

Isotope Applications in the Study of Processes and Dynamics of Groundwater Salinization

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Abstract

Naturally occurring stable isotopes of Oxygen and Hydrogen (^{18}O and ^2H) are often indicators of the origin (genesis) of groundwater, and they can be used effectively in identification of salinity sources and/or differentiation between various processes that may be involved in groundwater salinization. The stable isotopic composition of sea water is significantly different to that of freshwater resources and provides a conservative label for tracing of sea water mixing with groundwater. Furthermore, evolution of stable isotopic composition of groundwater due to different salinization processes (i.e mineral dissolution, leaching of salt formations, re-cycling of irrigation water, etc.) exhibit characteristic features as a means of studying salinization processes.

Environmental radioactive isotopes of ^3H and ^{14}C , with their known time-dependent input concentrations in groundwater systems, facilitate investigating the dynamics of the water salinization and estimating relevant time-parameters involved.

The paper summarizes basic concepts of natural isotope applications for the above purposes and provides summary results from isotope field investigations conducted by the IAEA in the West Asia region related to groundwater salinization.

Introduction

Methodologies based on the use of isotopes in a wide spectrum of hydrological problems encountered in water resources assessment, development and management activities are already an established scientific discipline recognized as "Isotope Hydrology".

During the last three decades, the International Atomic Energy Agency (IAEA) has been directly involved in efforts directed towards research and development of isotope techniques in water sciences, their actual field applications, and has acted as an international scale focal point for dissemination of information and promoting their wider scale use, within the framework of its activities related to peaceful nuclear applications.

Contributions of isotope methods in water resources can be grouped into the following general categories:

- **Determination of physical parameters** related to flow, its dynamics and structure of the hydrological system,
- **Process Tracing** - delineation of processes involved in circulation of water and mass transport of dissolved constituents,

- **Identification of origin (genesis)** of water,
- **Component Tracing** - determination of pathways and mixing ratios of component flows,
- **Study of "Time-scale"** of hydrological events.

Isotopes that are naturally produced and incorporated into the hydrological cycle, are referred to as "Environmental Isotopes". Temporal and/or spatial variations of concentration of these isotopes in the hydrological cycle cannot be controlled and they are governed by natural processes.

Natural isotopes commonly employed for hydrological applications are the heavy isotopes of the elements oxygen (^{18}O); hydrogen (^2H - deuterium, ^3H - tritium); and carbon (^{13}C , ^{14}C -radiocarbon). Of these, ^{18}O , ^2H and ^{13}C are stable isotopes; whereas ^3H and ^{14}C are radioactive, with half-life values of 12.43 and 5730 years, respectively [1]. Spatial and/or temporal variations of stable isotopes in hydrological systems are the result of isotope fractionation that accompanies physical, chemical and biological processes taking place in nature. Variations of ^{18}O and ^2H are mainly governed by isotopic fractionation during evaporation and condensation processes, so that water molecules with different isotopic species are preferentially removed from one phase to another due to differences in their partial vapor pressures. Consequently, freshwater exhibits stable isotope content governed by the history of its origin and processes during its formation [2]. The isotopic changes thus induced, are a conservative property of the water. Radioactive isotopes of ^3H (tritium) and ^{14}C (radiocarbon), with their known input concentrations in the hydrological cycle (both natural and anthropogenic origin) also provide a label for different water bodies. The unique radioactive decay property of these isotopes, particularly of radiocarbon with a steady-state input concentration, also facilitate time-domain estimation to be made of the physical parameters related to circulation dynamics of water in hydrological systems, and particularly in groundwater.

Specific types of information that can be obtained from applications of natural isotopes in groundwater systems are:

- system boundaries, hydraulic discontinuities and stratification,
- origin (genesis) of water and hydraulic interconnections between surface and groundwater or between different aquifer units,
- process and rate of replenishment of groundwater,
- source and process of groundwater salinization and its dynamics,
- travel times involved in groundwater flow, covering a time scale of up to 40 000 years,
- parameters related to mass transport characteristics.

Isotopic composition of oceans are rather uniform, and they exhibit slightly enriched concentration of stable isotopes (^{18}O and ^2H) as a result of surface evaporation which preferentially removes heavier isotopic species into the vapor phase. Freshwater derived from precipitation will always have lower stable isotopic composition than that of sea water. The tritium content of sea water is in the range of 10-20 Tritium Units (TU) in the northern hemisphere and around 5 TU in the southern

hemisphere. (1 TU corresponds to a concentration of one tritium atom per 10^{18} atoms of Hydrogen). Average radiocarbon (^{14}C) concentration of ocean water was about 85 pmc (percent modern carbon) prior to the thermonuclear period (1953-1963) and about 95 pmc at the ocean surface. (radiocarbon concentration is expressed as percent of pre-industrial radiocarbon concentration of the atmospheric CO_2 defined as 100 %). Groundwater concentration of both these isotopes, however, may be much higher or lower than the sea water concentration, governed by the distribution of travel times in the system. Most of the paleowaters encountered in regional coastal aquifer systems, and particularly deep confined aquifers in arid and semi-arid regions, will not contain any tritium and will exhibit rather lower concentrations of radiocarbon.

Isotope applications in groundwater salinization

Temporal and spatial variations of the above cited natural isotopes and the significant difference often encountered between the isotopic concentration of sea water and groundwater, together with characteristic isotopic evolution patterns associated with different salinization processes provide an effective tracing tool for investigating water salinization sources, processes and dynamics. Basic characteristics related to evolution of stable isotopic concentrations for sea water-freshwater mixing and other salinization processes are schematically shown in Fig.-1 as ^{18}O and ^2H relationship, which forms the basis for stable isotope applications for this purpose.

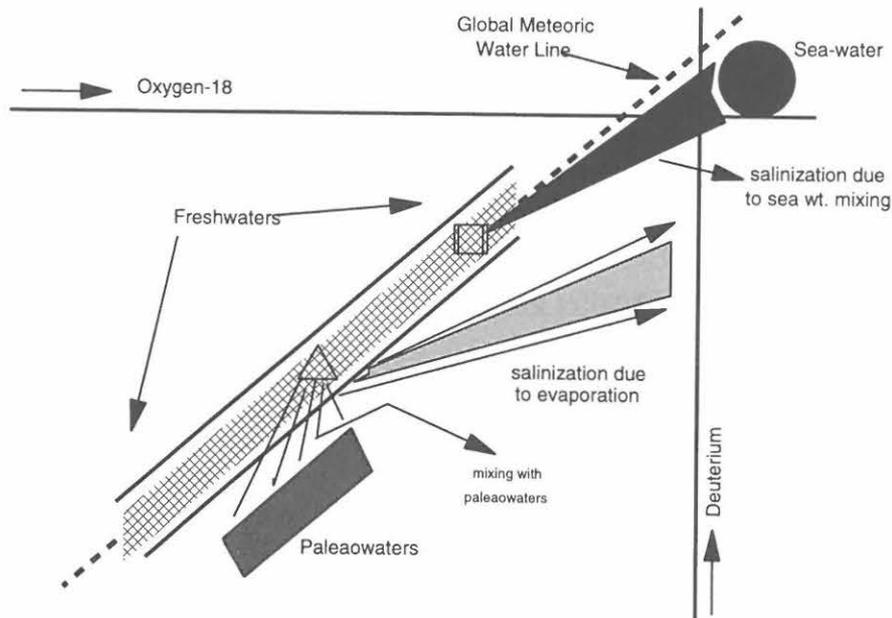


Figure-1. Evolution of stable isotopic composition of water for different water salinization processes

In studies dealing with water salinization, it is often more appropriate to consider both the isotopic and chemical evolution. Chloride ion concentration is often used as indicator of salinity, as it is one of the most conservative tracer in this regard. Such an approach will provide the basis for distinction to be made of different salinization processes. Typical relationships between stable isotope composition and salinity for different salinization processes are shown in Fig.-2. In the case of

salinity increase due to mineralization resulting from water-rock interactions (dissolution) or leaching of salt formations, stable isotope content of the water is not affected while the salinity of water increases.

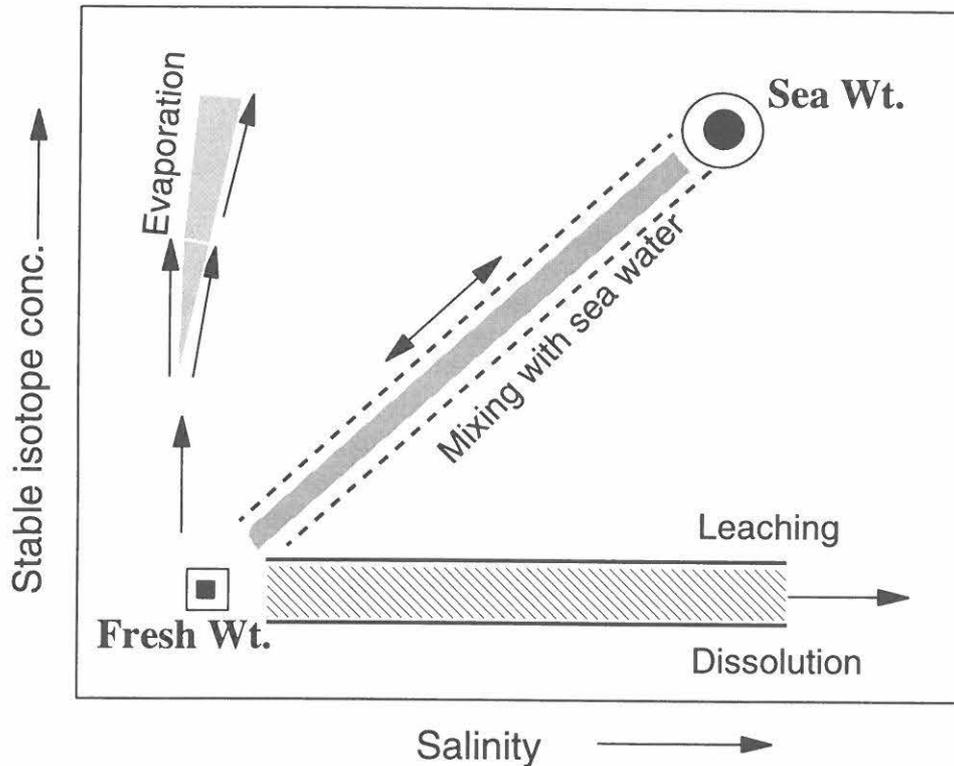


Figure-2. Relationship between stable isotope and salinity for various salinization processes

Example of application to a regional aquifer system

IAEA has been implementing isotope field investigations in the major aquifer systems of West Asia region with the aim of investigating the causes and sources of increasing salinity of groundwater. Existing data on the replenishment rates compared to the water extraction rates in most of the major groundwater resources of this arid region indicate substantial over-exploitation of the resources with resulting increase in groundwater salinity [3]. While direct sea-water encroachment due to over-exploitation is the main process occurring at coastal aquifer systems, increased salinity in inland aquifers should be due to induced leakage of brackish water in the underlying deeper aquifers or displacement of saline formation waters existing in the system due to induced hydraulic conditions through exploitation. Main geological features of the aquifer systems in the West Asia region are shown in Fig-3 [4], and the range of salinity observed in the aquifers being extensively exploited are given in Table-1 [3].

Long-term mean (weighted by amount) value of the stable isotopic composition of precipitation from selected meteorological stations in the region [5] as an indicator of the expected isotope composition of groundwater replenished under present climatic conditions together with the stable isotopic concentration of sea water in Mediterranean Sea and Persian Gulf are given in the ^{18}O - ^2H plot of Fig-4. Since the expected isotope content of groundwaters in the region is significantly different than that of the sea water (Fig-4), survey of isotope content in the aquifer systems would enable the

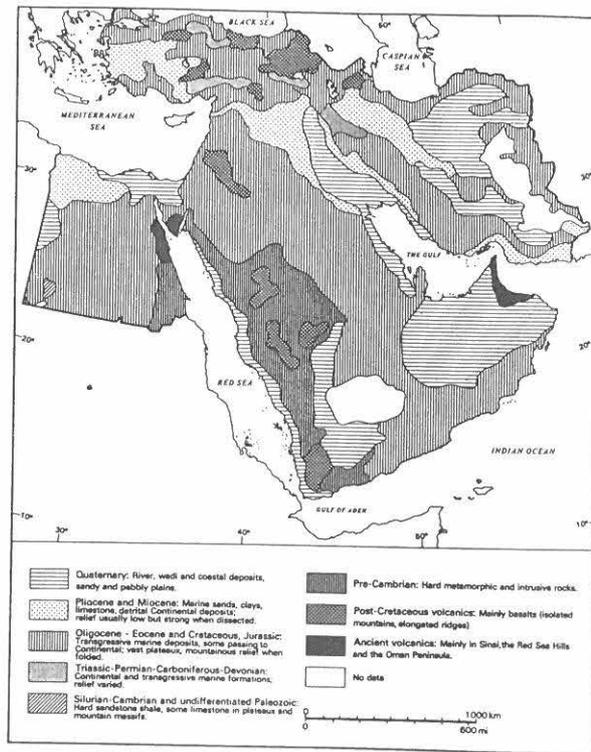


Figure-3. Geological settings of main aquifer systems in West Asia

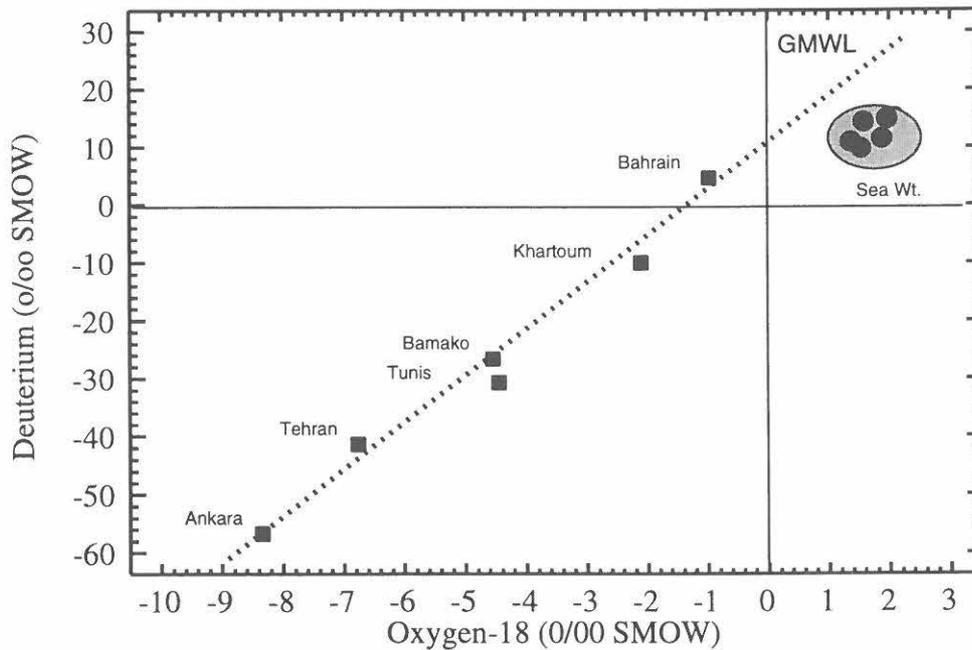


Figure-4. Long-term mean values of isotopic composition of precipitation in the region and isotope concentration of Mediterranean sea and Persian Gulf

Table-1 Present salinity levels in major aquifers in the region

COUNTRY	Brackish Water Location	Aquifers	Depth to Aquifers from ground (m)	Total Dissolved Solid (TDS-ppm)
Bahrain	Main Island of Bahrain	Khober	30-39	2200-8400
Egypt	Bahr El Baqar Sinai	Nubian Sandstone	200-300	1000-7000
Lebanon	Coastal regions	Recent Alluvium	5-10	1000-3000
Jordan	Jordan valley Azraq W.Dhuleil Wadi Araba	Alluvium Belqa-B2 Basalt Alluvium	0-100 10-50 10-60 30-70	> 5000
Kuwait	Soleibeyah Shagayah Wafra Abdali	Kuwait Gr. Khobar Umm Er Rhadu.	30-100	2800-5300
Qatar	Northern prov. Southern Prov.	Rusait Umm er Rhadu.	20-80	2000-2500
Saudi Arabia	Al-Qatif Hufuf Wadi Al-Mish Al-Quawayah Rus-south	Khobar Umm er Rhadu. Saq Khuff Wadi Alluvium	130 240-350 170-325 90-170 40-70	2450 2500-10 000 2000-10 000 2000-57 000

study of the sources/causes of increased salinity.

Data obtained from such a survey conducted in the regional aquifer system in Kuwait is presented as an example.

Main groundwater resources in Kuwait are encountered in the Eocene limestone formation of Dammam formation overlain by Mio-Pleistocene Kuwait group shallow aquifers. Three distinct aquifer units separated by aquitards are being exploited since 1960, at steady increasing rate and present extraction rate is around 170 million cubic meter per annum. Quality of groundwater in these aquifer units is generally brackish, with TDS values of 3000 ppm in the south west and gradually increasing towards eastern part, reaching to values around 50 000 ppm near the coast [6]. Groundwater salinity variations in the lower Dammam aquifer is shown in Fig.-5, and the general east-west hydrogeological cross-section is given in Fig.-6. Isotope sampling of wells tapping different aquifer units were carried out to study the genesis of saline waters and their hydraulic interconnections as the possible cause of increasing salinity in the shallow Kuwait group aquifer. The location of sampled wells are shown in Fig.-6.

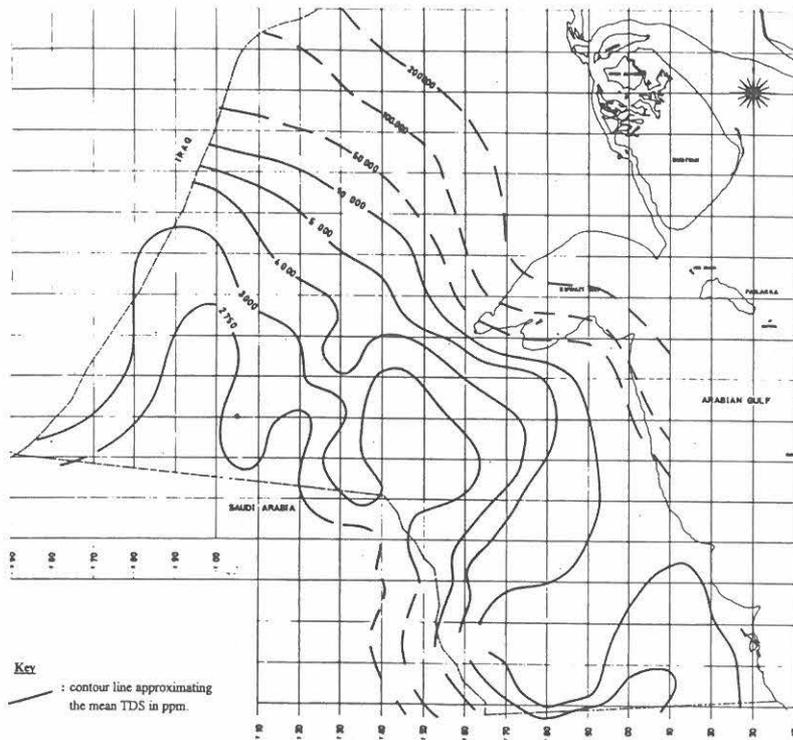


Figure-5. Salinity variations in Dammam aquifer in Kuwait

Results of stable isotope analyses are shown as $18O-2H$ plot of Fig-7, where the isotope content of the Dammam group in Saudi Arabia [7] providing main lateral recharge to the aquifers in Kuwait is also shown. Under present climatic conditions, direct recharge to the upper aquifer from precipitation is minimal, if any. The line representing the Local Meteoric Water line on Fig-6 is derived from the long-term isotope data available on monthly precipitation at Bahrain which has a slope of eight and deuterium excess value (intercept) of $+14.6$ [5].

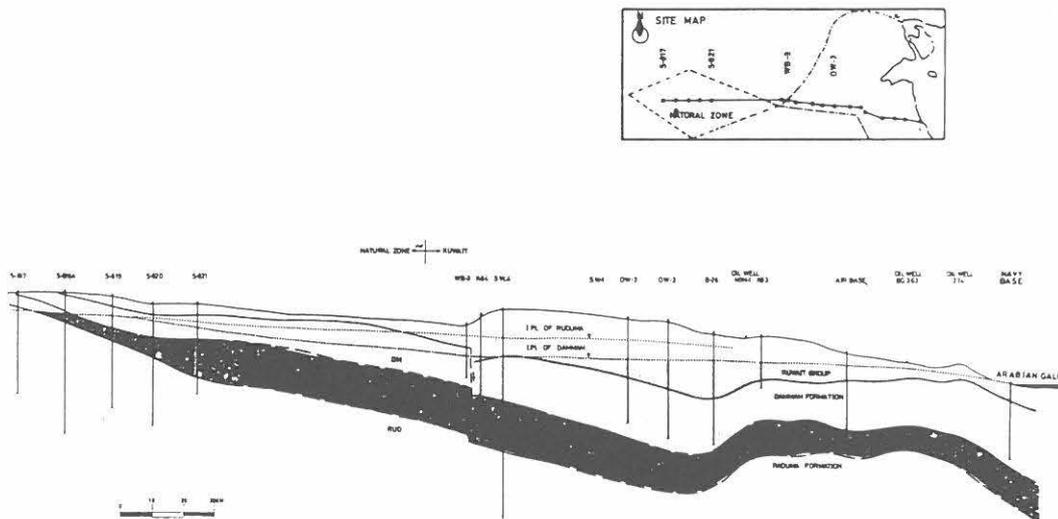


Figure-6. East-West hydrogeological cross-section of the aquifer systems

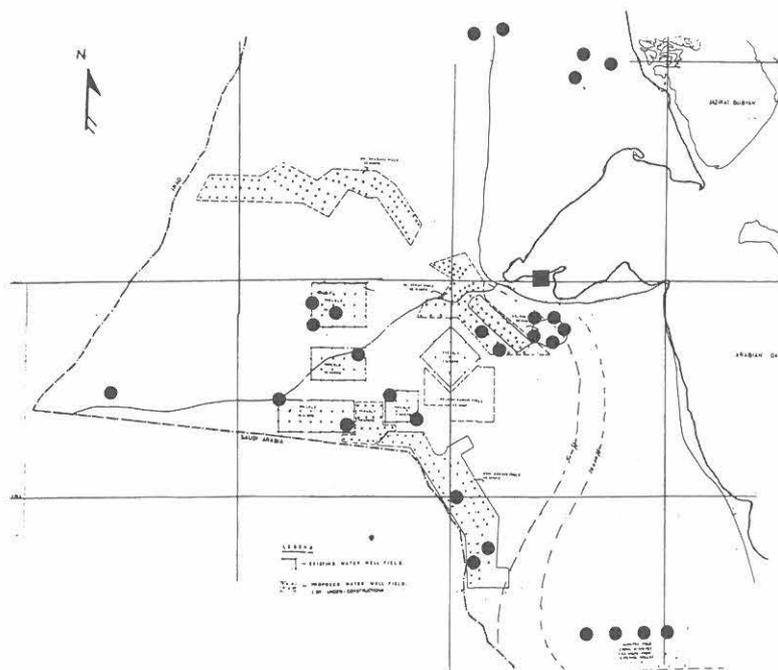


Figure-7. Location of sampled wells in the study area

Stable isotope data of both Dammam and Kuwait Group aquifers (Fig-8) exhibit characteristic features of paleowaters, with lower deuterium excess values as compared to the isotope content expected for meteoric waters under present climatic conditions in the region. None of the sampled wells, except the shallow freshwaters in the northern part, contain tritium. Radiocarbon dating of selected wells indicate the waters to have an age in the range of 17000 to 27000 years. Stable isotope data given in Fig-8, together with the results of radiocarbon dating is clear evidence of the groundwaters within both Dammam and Kuwait Group aquifers to have been replenished during earlier pluvial periods, with very limited replenishment at the present, if any. The least-square regression line calculated for the stable isotope data of the sampled wells (excluding the sea water isotope content in Fig-8) has the following equation:

$$\delta(H-2) = 6.95 * \delta(O-18) - 3.6$$

This regression line, when extrapolated passes very near to the sea water isotope composition, as an evidence of the spread observed in isotope content of the wells to be mainly due to mixing with saline water. It is most probable that, the paleowaters in these aquifers were significantly effected by mixing of sea water which has entered into the aquifers during earlier marine transgression. Thus the mixing line shown in Fig-8 is the result of mixing between saline water intruded into the aquifers and groundwater, at different proportions. Furthermore, the isotope content of Dammam and Kuwait Group aquifers have distinct grouping, and mixing between the two aquifer units at specific locations is evident (Fig-8). Thus, stable isotope data clearly provides information on the genesis of water in the aquifer units which is responsible for the salinity observed, as well as, mixing between two aquifer units to be partly also affecting the salinity distribution.

Salinity versus Oxygen-18 content of the sampled wells are shown in Fig-9, where the above depicted mixing processes are also evident.

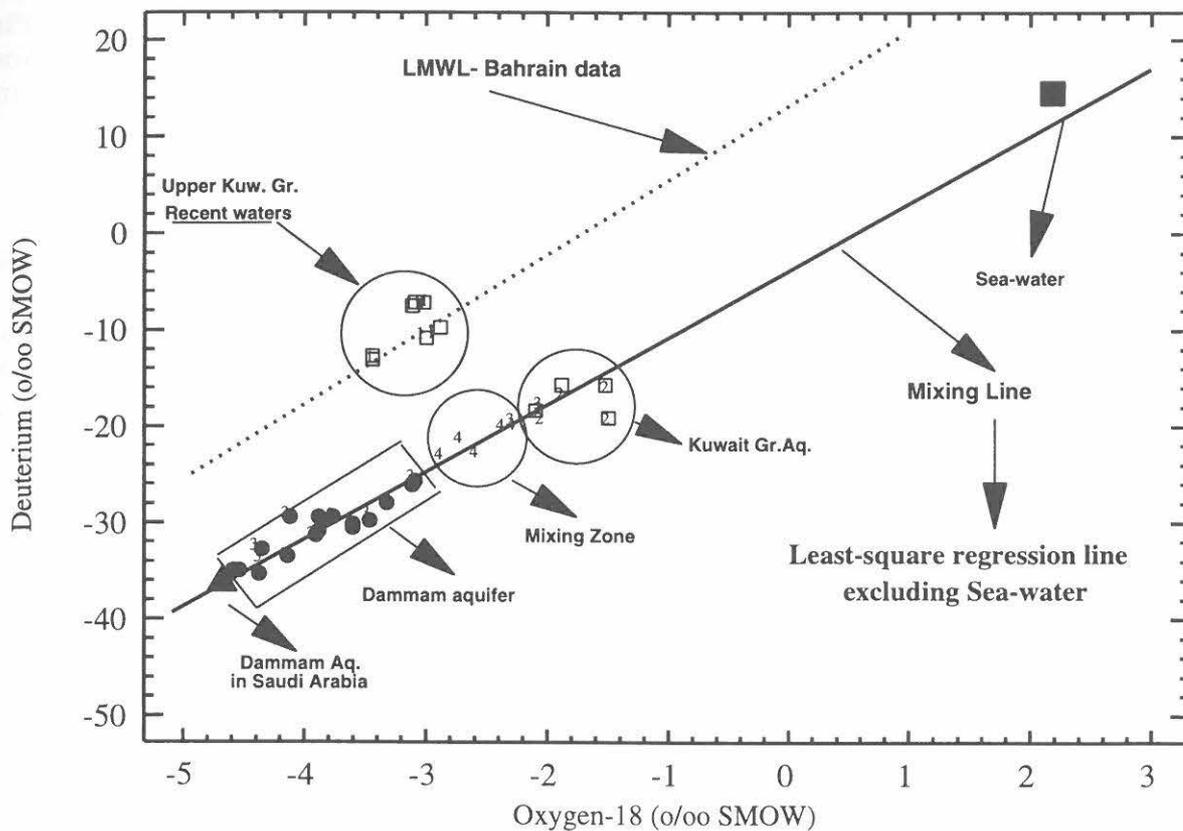


Figure-8. Stable isotope content of sampled wells

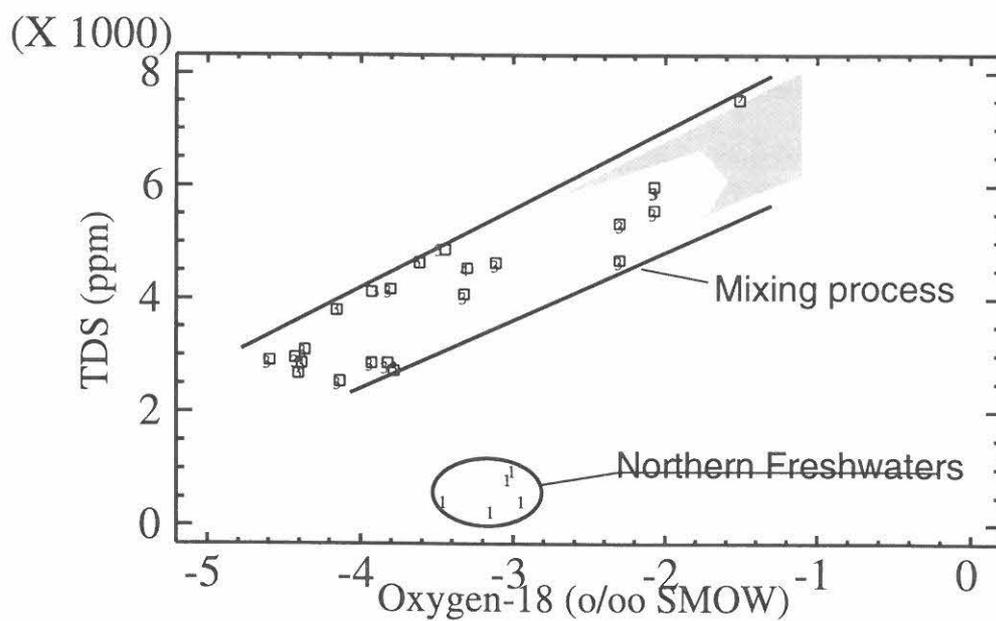


Figure-9. Salinity - Stable isotope relationship for the wells

The example presented above illustrates the capabilities and applications of isotope methodologies to studies dealing with sources, processes and dynamics of salinity in groundwater systems. Similar isotope studies are presently being implemented by the IAEA in major aquifer systems of the West Asia region, where the increasing salinity of groundwater is of major concern.

Acknowledgements:

The results presented from the regional aquifer system in Kuwait are part of the investigations being conducted in the region by the IAEA within the scope of an ongoing regional Technical Cooperation Project. The samples for analyses were collected by the staff of the Groundwater Department of the Ministry of Electricity and Water in Kuwait. Isotope analyses of the samples were undertaken at the Isotope Hydrology Laboratory of the IAEA in Vienna.

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