OPERATING PROCEDURES FOR GROUNDWATER AQUIFER'S TRACER TEST PROGRAM IN KUWAIT

M. Al-Senafy[1], A. Al-Khalid, A. Mukhopadhyay, K. Al-Fahad, and Harish Bhandary
Email: msenafy@kisr.edu.kw

ABSTRACT

In the water-starved arid climate of Kuwait, useable (both fresh and brackish) reserves of groundwater constitute a strategic resource. Although desalination provides bulk of the freshwater consumed in the country, the brackish groundwater is heavily exploited for agriculture, animal husbandry, industrial activities and mixing with desalinated water to make it potable. Due to the near nonexistence of direct recharge from rainfall within the limits of the country and withdrawal exceeding lateral recharge of the aquifers (Dammam Formation and Kuwait Group) through flow across the country boundary, the brackish water aquifers are practically being mined. The limited reserve of fresh groundwater has mostly been preserved for emergency use although a minor fraction is produced for bottling. Increasing use of brackish groundwater starting from the 70s, had led to the significant declines in the potentiometric heads in the aquifers in central and southwestern Kuwait. The scarcity of natural water demands that the long-term sustainable exploitation of the aquifers is ensured in Kuwait through proper understanding of the aquifer characteristics, groundwater flow, and quality regime in the country, the interactions among the groundwater in different aquifers and the aquitards especially when the aquifers are being exploited, the sources and age of the groundwater and other related information. The concentration distribution of the natural and environmental tracers (mostly in the form of isotopes) present in the groundwater often helps in deciphering this information. The data can be augmented by the results from tracer tests conducted using injection and sampling wells where artificial tracers like bromide, rhodamine and fluorescein are introduced in the aquifers through injection wells and are recovered either from the same well or from the surrounding wells after some time gap. Operating procedures for collection of the information on the distribution of selected natural tracers in the aquifer units of Kuwait, supplemented by tracer tests using artificial tracers is suggested in this paper. These data and information will be used in the evaluation of the aquifer hydrology, groundwater flow regime, its quality variation and age, which in turn should help in devising an exploitation plan for the aquifer system that should be sustainable in the long term.

Keywords: Dammam Formation, Kuwait Group, Isotope, Hydrology, Groundwater Quality

1 INTRODUCTION

Both natural and artificial tracers have been used extensively in various parts of the world to elucidate the flow path of groundwater through the aquifer system and to measure the flow velocity, hydraulic conductivity and other characteristics like natural attenuation potential of the aquifers. In the context of the proposed study, the role of tracers in the derivation of aquifer characteristics, mapping of the flow paths, and mixing of water from different sources is of main interest.

Kuwait has very limited amount of useable groundwater resource that is currently under severe strain due to its effective mining over the past several decades. Its consumption of brackish water (with total dissolved solids content in the range of 2500-5000 mg/l) has increased at a very rapid rate over the past. Production from the water fields operated by the Ministry of Electricity and Water (MEW) and Kuwait Oil Company (KOC) had jumped from 35.3 Mm3 in 1970 (MEW, 1998) to 142.3 Mm3 (MEW, 2009) in 2008. Brackish water in Kuwait is mainly used for irrigation and landscaping, livestock rearing, construction work, non-potable use in households and for mixing with desalinated water at ratios of up to 10% of the total volume to make the mixture potable. Additionally, the recent withdrawals of groundwater in the farm areas of Wafra and Abdally had been estimated to be 300,000-400,000 m3/d in each of the areas. Since there is practically no direct recharge to the aquifers within the State of Kuwait and the lateral recharge of approximately 67 Mm3/yr (Mukhopadhyay et al., 1994) from Saudi Arabia and Iraq is far less than the withdrawal, there are significant drops in the potentiometric heads in the two aquifers. The long-term sustainable management of this resource that is vital for the continued development of the country and well-being of its population requires a well thought of exploitation strategy that is backed up by accurate and credible field data.

The proposed tracer study is expected to provide the groundwater administrators of the country with the information on the groundwater flow and transport conditions in greater details that will give clearer picture of water movement paths and flow rates within the aquifer system.

2 OBJECTIVES

The objectives of the study will be as follows:

1. To determine the groundwater flow directions, flow rates and aquifer characteristics in the established water fields of Kuwait in greater details than hitherto available.
2. To update the conceptual hydrogeological model of Kuwait for use in supporting the decision making process on sustainable groundwater management and development in Kuwait

3 HYDROGEOLOGY

In Kuwait, useable groundwater (salinity < 5000 mg/l) occurs in the aquifers of the Dammam Formation and the Kuwait Group. The recharge in these aquifers from rainfall mainly takes place outside the territory of Kuwait in Saudi Arabia and Iraq. The regional setting suggests that the groundwater flows from these recharge zones toward the north and east, and becomes more saline as it reaches the discharge zone along the coast of the Arabian Gulf. The Gulf is underlain by a static body of saline water of very high total dissolved solids (TDS) content (≥ 150,000 mg/l). Kuwait is situated in the northwestern corner of this discharge zone.

Due to the higher TDS (a minimum of 4000 mg/l), hydrogen sulfide (H2S) content and low productivity (transmissivity in the upper part of the aquifer around 40 m2/d in the southwestern part of the country), the Umm Er-Radhuma Aquifer is not exploited in Kuwait (Omar et al., 1981).

The anhydritic Rus Formation and the basal shales of the Lower Members of the Dammam Formation act as an aquitard in Kuwait, separating the underlying Umm Er-Radhuma Aquifer from the Dammam Aquifer. The lithology, petrophysical characters (porosity and permeability) and distribution of the lost circulation zones suggest that the Upper Member, and possibly the Middle Member constitute the main aquifers in the Dammam Formation (Al-Awadi and Mukhopadhyay, 1995). Because of its karstic nature, the transmissivity in the Dammam Formation is variable, especially in the south and southwestern parts of Kuwait. But, it shows a general decreasing trend toward the north and east.

The silicified topmost part of the Dammam Formation, in conjunction with the basal shaley/clayey layers of the Kuwait Group, forms an aquitard that separates the Dammam Aquifer from the overlying Kuwait Group Aquifer, although hydraulic continuity is maintained possibly through fractures that are present in the top part of the Dammam Formation.

The undifferentiated Fars and the Ghar Formations of Kuwait constitute the main Kuwait Group Aquifer. A sandy-shaley unit that acts as an aquitard divides this aquifer into two units such as: upper and lower. The lower aquifer is semi confined in nature, and the upper aquifer is unconfined in the central and southern parts of the country. The total transmissivity of the Kuwait Group Aquifer increases from southwest (10 m2/d and less) to northeast (1500 m2/d and more) with the increase in saturated thickness in this direction (from 0 to 400 m).

The Dibdibba Formation that overlies the Ghar and the Lower Fars Formations in the northeastern parts of Kuwait, to the northwest of Kuwait Bay, forms the uppermost aquifer of the Kuwait Group. A shaley unit separates the aquifer from the underlying main Kuwait Group Aquifer. The aquifer is unconfined. Within the confines of Kuwait, the transmissivity of the aquifer increases from about 10 m2/d in the areas adjacent to Kuwait Bay to 150-200 m2/d in the northeastern corner of the country. In the Raudhatain freshwater field, the transmissivity of 800 m2/d or higher for this aquifer has been measured by Senay (1977).

In the areas occupied by the topographic depressions of the Ar-Raudhatain and Umm Al-Aish areas, occasional rainstorms during the winter give rise to freshwater ponding that infiltrates downward, and in turn, has created the freshwater lenses floating over the brackish water in the freshwater fields of Ar-Raudhatain and Umm Al-Aish.

4 SELECTION OF TESTING SITES

The aim of the study will be to characterize the aquifers and define the groundwater flow characteristics over the established water fields of Kuwait in greater details than what has been hitherto possible. Maximum effort will be made to utilize the available water wells in the established water fields for this purpose. Where such wells are not available or not in working conditions, new wells may need to be drilled for the tracer testing purpose. Large areas in the western and northern parts of Kuwait are devoid of any working wells, and so is the case for the southeastern parts of the country. These areas are however important because as has been stated earlier, most of the groundwater inflow takes place across the western border of the country, and the water is discharged in the coastal parts to the east. So, a few wells may need to be drilled in these areas to carry out tracer tests to characterize the aquifers in such areas adequately.

For the established water fields in the central and southwestern parts of Kuwait, mostly the existing wells (both production and monitoring) will be used for tracer tests to decipher the aquifer properties and current flow regime in the brackish water fields of Kuwait. Five to six such sites will be selected for this purpose where four to five wells will be utilized for the test at each site. At least, one tracer test involving the existing production and monitoring wells will be carried out in the freshwater field of Raudhatain in north Kuwait. It is hoped that the test will help in better definition of the aquifer units in this area, and further elucidation of groundwater recharge and flow conditions that have given rise to this strategic reserve of freshwater. One such test may also be conducted in the Umm Al-Aish freshwater field if suitable combination of injection and observation wells is available. One or two tracer tests may also be conducted in Kuwait City area if suitable wells are available. The tests should clarify the groundwater flow conditions in the urban areas and help in controlling the water level rise and the problem of hydrogen sulfide in the dewatering water. Possible sites for conducting tracer tests are indicated in Fig. 1.

The rationales behind the selection of these sites are as follows:

- Site A-01: To determine the current flow system within the Abdally farm area where groundwater withdrawal and irrigation for farming are both affecting the aquifer system.
- Site A-02: To determine the current flow system within the freshwater aquifer of the Raudhatain field.
- Site A-03: To determine the current flow system in the aquifers underlying the wadi system of North Kuwait.
- Sites A-04, A-05, A-09, A-13 and A-14: To determine the flow paths and lateral recharge rates through the aquifer system across the political boundary of Kuwait.
- Sites A-06, A-10 and A-12: To determine the current flow paths and inter-aquifer exchange rates within the zone of influence of the brackish water fields of Kuwait.
- Sites A-07, A-08, A-11 and A-15: To determine the discharge paths and discharge rates from the aquifer system to the Arabian Gulf.

The actual locations of the sites will be determined based on the hydrogeological knowledge of the area, presence of already existing wells (both production and monitoring) and operational considerations.

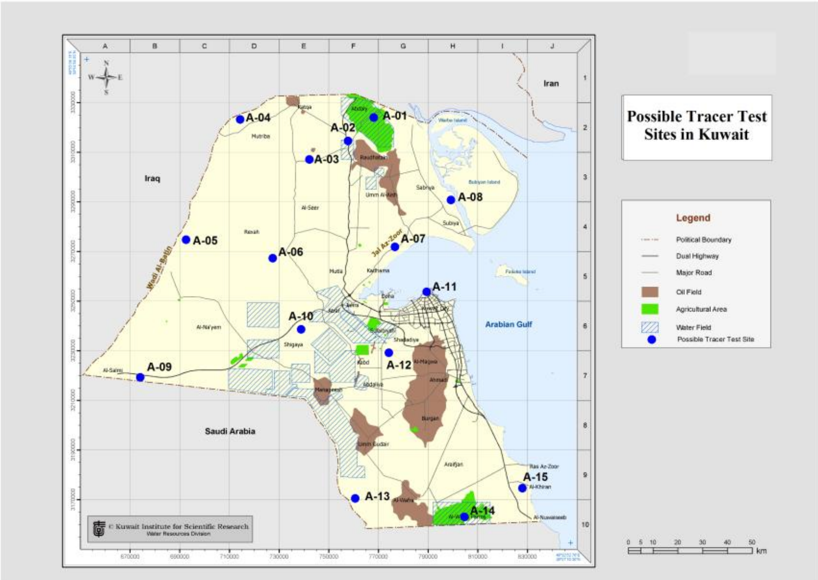

Figure 1. Possible locations of tracer test sites in Kuwait.

5 TRACER TESTS

Tracer tests are the most reliable methods for establishing flow trajectories and hydrological connections in an aquifer system, leading to the determination of hydraulic and geometric parameters. An ideal tracer should have the characteristics as follows:

Nontoxic to the handlers, to the ecosystem, and to consumers of the labeled water,

Soluble in water with minimum effect on its density;

Neutral in buoyancy, and in the case of particulate tracers, sufficiently small to avoid excessive losses by natural filtration,

Unambiguously detectable in very small concentrations,

Resistant to adsorptive loss, cation exchange, photochemical decay, and quenching by natural effects such as pH change and temperature variation;

Susceptible to quantitative analysis;

Quick to administer and technologically simple to detect; and

Reasonably inexpensive and easily obtainable.

Depending on the field conditions and specific objectives of the tests, various types of arrangements of injection and monitoring wells and natural or artificially induced hydraulic gradient conditions are used in conducting tracer tests. The hydraulic gradient conditions can be of types as follows:

- Natural gradient,
- Forced gradient (created by employing extraction well),
- Injection/withdrawal (injection well rate = pumping well rate),
- Recirculation (injection well rate = pumping well rate while recirculating the tracer back to the injection well).

For the success of a tracer test, these conditions should be met as follows:

- Release of sufficient, but not excessive tracer for a reliable detection,
- Appropriate initial sample collection time, and
- Subsequent sampling frequency.

The aforementioned conditions are dependent on the following:

- Volume of water that dilute the tracer,
- Hydrologic conditions during high flow and low flow periods,
- Residence time,
- Number and direction of discharge points,
- Transport distances,
- Sorption,
- Decay, and
- Degree and type of pollution.

Therefore, it may significantly differ from site to site, or at the same site at another time. The planning for a successful tracer test should thus involve the following:

- Formulation of a conceptual design of the test involving review of available hydrogeologic information about the site, setting of the objectives of the test, selection of the type of the test, and the tracer to be used as dictated by cost-benefit analysis.
- Determination of the optimum tracer mass to be used based on measurements or estimates of discharge, transport distance, and likely transport time.
- Determination of the optimum location of the injection well and its construction that depends on the hydrogeologic conditions and length of tracer application (slug test or continuous injection).
- Determination of the optimum location of the monitoring wells and their construction that depends on the hydrogeologic conditions and the test type (recirculating or not).
- Drawing of sampling schedule based on the type of the test (instantaneous or continuous tracer injection), initial mass of the tracer injected, estimated time of the first arrival of the tracer at the monitoring site, and the tracer detection limit.
- Monitoring of tracer concentration in real time as soon as a sample is collected to guard against sample deterioration with time.

Care will be taken in employing artificial tracers that will have the least or no adverse health and environmental effects, and at the same time will be easily soluble in water, and conservative as these pass through the aquifers. Bromides and iodides have proven track records in this regard (Hess et al., 2002; Rugh and Burbey, 2008), and one of them (preferably sodium bromide) will be used in the field tests. Fluorescein may be used as a second tracer, because of its conservative nature in moderately saline water and ready availability, although Na-Naphthionate should be a better option because of its conservative nature in water of all salinity (Magal et al., 2008). Bromide has no adverse health or environmental effects. Fluorescein is widely used in ophthalmology and optometry as a diagnostic tool. Intravenous or oral fluorescein is used in fluorescein angiography in research and to diagnose and categorize vascular disorders. It may, however have adverse health effects (mostly nausea) when used topically, orally or is administered intravenously. With proper precautions however, fluorescein can be safely used as a tracer, and there are many instances where it has been used without any problem.

The tracer tests that are normally used in the field had been categorized by Reimus and Robinson (2004) as follows:

– Single well injection and withdrawal tests
– Multiple well tests
– Forced gradient
– Convergent
– Divergent
– Dipole
– Natural gradient

The different types of tests are presented schematically in Fig. 2. As explained earlier, tracer tests are used to derive information on groundwater velocity, its flow direction, effective aquifer flow porosity, hydraulic conductivity, and dispersion, diffusion, retardation, and desorption characteristics of the chemical components in water (Morales et al., 2007; Tiedeman and Hsieh, 2002; Hess et al., 2002).

There are several possible setups for conducting the tracer tests. One of these setups is presented schematically in Fig. 3. The intervals for sampling the observation wells will depend on the initial concentration of the tracer, the distances of the wells from the injection well, existing lateral and vertical hydraulic gradients (natural in the case of natural gradient tests and imposed in the case of forced gradient tests) and available knowledge about the hydraulic conductivity of the aquifers and the intervening aquitards. In general, sampling will be carried out at close intervals (in terms of minutes and hours) till the breakthrough of the tracer in the observation wells after which the sampling intervals will be longer (from every few hours to daily) till either the background conditions are restored in the observation wells (in natural gradient tests) or the tracer concentration stabilizes (in forced gradient tests).

It is estimated that up to about 3000 samples will be collected from a maximum of 15 tracer tests, and for each sample, the concentrations of at least two tracers will need to be determined. Approximately 300-400 duplicate samples will be collected and sent to laboratories for tracer content analysis for the verification purposes.

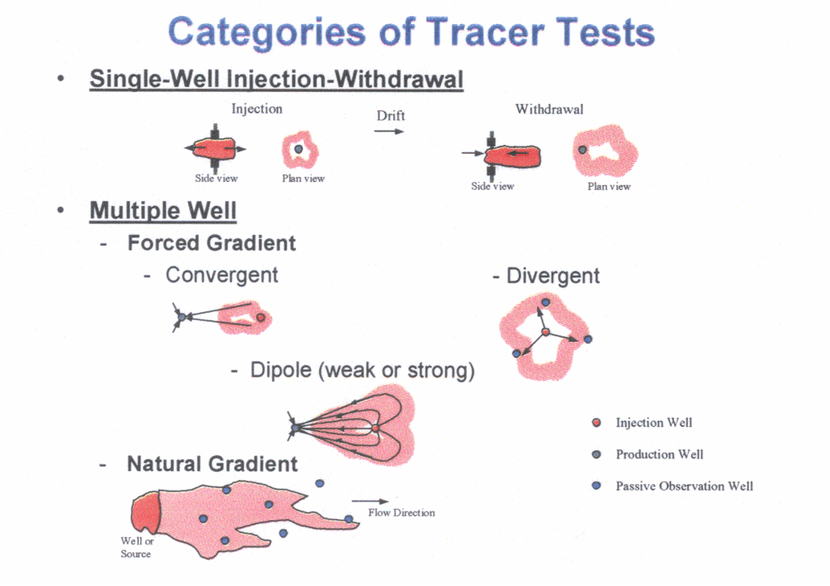

Figure 2. Categories of tracer tests (Source: Reimus and Robinson, 2004).

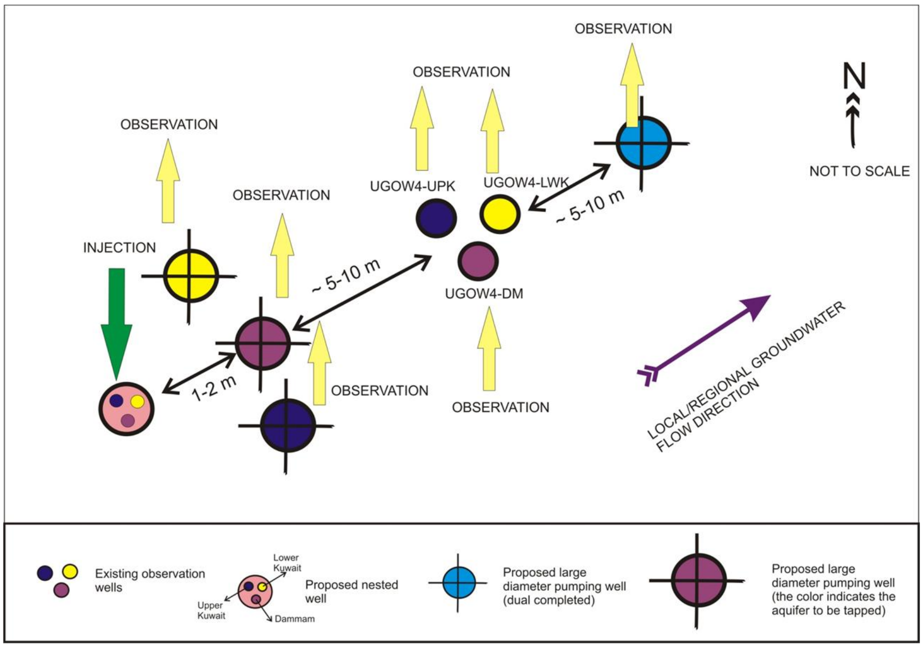

Figure 3. Schematics of natural gradient tracer test

6 EXPECTED OUTPUTS

The outputs expected from this study are as follows:

- The knowledge on the groundwater flow directions, flow rates, and aquifer characteristics in the established water fields of Kuwait in greater details than hitherto available.
- An updated conceptual hydrogeological model of Kuwait for use in supporting the decision making process on sustainable groundwater management and development in Kuwait.

7 ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Kuwait Foundation for the Advancement of Sciences (KFAS) for partially funding the project. The constant support and encouragement of the management of Kuwait Institute for Scientific Research (KISR) is gratefully acknowledged. The authors would also like to express their thanks to the contributors of the study for their efforts in preparation of this paper.

REFERENCES

Al-Awadi, E. A. and Mukhopadhyay, A. (1995) Hydrogeology of the Dammam Formation in Umm Gudair area, Kuwait. In *Proceedings of International Conference on Water Resources Management in Arid Countries*, Muscat (Sultanate of Oman) 12-16 March.

Hess, K. M., Davis, J. A., Kent, D. B. and Coston, J. A. (2002) Multispecies reactive tracer test in an aquifer with spatially variable chemical conditions, Cape Cod, Massachusetts: Dispersive transport of bromide and nickel. *Water Resources Research* 38(8), pp.361-3617.

Magal, E., Weisbrod, N. , Yakirevich A. and Yechieli Y. (2008) The use of fluorescent dyes as tracers in highly saline groundwater. *Journal of Hydrology* 358(1/2), pp.124-133.

MEW. (1998) *Statistical Year Book*: Water. Ministry of Electricity and Water, Kuwait.

MEW. (2009) *Statistical Year Book*: Water. Ministry of Electricity and Water, Kuwait.

Morales, T., Fdez. de Valderrama, I., Uriarte. J. A., Antigüedad, I. and Olazar, M. (2007) Predicting travel times and transport characterization in karst conduits by analyzing tracer-breakthrough curves. *Journal of Hydrology* 334(1-2), pp.183-198.

Mukhopadhyay, A., Al-Sulaimi, J. and Barrat J. M. (1994) Numerical modeling of ground-water resource management options in Kuwait. *Ground Water* 32(6), pp.917-928.

Omar, S. A., Al-Yacoubi, A. and Senay, Y. (1981) Geology and groundwater hydrology of the State of Kuwait. *Journal of Gulf Arabian Peninsula Studies* 1: pp.5-67.

Reimus, P. W. and Robinson, B. A. (2004) Characterization of groundwater using nonreacting and reacting tracers. Paper presented in Identifying Technologies to Improve Regional Water Stewardship: *A Conference Series Featuring Intersections of Technology and Water Management North-Middle Rio Grande Corridor,* Albuquerque, (New Mexico), 21-22 April.

Rugh, D. F. and Burbey, T. J. (2008) Using saline tracers to evaluate preferential recharge in fractured rocks, Floyd County, Virginia, USA. *Hydrogeology Journal* 16(2), pp.251-262.

Senay, Y. L. (1977) Groundwater resources and artificial recharge in Rawdatain water field. Groundwater Section, Ministry of Electricity and Water, Kuwait.

Tiedeman, C. R. and Hsieh P. A. (2002) Evaluation of longitudinal dispersivity estimates from forced-gradient tracer tests in heterogeneous aquifers. *IAHS-AISH Publication* 277, pp.168-174.