. Also, ASR is being used to optimize available water resources and as a method of improving water supply reliability and water quality by controlling a groundwater basin or aquifer. Subsurface water storage for later use is an efficient way to store water because it is not vulnerable to evaporation losses and it is relatively safe from contamination. In this framework, it is a form of water conservation, in that water that is lost through evaporation from dams and rivers or from outflows to the sea (fresh or waste water), can be captured and made available for later use. The criteria to design the volume, duration, distribution of wells and number of cycles for the operation to achieve the desired recovery efficiency of an ASR are based on the water demand and source water availability and quality. The target storage volume (TSV) of an ASR is the volume of water needed for the storage and buffer zones for the ASR to reach the optimum recovery efficiency. The deficit in supplying freshwater in summer months is one of the problems of supply and demand in Kuwait. ASR basically functions as a water bank and it provides a guaranteed water supply in the future if one of the water resources is depleted.

ASR can remove the stigma of using treated water from wastewater by injecting the effluent in the ground and recovering it later as groundwater. The numerical modeling used in this study to simulate ASR operations was Groundwater Vistas (Environmental Simulations, Inc, 1998), which is a sophisticated graphical user interface for 3-D groundwater flow and transport modeling. Groundwater Vistas can be used to evaluate and analyze the result of injecting water into aquifers with respect to the water level, water quality and movement of water in the aquifer.

Sustainability is the main framework which has emerged as a planning and management concept and has commonly been applied to urban development in the fields of environmental, social, and economic planning which they are the triple bottom line of sustainability. In addition, sustainable development has become a tool in engineering with the most popular and clear definition of sustainable development (SD) coming from the Brundtland report as the development that meets the demands of the current generation without

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compromising the ability of future generations to meet their own demands [2]. Sustainable infrastructure provides and maintains physical infrastructure (water supply systems in our case) to enable reliable and accurate consumer use for the predictable future with attention on the infrastructure systems themselves, taking into account the adequacy of these systems to serve an increasing population, satisfy public service demands, remain in satisfactory working order, and be supported by reliable economic resources.

II. The Conceptual Design for ASR

This study applied the ASR technique in Kuwait to develop subsurface storage in the Dammam aquifer that sustains other water resources to meet water demand. The volume of water that needs to be injected and recovered is the most essential to building a conceptual design for ASR operation that also considers the daily volume of demand and supply. First, the difference between production and consumption in different months is determined. Then, the months that demand reaches the value of supply, or is close to it, are determined.

TABLE I
DAILY FRESHWATER SUPPLY AND DEMAND (MEW, 2005)

Avg. Daily Production (Mm3/day)	Avg. Daily Consumption (Mm3/day)	Month. Year	ASR recovery	Volume needed (Mm3/day)
1.100	1.111	1.2005	Yes	-0.01
1.162	1.155	2.2005		0.00
1.205	1.212	3.2005		0.00
1.378	1.364	4.2005		0.01
1.444	1.459	5.2005	Yes	-0.01
1.525	1.531	6.2005	Yes	-0.01
1.525	1.537	7.2005	Yes	-0.01
1.529	1.543	8.2005	Yes	-0.01
1.538	1.538	9.2005		0.000
1.530	1.514	10.2005		0.01
1.424	1.381	11.2005		0.044
1.293	1.305	12.2005	Yes	-0.01

The difference between supply and demand is the daily volume of freshwater needed to meet the requirements in one month. In Kuwait, June, July, and August are the critical months that need more supply from an ASR operation to sustain the production from the desalination plants to meet the demand. The mechanism for injection and recovery is cyclical which helps to control the head level and build the buffer zone around the subsurface storage. The Target Storage Volume (TSV) is defined as the total volume of water injected in subsurface storage zone and the buffer zone (Pyne, 2005) which is needed to build up the buffer zone before starting the actual cycles to create the TSV. Many cycles of injection and recovery must take place to determine the buffer zone and keep the native groundwater away from the storage zone. The prior cycles are a one-time investment volume of water in injection and recovery cycles to create buffer zone. At the study site, the time to create the buffer zone is estimated to be one year due to the high TDS value in the groundwater of Kuwait with short prior cycles before the actual cycles of ASR operation. Eight ASR wells are a good starting point for ASR operations. The rate of injected water in the prior cycles is assumed equal to or higher than the rate of recovery in the actual ASR cycles (Pyne, 1995).

The recovery cycle of the ASR operation will produce for three months each year starting in June and stopping at the end of August and the total daily recovery volume from these 8 ASR wells is 100000 m3. On the other hand, the injection cycle for the ASR operation starts after the end of the last recovery cycle to build up the buffer zone. If the daily rate of injection in each ASR cycle is lowered to 550 m3/d per well, which is less than half of the daily rate of recovery per well, the duration of injection in each ASR cycle is 9 months. The daily rate of injection in buffer zone cycles is 1500 m3/d per well, which is slightly more than the rate of recovery per well to leave a small volume for improvement of the water quality. The daily rate of prior recovery cycles is 250 m3/s per well. Three prior cycles are implemented to build up the buffer zone including 3 months of injection and 1 month of recovery. The recovery volume is 100000 m3/d for 3 months while the production should be stopped when a TDS value of 1500 mg/L is reached, that is the standard of drinkable freshwater in Kuwait. The recovery efficiency is affected by the well arrangement in the ASR field, which should minimize the mixing between the stored and the native water.

Figure 1 shows examples of some of the alternative ASR well arrangements to get high recovery efficiency. The well spacing is determined by finding the theoretical radius of the TSV (Pyne, 2005), which is estimated to be between 200 and 400 m in this case.

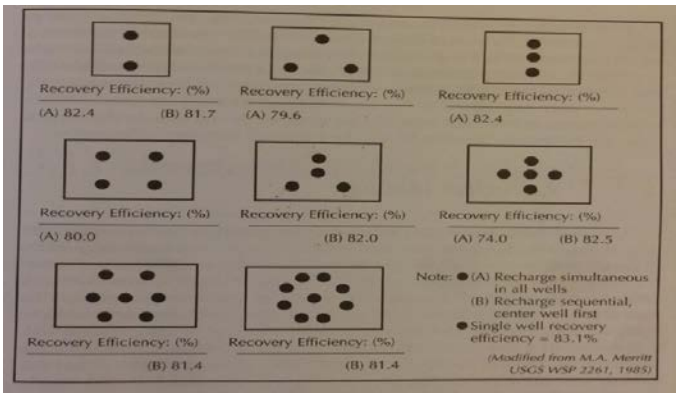

Fig. 1 Types of Distribution of ASR Wells (Source: Pyne, 2005)

- Groundwater Vistas software

Groundwater Vistas is a unique groundwater modeling environment that combines powerful finite-difference groundwater models with comprehensive graphical analysis tools. It can display the model in both plan and cross-sectional view. GV is designed to be an independent modeling system and supports many groundwater models such as MODFLOW, MODPATH, MT3D, etc. (Environmental Simulations, Inc, 1998). Also, it is easy for the user familiar with different software making it possible to import and export hydraulic or

geographic data from Surfer and ArcGIS software. GV imports a wide variety of files such as MODFLOW data sets, boundary condition data and aquifer property data. The results can be displayed in both plan and cross-sectional windows as contours or color flood for the water head and the concentration.

TABLE II
HYDRAULIC PARAMETERS OF KUWAIT GROUP AND DAMMAM (MUKHOPADHYAY ET AL., 1994)

Parameter	Kuwait Group Aquifer	Aquitard	Dammam Aquifer
Specific storage/ Specific yield	1.8×10^{-4}/ 0.18	1.8×10^{-4}	5×10^{-6}
Porosity	0.20	0.05	0.05
Transverse Dispersivity (m)	0.1	0.1	1
Longitudinal Dispersivity (m)	1	1	10

III. NUMERICAL SIMULATION OF ASR OPERATIONS:

The ASR approach followed in this study is to create a strategic reserve of freshwater in the Dammam aquifer as a seasonal storage. Groundwater Vistas software was used to evaluate the hydraulic effects of injection and recovery operations on the Dammam aquifer under certain conditions. The model design has 2 aquifers (the Kuwait Group and the Dammam Formation) that are separated by an aquitard layer (Omar et al., 1981). The aquitard is formed from a clay layer at the lower part of the Kuwait Group and a chert layer at the top of the Dammam Formation. The surface area for the whole model is 20 km by 20 km. The modeled surface area is divided into a grid of 50 by 50 cells in each of three layers. The grid spacing varies in the model, being large near the border and decreasing until it reaches the area selected as suitable for ASR with a grid spacing 100 m in the center of the ASR field and 125 m surrounding it to provide more accurate modeled values. Raster layers were imported from the database of groundwater in Kuwait; they are converted to shapfiles in ArcGIS to use them as input for initial heads, initial concentration, top elevation, bottom elevation and hydraulic conductivity for each layer of the model in the property files in GV (Alrukaibi et al., 2010; Mukhopadhyay and Al-Otaibi, 2002). The constant head and concentration in the boundary conditions (BCs) file is assigned to the boundary cells of the model in all three layers, where the water heads and TDS concentration were held constant for the simulation period. The most suitable area for ASR operation has been selected (using ArcGIS tools) and it occupies almost 2.5 km by 4 km, while the ASR field needs a small area for operation based on the well arrangement and the spacing between wells (Alrukaibi et al., 2010). The criteria for spacing and arrangement of ASR wells were considered to achieve the desirable recovery volume with the TDS limit of 1500 mg/L. Model runs started with prior cycles to create the transition zone between the stored and native water. The daily demand requirement must be met daily from 8 wells within the ASR field area in the summer months and injection starts after the prior cycles end. MODFLOW is used to determine the effect of injection and recovery during the simulation period while MT3D is used to find the TDS concentration during the ASR operation.

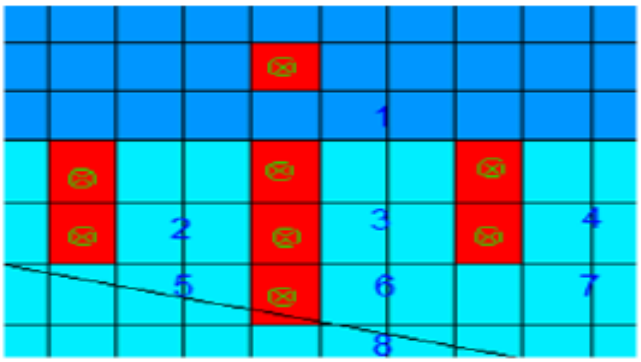

Figure 2 Location of ASR Wells

IV. CONCEPTUAL DESIGN RESULTS

The scenario considered for applying ASR technique in the Dammam aquifer of Kuwait has two phases; the first phase (prior cycles) creates the buffer zone between the storage zone and the native groundwater (which has a high TDS value). The second phase, called the basic ASR cycles, is designed to provide consumers the required volume of water after each injection phase and uses subsurface storage for emergency conditions. There is not any inactive period between the injection and recovery cycle in both phases to increase the recovery efficiency for the basic cycle.

TABLE III
SCENARIO MECHANISM

Phase	Type of cycle	Duration	The daily Volume of water per well
Prior cycles	Injection	92 days	1500 m^3
	Recovery	30 days	-250* m^3
	Injection	92 days	1500 m^3
	Recovery	30 days	-250* m^3
	Injection	92 days	1500 m^3
	Recovery	30 days	-250* m^3
First cycle	Injection	273 days	550 m^3
	Recovery	93 days	-1250* m^3
Second cycle	Injection	273 days	550 m^3
	Recovery	93 days	-1250* m^3
Third cycle	Injection	273 days	550 m^3
	Recovery	93 days	-1250* m^3

*negative sign means this volume is pump out from the well.

V. NUMERICAL MODELING RESULTS DISCUSSION:

The model runs simulated the injection and recovery phases for 8 wells to evaluate the possible impact to the

potentiometric head in the aquifer and determine the engineering feasibility of the injection phase and the provided water quality and volume information that are needed to determine the recovery efficiency. The horizontal hydraulic conductivity was 2.027 m/d for all wells except well number 1 was 1.351 m/d while the initial vertical hydraulic conductivity was one-tenth of the horizontal hydraulic conductivity in the ASR field. The horizontal spacing between all wells was almost 300 m from center to center. The head and TDS concentration in the Dammam aquifer were assigned to be the starting values for the run (initial head and initial concentration values imported from the groundwater database as shapfiles).

MODFLOW was used to simulate the head in the injection and recovery phases. Then, MT3D used the head output from MODFLOW with initial TDS concentrations as input to simulate the TDS during the ASR operation. A monitoring well was located close to each ASR well to measure the rise and decline of head and concentration. The hydrograph illustrates the head level and concentration over the duration of the ASR scenario for each monitoring well. The hydrograph for ASR well number 1 showed that the head level fluctuated starting at 58 m (amsl) and reached 44 m (amsl) at the end of the last cycle.

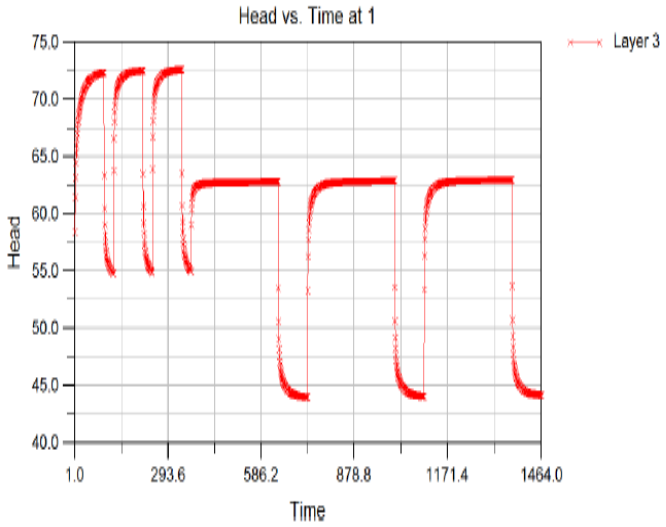

Fig. 3 Hydrograph of Head for ASR well 1

It was assumed that the allowable limits for head level rise and decline is 20 m above and below the initial value of water level (as reference). Head in ASR well number 1 rose up to 73 m in the third prior cycle which was 15 m above the reference. In the last cycle, the head was 14 m below the reference. The head in the other wells are shown in Table 4 with reference to the initial head.

After the end of the prior cycles (one year), the target storage volume (storage zone and buffer zone) has developed around the well. The results from MT3D (Fig. 4) show that the buffer zone (light blue) is a barrier to the native groundwater (green), that has high TDS value, from the storage zone (dark blue) that has potable water.

TABLE IV
MAXIMUM AND MINUMUM WATER HEAD VALUES FOR ASR WELLS

ASR well	The initial value (amsl)	Max. rise above ref.	Maximum decline below ref.
ASR well 2	58 m	+14 m	-12 m
ASR well 3	60 m	+14 m	-17 m
ASR well 4	58 m	+14 m	-14 m
ASR well 5	58 m	+14 m	-12 m
ASR well 6	60 m	+14 m	-16 m
ASR well 7	58 m	+15 m	-13 m
ASR well 8	59 m	+14 m	-14 m

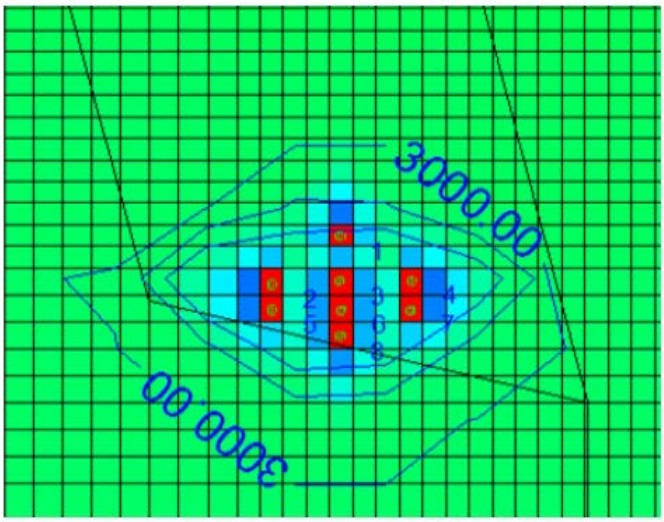

Fig. 4 Top View for the Buffer zone storage zone after the end of first year

Figure 5 displays the result from MT3D in cross-section along the row or column in the model, which helps to define the storage zone and buffer zone around the well. The diameter of the storage zone is almost 100 m after the prior cycles (one year) and the distance from the end of storage zone to the buffer zone is 100 m.

The TDS concentration over time for ASR well number 1 (shown in Fig. 6) shows that the TDS has improved around the well due to operation of the prior cycles. The concentration reached 500 mg/L at the beginning of the first basic cycle. Then, it fluctuated between 500 mg/L and 1000 mg/L, which is the concentration of the recovery volume and less than the allowable standard limit of potable water in Kuwait.

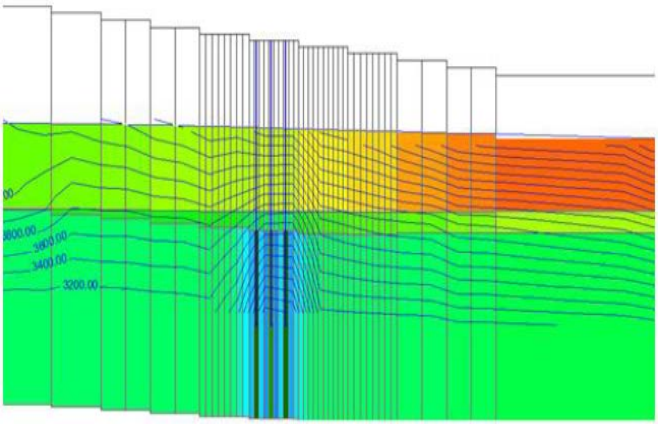

Fig. 5 Cross-Section a long Row 38 after the end of first year

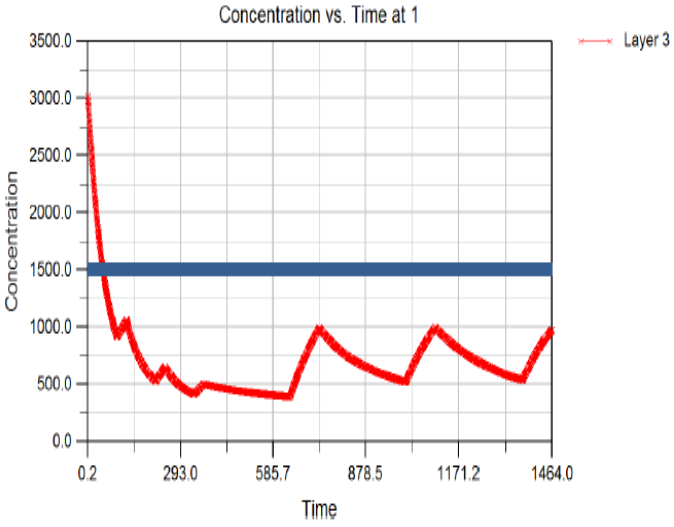

Fig. 6 Hydrograph of TDS Concentration for ASR well 1

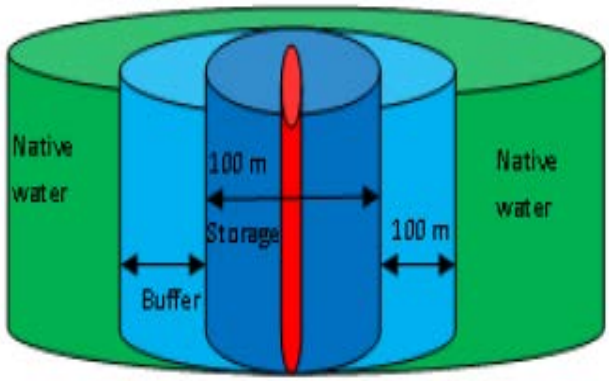

Fig. 7 schematic for storage zone and buffer zone after the end of first year

The recovery efficiency for ASR well number 1 for each basic cycle was calculated as All of the other ASR wells had the same recovery efficiency (77.42%) based on the hydrograph chart for each well. The recovery efficiency can be increased by increasing the total recovery, but one of the objectives of applying ASR was improvement in water quality in the aquifer by leaving a small percentage (22.57%) of the injected water in the aquifer. The injected and recovered water in prior cycles were a one-time investment to create the transition zone and they were not considered in the calculation of the recovery efficiency percentage. The total daily recovery volume from 8 ASR wells with TDS less than 1500 mg/L is designed to provide 10000 m^3/d.

$$Recovery\ efficiency = \frac{Volume\ of\ water\ recovered\ with\ TDS \le 1500 \frac{mg}{L}}{Volume\ of\ water\ injected}$$

$$= \frac{(1250\ m^3\ per\ day) * (93\ days)}{(550\ m^3\ per\ day) * (273\ days)} * (100) = 77.42\ \%$$

TABLE V
TDS VALUES AT END OF PRIOR CYCLES AND BASIC CYCLES FOR ASR WELLS

ASR well	Initial TDS value	TDS at end of prior cycles	TDS at end of basic cycles
ASR well 2	3000 mg/L	450 mg/L	800 mg/L
ASR well 3	3000 mg/L	510 mg/L	760 mg/L
ASR well 4	3000 mg/L	500 mg/L	800 mg/L
ASR well 5	3000 mg/L	600 mg/L	1200 mg/L
ASR well 6	3000 mg/L	400 mg/L	760 mg/L
ASR well 7	3000 mg/L	600 mg/L	1150 mg/L
ASR well 8	3000 mg/L	500 mg/L	1150 mg/L

VI. CONCLUSION

Due to the population growth and increase in the standard living in Kuwait, the demand for freshwater has become extremely high in last two decades. Kuwait depends completely on desalination plants to provide freshwater. Sustainable water management is one of the solutions to reduce the pressure on the desalination plants in Kuwait. Aquifer Storage and Recovery (ASR) is a powerful technique for managing water resources for aquifers that have non-potable water or poor quality water and can be used for seasonal storage and a secondary water resource in time of need. The unused treated wastewater effluent (70% of the total production) from the Sulibiya wastewater plant (one of the biggest wastewater plants in the world) was investigated for injection in a suitable ASR site during the injection phase to create a potable water reserve. Numerical modeling was used to predict and analyze the best scenario for ASR in Kuwait that provides the best water quality in the recovery phase and improves the native groundwater. The produced water from ASR wells in the recovery phase is considered as groundwater and ASR removes the stigma of treated wastewater by injecting the water in the ground and then recoveries it later.

ASR scenario was simulated in Groundwater Vistas software (using the MODFLOW and MT3D groundwater models) for the selected ASR operation site (Kabd area in Kuwait). The first scenario used prior ASR cycles in the first year and basic ASR cycles for 3 years after that. The prior ASR cycles use 3 months of injection then one month of recovery implemented in one year to create a buffer zone between the injected water and native groundwater. The basic ASR cycle has 9 months injection followed by 3 months of recovery The basic ASR cycles are used in this study to determine the recovery efficiency each year. The total daily recovery was 100000 m^3/d from 8 ASR wells with a 77.42 % recovery efficiency. The basic ASR cycle was started one year after the beginning of the ASR operation and used 9 months injection and 3 months recovery.

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