Recharge and Turnover of Groundwater in Coastal Aquifers with Emphasis on Hydrochemistry and Isotopes

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.73301

Abstract

Coastal aquifers are globally subject to considerable stress. The population density is often high in coastal areas, and in addition, the coastal plains often have good agricultural soils demanding irrigation. While a portion of the irrigation can be provided by rivers, local groundwater is also used adding to the water requirement. Many coastal aquifers are large with a slow turnover of the groundwater and recharge is difficult to assess. This review is aimed at giving an overview of the hydrochemistry with an emphasis of giving insight into the groundwater recharge and the sustainability of the groundwater quality. The past climate history has given an imprint of hydrochemistry of especially coastal aquifers.

Keywords: groundwater, aquifer, coastal, recharge, hydrochemistry, isotopes

1. Introduction

About 1 billion out of 7 billion people in the world live in coastal areas and rely on coastal aquifers for their water supply and irrigation [1]. A simple calculation of the water requirement can be done by assessing that the population density is 2000/km^2, a figure taken from the Kerala coast in SW India. With the proposed population density, each person has an area of 500 m^2 to reside on. The water need is dominated by the water requirement for food production and varies from 2500 l/day and person in developing countries to 5000 l/day in industrialized countries [2]. The water use in households is in the order of less than 200 l/day and person. If using the figure 2700 litres per day and person for total water demand, then this would be equal to a water requirement of around 2000 mm/year or of the same order as the yearly rainfall in the actual area. Thus, even in rather rainfall-rich areas, coastal aquifers are subject to a considerable stress.

Coastal plains are often underlain by thick sediments, and they are complex intercalations of finer and coarser sediments formed under different climatic conditions. Looking back on the recent past climatic history, just a few thousands of years back, there have been large variations in sea level and locally, there have been considerable tectonic movements.

This review will be focused on using the hydrochemistry of the groundwater and isotopes to decipher the groundwater exchange in coastal aquifers. This approach is especially useful in coastal aquifers where salt water intrusion could complicate the picture. In view of the authors' experience, there will be a focus on South and Southeast Asia, however, with some examples from other regions such as Europe.

2. Groundwater recharge

Groundwater recharge can occur in different ways:

- recharged locally by rainwater
- recharged from coastal plain rivers
- being a mixture of intruded saltwater and freshwater

Local groundwater is in many places not sufficient to recharge the aquifers. There are many aquifers in semiarid areas that are overused. Examples are common in S and SE Asia. Megacities with groundwater supply have in several places salinity problems resulting from land subsidence like in Bangkok and Jakarta [3]. In view of the climate change foreseen, there will be increase in sea levels that will affect the balance between groundwater and seawater. Ericson et al. [4] have evaluated 40 deltas regarding the effective sea level rise (ESLR), which in their evaluation is a combined effect of sea level rise and subsidence of the deltas. The Bengal delta in Bangladesh and India is experiencing an ESLR rate as high as 25 mm/year, while the Mississippi delta in USA has a rate of around 10 mm/year. The sea level rise as such is in the order of 3.3 mm/year, and the rate is expected to increase in the coming decades [5]. Ericson et al. [4] estimate that by 2050, about 8.6 M people are at risk due to ESLR. Local conditions such as tectonic movements and land subsidence due to excessive groundwater extraction thus play a large role in the risk of saline intrusion into costal aquifers in coming years [3]. The shoreline displacements may have a variety of reasons such as neo-tectonic movements but also anthropogenic activities such as deforestation and increased erosion [6].

Fog water condensation is a rare mechanism of groundwater recharge, but it may play a limited role under specific conditions. An example is the Al-Qara Mountain behind the Salalah Plain in Oman [7]. The browsing of a large population of camels has caused the degradation of mountain forest and decrease in recharge. The local precipitation is 100 mm, and the fog collection now adds just 10 mm to the recharge.

http://dx.doi.org/10.5772/intechopen.73301

3. Groundwater recharged from rivers

This is a common case. To trace the river water into the aquifer is of interest to assess the recharge. In this case, isotope investigations may be of good use. In some cases, the river water has a specific composition not only regarding water chemistry but also regarding isotopes of some elements. This could be traced in the aquifer mirroring where the river is recharging the aquifer.

With a past history of saline groundwater being refreshed by recharge, there are cases with elevated chloride ratio that could be interpreted as salt water intrusion. If the recharge occurs in a located area giving kind of a piston flow, a sequence of defined water types could be observed. These water types range from a typical fresh water of Ca-HCO_3 type via a Na-HCO_3 type to a brackish mixed type of water. The Na-HCO_3 type is formed by ion exchange, the Na-saturated aquifer material from the saline period, picks up calcium from the fresh recharged water and releases sodium into the groundwater. This is observed in a Tertiary aquifer on the Kerala coast in India [8] and in the Tertiary and Cretaceous aquifers in Tamil Nadu [9] (**Figure 1**).

If the recharge area is scattered, not creating piston flow of recharge, mixtures of water types are found [10, 11].

Elevated chloride levels in the local Kerala Tertiary aquifer [8] were in places caused by diffusion of chloride from intercalated clay beds. Drilling and sampling of sediments, sand, and intercalated clay showed that the pore water in the clay contained elevated salinity with chloride that diffused into the surrounding coarser sediments (**Figure 2**).

This could also be seen by plotting the $\delta^{18}O$ ratio in the water versus chloride. There was no mixing line toward sea water composition, but the $\delta^{18}O$ ratios remained constant irrespective of the chloride concentration (**Figure 3**) (**Table 1**).

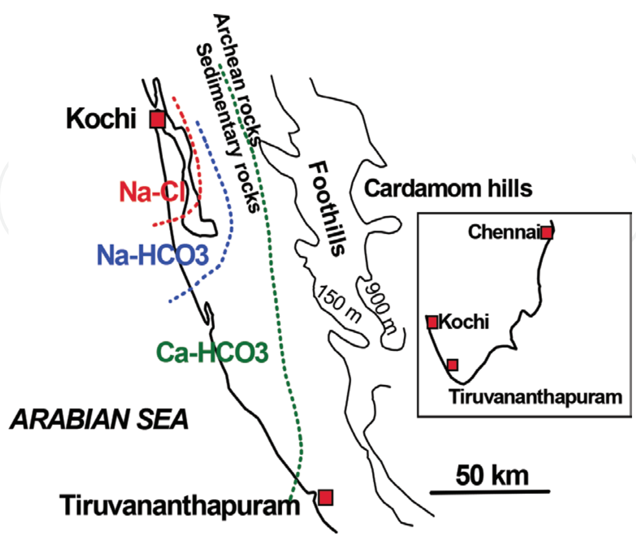

Figure 1. Water types in the Kerala Tertiary coastal aquifer resulting from flushing by recharge before the Last Glacial Maximum. The Precambrian, under-laying the Tertiary strata, are faulted in the SE-NW direction, which also guides the recharge in the same direction.

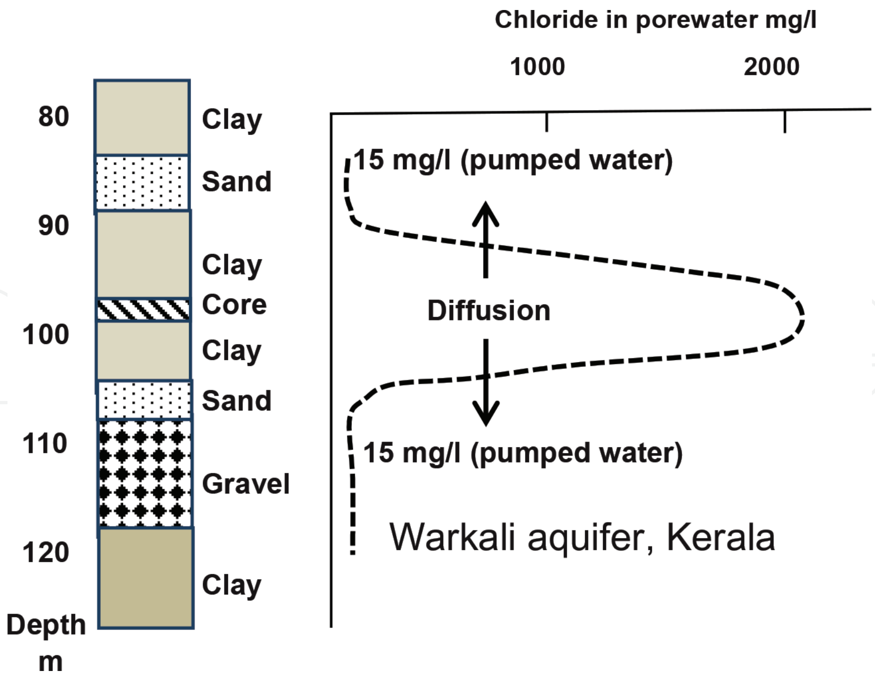

Figure 2. Residual pore water chloride in a clay layer dating back from a previous saline period was found in the Kerala coastal aquifers. The pore water was extracted from the core in the center of the clay layer.

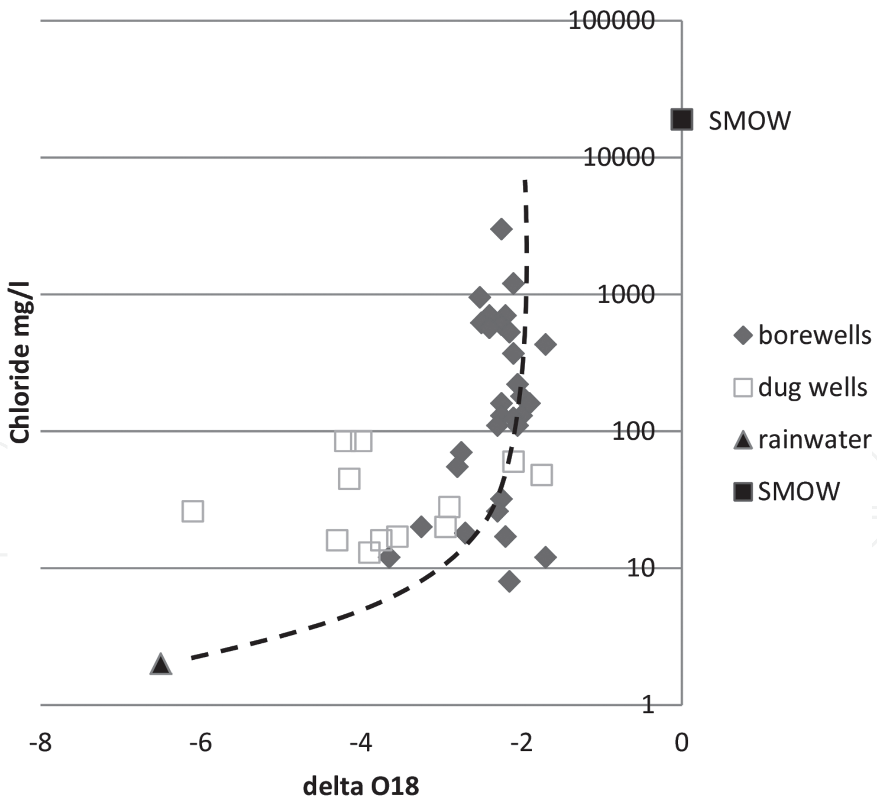

Figure 3. $\delta^{18}O$ ratios in groundwater plotted versus chloride. Data from Kerala coastal aquifers. There is no mixing in of sea water, but the increase of chloride above about 80–100 mg/l is likely to come from pore water in clay layers as is seen in **Figure 2**.

Sample	δD (‰)	$\delta^{18}O$ (‰)	Chloride (mg/l)
1	−44.20	−7.46	4.9
2	−43.85	−7.14	10.0
3	−44.52	−7.36	146
4	−44.83	−7.83	995
5	−48.12	−7.04	76
6	−47.12	−7.75	60.1
7	−43.10	−9.30	1220
8	−46.15	−8.35	392
9	−44.82	−8.22	819
10	−44.32	−8.46	191
SMOW	0.00	0.00	19,345

Table 1. δD and $\delta^{18}O$ in groundwater in Mati Plain in Albania have no relationship with chloride concentration showing that sea water intrusion is not the source of chloride.

The groundwater in Mati coastal plain in the northern Albania serves as water source for about 400,000 people, and there was a concern that this pumping rate may cause salt water intrusion [12]. In the catchment, there are several abandoned and active copper mines and the sulfate in river has an isotopic ratio typical of sulfides. This could be traced over large areas of plain showing that the recharge from the river is good. Close to the seaside, there were elevated chloride and sulfate levels that could be of old sea water origin. The $\delta^{34}S$ ratio was 24‰, thus well over the sea water ratio at 21‰. This can be explained by sulfate reduction in the intercalated clay layers (**Figures 4** and **5**). Thus, sea water intrusion is not a current threat.

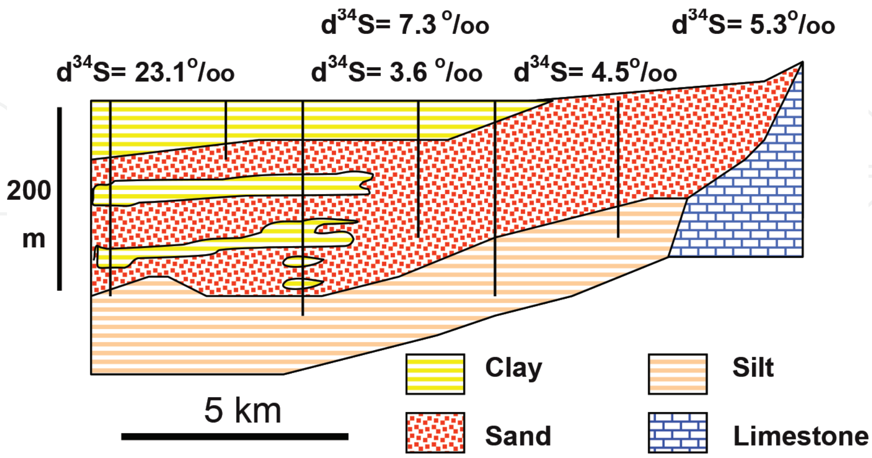

Figure 4. Cross section of the Mati Plain aquifer in Albania with $\delta^{34}S$ ratios in groundwater [12]. In the plain, the $\delta^{34}S$ ratios are mirroring recharge from river Mati, which has a $\delta^{34}S$ ratio mirroring sulfide oxidation in mining areas in the catchment. The left well, close to the seaside, has a $\delta^{34}S$ ratio above the sea water, likely to be caused by sulfate reduction in clay layers.

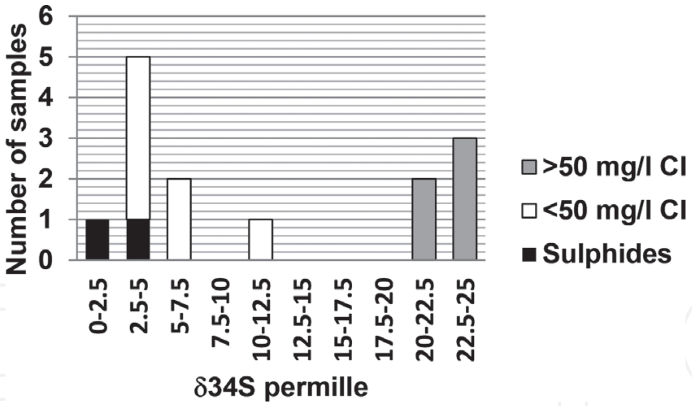

Figure 5. Staple diagram with $\delta^{34}S$ ratios in groundwater indicating recharge from the river Mati with sulfate having sulfide origin from oxidation of waste rock from copper mines [12]. The high $\delta^{34}S$ ratios in sea near wells are above the sea water ratio (21‰), which indicates sulfate reduction in intercalated clay layers. The black bars are samples from copper mine waste in the catchment.

4. Measures to halt sea water intrusion

Where sea water intrusion is already a fact, there are measures to halt it. First of all, groundwater extraction should be diminished. While there are no visible signs of sea water intrusion in the Kerala Tertiary aquifers, there is a gradual development of surface water utilization for the larger towns in the coastal plain, which is a good measure to protect the coastal aquifers. On the Indian east coast, this is more difficult as the river flows are lesser there. Ballykraya and Ravi [13] describe the creation of a barrier by artificial recharge near the coast. A similar measure has been taken in the Salalah plain by well recharge of treated waste water along the coast line [14, 15]. A new approach, which could be more efficient, is when fresh water recharge into the nonsaline part of the coastal aquifer is combined with pumping of saline water near the shoreline [16].

5. Effects of past climate change

The last glaciation has implied large variations in sea level, in the order of 125 m. Several areas that were under the sea level in preglacial time were drained from the sea during the Last Glacial Maximum (LGM).

This could enhance the recharge with fresh water. A Tertiary aquifer on the Kerala coast in SW India has groundwater dates varying between 23 and 34 kA BP (kA BP = kilo-annum, thousands of years before present) [8] and should thus have been recharged just before LGM. This is reasonable as the head for recharge was large, 60–80 m. However, just before LGM, the recharge has obviously been interrupted. In this case, the paleoclimatic conditions seem to have promoted the recharge during a wet SW monsoon which just before LGM was interrupted by a dry monsoon (**Figure 6**).

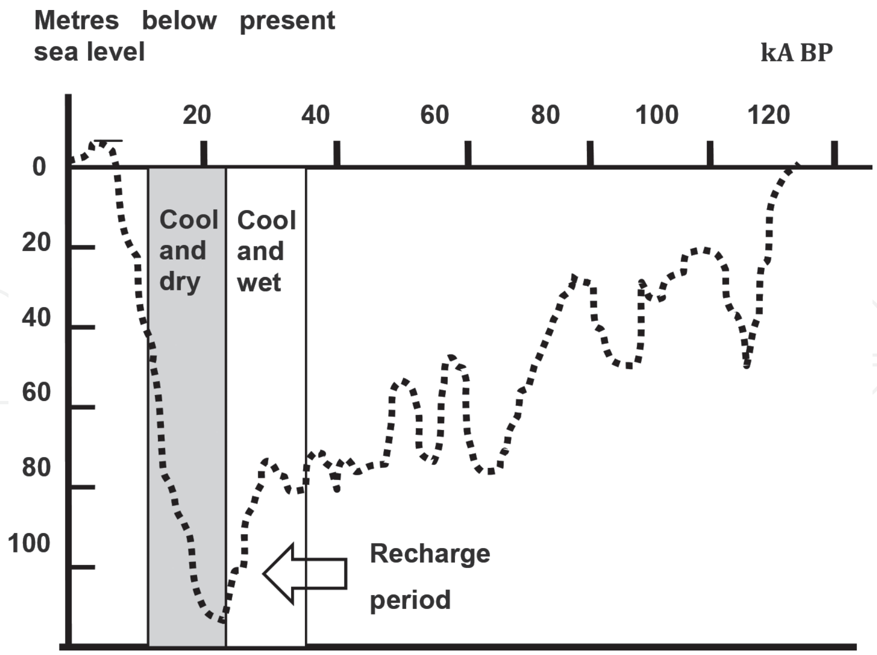

Figure 6. Sea water levels during the last glacial period. The SW monsoon had, as per the abundant paleoclimatological data published, a wet period before LGM followed by a dry period after the LGM.

Other aquifers on the Indian east coast has groundwater of a similar age and the same period and mechanisms of recharge may apply [9, 17]. The paleoclimatic data from India are abundant from both marine sediments as well as local pockets on current land illustrating the variations in the strength of the SW monsoon [18–23].

The past climate change has, in several aquifers near sea, formed a sequence of Ca-HCO_3 → Na-HCO_3 → Na-Ca-Cl types of groundwater formed by flushing of an initially formed saline/brackish aquifer by fresh water [24, 25]. This could be seen laterally in Kerala (**Figure 1**). The direction of the recharge flow is from SE toward NW directed by the topography of the underlying Precambrian, which is likely to be intersected by faults in the same direction. The same zonation is seen depth-wise for instance in the Mekong river delta and in the Red River delta in Vietnam [26].

A secondary effect of flushing is that the softening effect of the process creates Na-HCO_3 type of groundwater (**Figure 7**) which tends to mobilize fluoride [27–30]. Where the recharge is less of a "piston flow" process, there will be more mixed forms of groundwater types. This is often the case on the Indian SE coast where the sedimentology is more intricate [10, 11].

Another effect of the last glaciation is the common occurrence of arsenic in groundwater in Holocene sediment, for instance not only in the Bengal delta [31–36] but also in other coastal plains in S and SE Asia [37–39] like in the Mekong river delta, the Red River delta, and the Irrawaddy river delta. When the sea level was lowered before Last Glacial Maximum (LGM) at around 18 kA before present, the sediments were subject to erosion and redeposition and this lowered the organic matter content [39]. Contrarily, after LGM, the sea level rose and created abundant wetlands rich in organic matter [40]. These sediments become easily anoxic with reduction of ferric oxyhydroxides and mobilization of arsenic into groundwater [41].

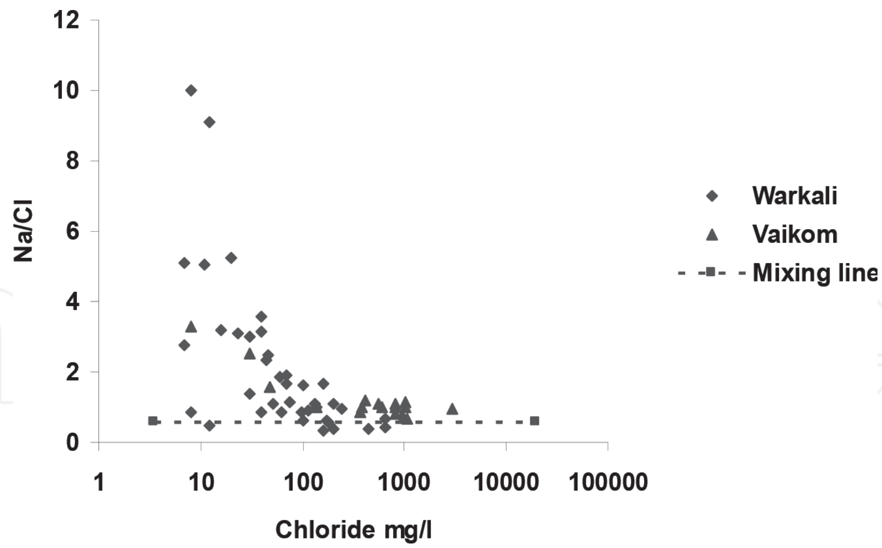

Figure 7. Na/Cl ratios versus chloride, showing the mobilization of sodium during the late stage of fresh water flushing. When the fresh water stage is approached, there is mobilization of sodium creating a Na-HCO_3 type of water often with elevated levels of fluoride.

6. Conclusions and summary

Coastal aquifers and their recharge is a crucial issue for approximately 1 billion people who are living on coastal plains globally. Due to high population density and high water demand for domestic and more so for food production, there is a high stress on the water resources. There are modeling tools that can be used to assess the sustainability of the groundwater in coastal aquifers, but in addition, hydrochemistry and isotopes may be a substantial help in the assessment, especially in costal aquifers where a possible sea water intrusion adds to the complexity. Dating, mostly by ^{14}C methodologies gives reliable results adding to the assessments of the groundwater turnover [42]. For aquifers that that have a past memory of salinity, there may be a good relationship between age and chloride levels, chloride which is retained in parts of the aquifer where groundwater turnover is slower (**Figure 8**). Chloride in this case, as is shown in **Figure 2**, is not derived from salt water intrusion. For shorter turnover rates, tritium is used especially after the bomb tests in the 1960s has faded out [43].

Elevated salt content in coastal aquifers could have many sources in addition to salt water intrusion. A common case is found in coastal aquifers that consist of sand and gravel intercalated with clay layers. As the groundwater turnover is slow, often in the range of thousands of years, there might still be more or less saline pore water in the clay layers that continue to diffuse into the coarser material (**Figure 8**). In some, there is sulfate reduction in the clay due to elevated organic matter content and this is mirrored as elevated $\delta^{34}S$ ratios.

The often intricate mixtures of water and dissolved salt in coastal aquifers could be interpreted by suitable isotopes such as δD, $\delta^{18}O$, $\delta^{34}S$, if different sources of the isotope ratios can be traced back to the source of the water. A good example is $\delta^{34}S$ on a coastal aquifer in Albania where there were two main sources, sulfide-related sulfate from mines and sulfate in the groundwater formed by sulfate reduction in intercalated clay layers in the aquifer. A common feature often formed by flushing in postglacial time of formerly saline aquifers is the

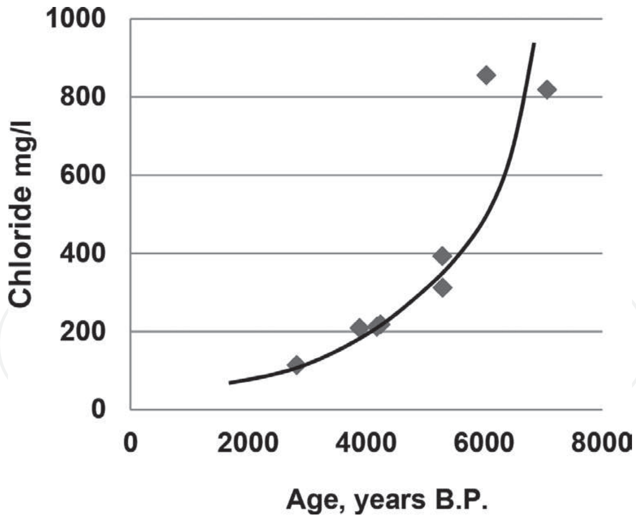

Figure 8. Age of groundwater in the Mati plain aquifer related to the chloride levels [12]. The slow turnover rate has left portion of the aquifer with elevated chloride levels.

appearance of specific water such as $NaHCO_3$ formed by ion exchange. At the end of the flushing period, there is a pronounced increase in the Na/Cl ratio formed by the uptake of calcium in the fresh water recharge and release of sodium at adsorption sites from the saline period.

Abbreviations

^{18}O	$^{18}O/^{16}O$ for oxygen isotopes
ESLR	Effective sea level rise
ka BP	Thousands of years before present
LGM	Last Glacial Maximum
SMOW	Surface mean ocean water
SW monsoon	Southwest monsoon
$\delta^{34}S$	$^{34}S/^{32}S$ ratio for sulfur isotopes
δD	Isotopic ratio for hydrogen isotopes ($^2H/H$ or deuterium/common hydrogen)

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