Chapter 4
Methods and Techniques to Define Base-Level Elevation and to Measure and Assess the Effect of Their Variation on Adjoining Groundwater Systems

This chapter describes the different methods employed to detect, measure, monitor and estimate current and paleo base-levels in time and space. These include ground elevation as well as sea and lake levels. These methods include direct measurement, such as geodetic methods and level gauges and indirect methods, using proxies such as sedimentological, morphological and chemical data for past records. The methods of measuring the response of groundwater system to the base-level changes are also described.

4.1 Base-Level Elevation

4.1.1 Current Ground Level Measurements

Current ground levels and their changes are instrumentally measured and monitored by repeated geodetic measurements employing the following techniques:

4.1.1.1 Precise Geodetic Leveling

Repeated precise geodetic levelings are used to define elevations and to monitor current vertical movements of uplift and subsidence. The first order precise leveling method (Rappleye 1948) was often used to study Recent Crustal Movements attaining a precision of a few millimeters. The usage of the above was reported, for example, from Israel by Kafri (1969) and Karcz and Kafri (1971, 1973). Vertical deformation in the Main Ethiopian Rift was also recorded employing repeated leveling (Asfaw et al. 2006). Precise leveling of geodetic networks can thus be a helpful tool to monitor current elevation changes of continental base-levels.

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4.1.1.2 The GPS Technique

The Global Positioning System (GPS) is a system developed by the U.S. Department of Defense. It uses a constellation of between 24 and 32 earth orbiting satellites that transmit precise signals to receivers on earth thereby enabling to determine their location and elevation. The basics of the method are described for example by Vanicek and Krakiwsky (1986). The vertical precision of the system is around a few millimeters.

GPS measurements are used to define elevations. Repeated GPS network measurements enable to detect current vertical elevation changes of uplift and subsidence on land. Examples to such studies were described from Greenland (Forsberg et al. 2000), from Tibet (Xu et al. 2000) and from Turkey (Ustun and Demirel 2006). Thus, The GPS technique can serve as a useful tool to detect on-land vertical base-level changes.

4.1.1.3 The INSAR Technique

The Interferometric Synthetic Aperture Radar (INSAR) technique has become a valuable technique to measure displacement at the ground surface (i.e., Gabriel et al. 1989; Massonnet and Feigl 1998). When two radar scans are made at different times from the same viewing angle, a small change in the position of the target, namely the ground surface, may create a detectable change in the phase of the reflected signals. The resulting phase differences are expressed in interferograms in which the fringe pattern reflects the ground displacement that occurred between the two acquisitions.

Reported studies that used the INSAR technique to measure land subsidence are, among others, from California (Galloway et al. 1998) from the Dead Sea (Baer et al. 2002) and in the Asal Rift, Djibouti (Doubre and Peltzer 2007).

4.1.2 Current Sea and Lake Level Measurements

The instrumental technique to measure and monitor current sea and lake levels is by using tide gauges (i.e., Douglas et al. 2001). The current global sea level rise due to the on-going global warming process is being an important issue and thus being detected by tide gauges from all over the world (i.e., Cazenave et al. 1999; Miller and Douglas 2003; Holgate et al. 2008; Blasi 2009). In addition, Satellite Radar Altimetry is also often used to monitor lake level changes attaining a precision of a few centimeters (i.e., Birkett 1995; Cretaux and Birkett 2006).

Significant declines of lake levels in the last decades, using the above techniques, were reported among others from the Caspian Sea (Cazenave et al. 1997), from Lake Chad (Birkett 2000), from the Aral Sea (Peneva et al. 2004) and from the Dead Sea (Yechieli et al. 2006).

4.1.3 Paleo- and Historic Shorelines

The indicators that enable reconstruction of paleo-shorelines include near-shore marine terraces, wave-cut platforms and notches, near-shore cave formation, submerged archeological sites, geomorphological features, as well as sedimentological evidence for near-shore marine or lacustrine environments. Geochemical and isotopic data are able to reveal the specific (e.g., salinity, temperature, water levels) conditions of the ancient environments. All the above evidences are often found above or below the present base-level due to tectonic vertical displacements as well as global or local climatic changes which may lead to desiccation of lakes.

4.1.3.1 Near-Shore Marine Terraces

Near-shore marine terraces are basically divided into two main types, namely the constructional type and the erosional one. The constructional type consists of reef platforms which typify the shallow near-shore zone. The erosional type consists of wave-cut platforms or abrasion ramps as well as wave-cut notches that are formed by destructive wave action along shore lines and against the base of sea cliffs. These two phenomena are described and exhibited (Fig. 4.1) by Burbank and Anderson (2000).

Thus, ancient wave-cut platforms and notches are indicative of ancient shore lines and provide evidence of past eustatic sea level changes. Raised and abandoned platforms and notches as well as coastal sediments and reefs are evidences of higher past sea levels. Such were described from Australia (Cooke 1971), from the Cayman Islands (Jones and Hunter 1990) and from Barbados (Johnson 2001).

Ancient shore lines phenomena were also often subjected to later tectonic displacements both uplift and subsidence. Examples are described from Mexico (Ramirez-Herrera and Urrutia-Fucugauchi 1999), from Italy (Cucci 2004; Dumas

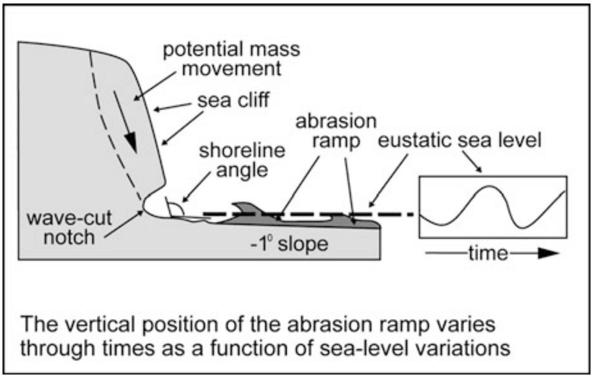

Fig. 4.1 Schematic description of a near shore abrasion ramp and a wave-cut notch [after Burbank and Anderson (2000)]

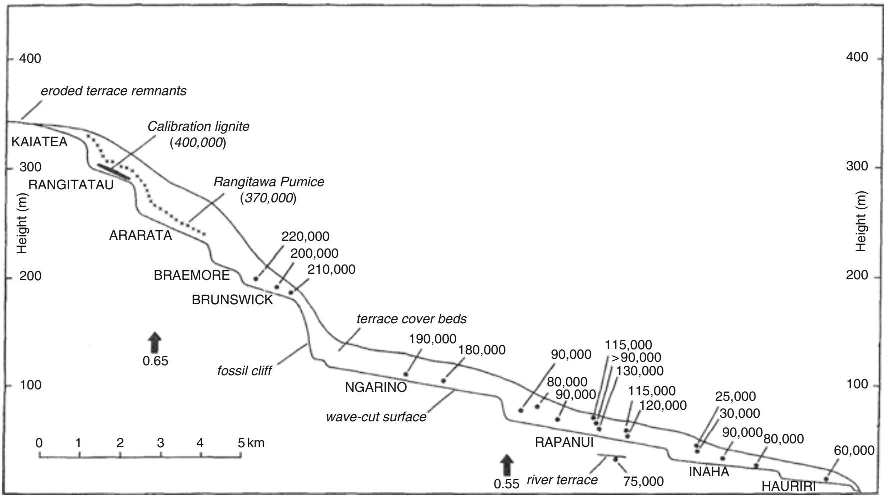

Fig. 4.2 Tectonically uplifted ancient shore terraces in New Zealand. Uplift rates in millimeter/year are shown by *large arrows* [after Pillans (1983)]

et al. 2006), from Spain (Alvarez-Marron et al. 2008), from Argentina (Rostami et al. 2000) and from New Zealand (Pillans 1983) (Fig. 4.2). Raised shorelines due to glacial isostatic uplift in Fennoscandia were also described, among others by Moerner (1991) (see also Sect. 3.4).

The slope of the surfaces of near-shore terraces can serve as a tool to assess a down-stream lake level, since the evolution of the alluvial fans surfaces and the lakes are interrelated. Thus, an approximate record the lake level at different times is obtained (Bowman 1971; Sneh 1979).

4.1.3.2 Karstification and Cave Formation

The delineation of paleokarstic features in carbonate aquifers, and mostly horizontal cave levels, is a powerful tool to allocate and interpret paleo base-levels.

Horizontal or sub-horizontal cave systems, which are not formed by hydrothermal processes, are usually related to enhanced carbonate dissolution due to fast horizontal flow in the shallow phreatic zone of the aquifer, close to the water table (i.e., Swinnerton 1932; Rhoades and Sinacori 1941; Davis 1960; Thrailkill 1968; Esteban 1987; Hill 1999; Flugel 2004). According to the above, enhanced dissolution and cave formation (speleogenesis) in the shallow phreatic zone, takes place in cases of long period of stable water table, and rapid groundwater flow. Thus, a cave system level, whether above the current groundwater table and sea level or submerged below it, might reflect a paleo-groundwater level. When extending these levels using reasonable water table gradients, the location and elevation of the adjoining paleo base-level can be obtained.

High groundwater fluxes are especially evident in an aquifer adjacent to its base-level where the latter is marine or saline lake. In such a case, an interface between the overlying flowing fresh groundwater and the underlying saline water body exists. As a result, the fresh groundwater flow converges, close to the base-level to a very narrow discharge zone accompanied by rapid fluxes (Fig. 4.3). Such cases were described from the Dead Sea coastal aquifer by Yechieli et al. (2001) and Kafri and Yechieli (2010) and from North Carolina by Evans and Lizarralde (2003). In the case of hypersaline lakes, the interface is shallower than in the case of normal seawater, and the overlying groundwater velocity therefore is more rapid (see also Sect. 6.2.2), which might enhance cave formation.

Another factor which controls carbonate dissolution and cave formation in the near-shore of coastal aquifers is the mixing zone between fresh and saline waters. Cave formation related to the mixing zone were described, among others, from Yucatan by Back et al. (1986), from south Pacific by Murgulet and Aharon (2005) and in relation to carbonate islands by Mylroie and Carew (1995) and Jenson et al. (2006).

Paleokarstic features related to paleo-water tables and/or base-levels are often found at different levels above the present base levels or submerged below them as a result of global eustatic sea level changes, drop or rise of lake levels due to global

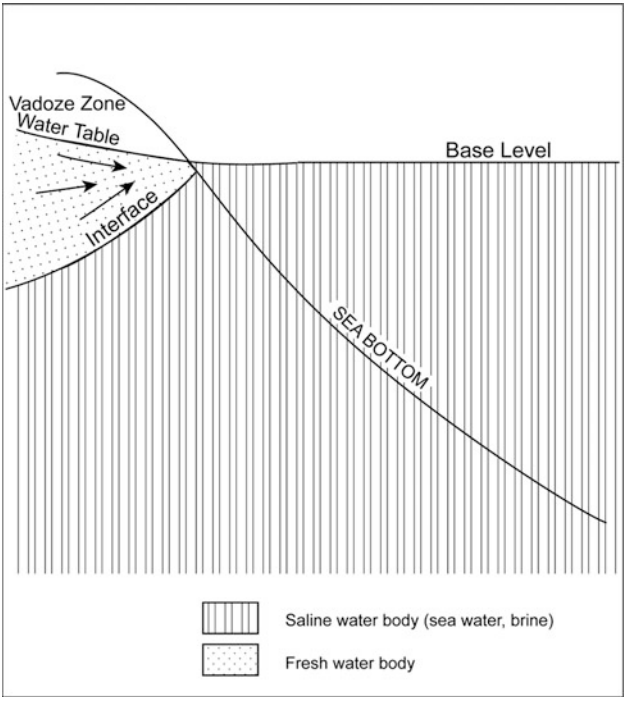

Fig. 4.3 Schematic cross-section exhibiting converging rapid groundwater flow above the interface, close to a saline base level

or local climate changes, and vertical tectonic displacement. The age of the formation of such paleokarstic cave systems can be obtained by the following:

(a) Absolute elevation of a cave system as compared to known eustatic elevation curves, provided the age of the eustatic level is known.
(b) When associated with nearby near shore sediments, beach terraces or coral reefs, paleontological or absolute dating might yield the date of the caves (i.e., Williams 1982; Florea et al. 2007) (Fig. 4.4). Dated lacustrine sediments, which were deposited within an already existing cave adjacent to the shore line, can also yield the youngest age threshold of the cave as shown by Lisker et al. (2009).
(c) Absolute dating of speleothems in caves yields a minimal age of cave formation since speleothems are formed only in air filled caves in the vadose zone following their emergence above the groundwater table (i.e., Atkinson et al. 1978).

Caves ceased to develop when they were subsequently submerged below the rising sea levels. Examples of raised and submerged, often multiple, caves systems and related coastal terraces were described among others by Gascoyne et al. (1979), Williams (1982), Li et al. (1989), Collier (1990), Richards et al. (1994), Carew and Mylroie (1995), Jenson et al. (2006) and Florea et al. (2007).

Data which might support paleo base-level delineation and interpretation becomes more abundant when younger base-levels are studied, partly due to a better dating resolution (e.g., radiocarbon dating) and partly to better preservation. The Neogene period already provides some information but considerably more information is available regarding Quaternary paleo-karst and base-levels.

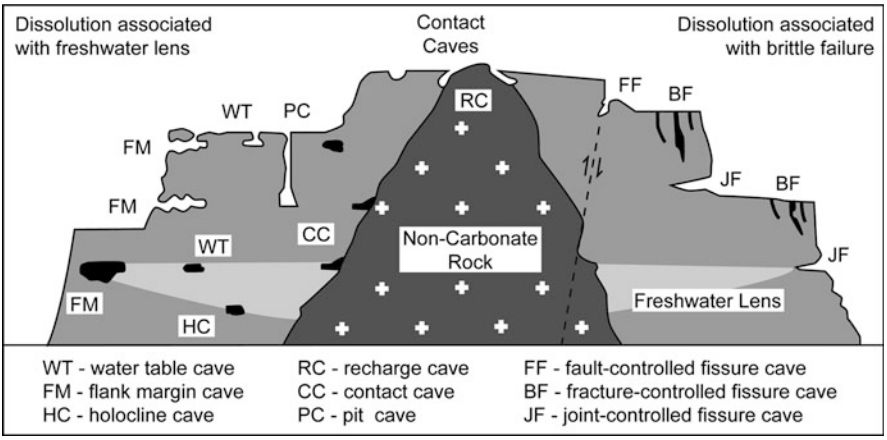

Fig. 4.4 Uplifted cave levels in the Mariana Islands [after Jenson et al. (2006)]

4.1.3.3 Erosional and Other Geomorphological Evidence

Among the erosional and geomorphological features which are indicative of past base-level elevations are coastal abrasion platforms and lake shore terraces (Figs. 4.5 and 4.6) (i.e., Bowman 1971; Kafri and Arad 1978). All the above listed features are described in detail, among others, by Reading (1996) and Cohen (2003).

Receding paleo-lake shorelines are also detected by analysis of longitudinal profiles of streams that drained to those lakes. Receding shorelines in the Dead Sea Basin are manifested in adjoining longitudinal stream profiles as well as by a sequential development of alluvial fans (Bowman et al. 2007).

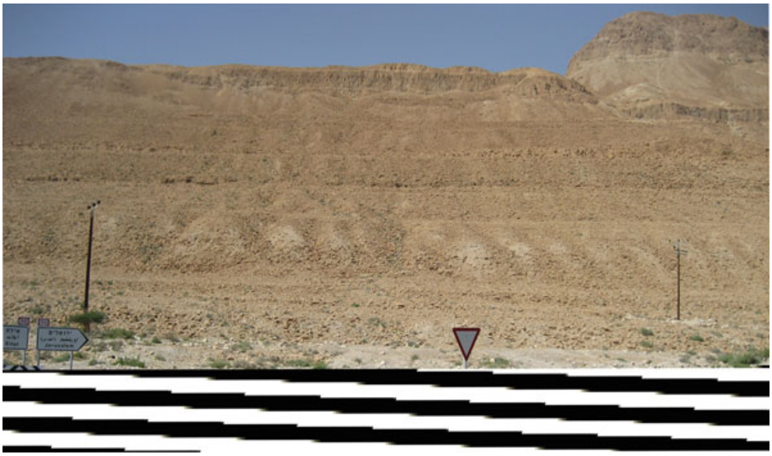

Fig. 4.5 Dead Sea coastal abrasion lake shore terraces

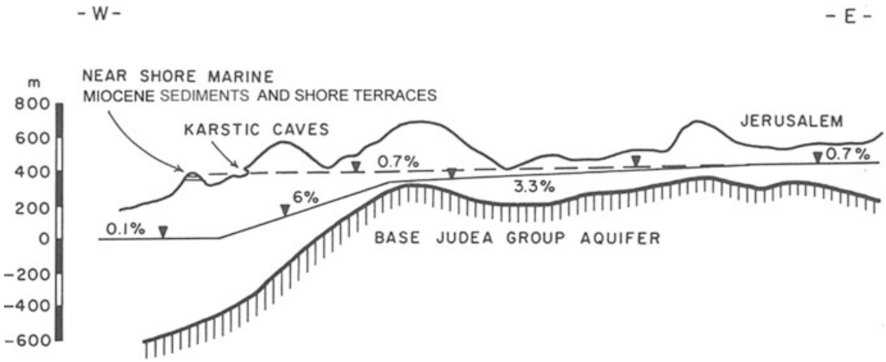

Fig. 4.6 Tectonically raised Neogene abrasion plain and related paleohydrological system [after Kafri and Arad (1978)]. The *solid line* represent the present water table connected to the present Mediterranean base level. The *dashed line* represent the reconstructed paleo water table related to the Miocene base level

4.1.3.4 Sedimentological Indicators

The role of different sediments as indicators of the environment of deposition was discussed in numerous books and articles (i.e., Nicols 1999).

Among the sedimentological indicators are lacustrine sands and laminated sediments, deltaic sediments, beach ridges, alluvial fans as well as evaporites in cases of saline lakes. Some sediments, such as beach ridges, indicate the exact location of the shoreline (Bartov et al. 2006; Bookman et al. 2004) while others indicate minimal or maximal water level. Lacustrine sediment (e.g., aragonite, gypsum, halite) indicate the existence of a lake whereas alluvial sediments (e.g., gravel and conglomerate) imply that the lake did not exist there at that time. An exception could be in case of submarine erosion, depositing detrital material offshore in the lake, at the mouth of big rivers.

Paleontological or pollen studies of lake sediment yield information regarding lake and/or sea water depth and salinity (e.g., Migowski et al. 2006; Begin et al. 1980). Geochemical ratios and stable isotope values (e.g., Na/Cl, $\delta^{18}O$) also serve as good proxies for the determination of the specific salinity and temperature conditions of ancient environments (i.e., Katz et al. 1977). Thus, a water level profile can be obtained from sedimentological sequences.

The reconstruction of paleo-shorelines and lake levels from the sedimentological data requires dating of these sediments. The most commonly used dating method is that of radiocarbon, employed for carbonates such as aragonite or calcite minerals. The ^{14}C radioisotope has a half life of 5,700 years and thus the method enables dating of material up to ~40,000 years old. Other dating methods include the U-Th method, mostly for carbonates (e.g., Kaufman and Broecker 1965) and the OSL method (Aitken 1998) which can be applied to a variety of sediments (e.g., quartz grains) and to sediments older than 500,000 years.

Dated Quaternary shorelines were described from numerous places such as Lake Van, Turkey (Landmann et al. 1996), from Lake Baikal (Colman 1998; Kolomiets 2008), from the Great Lakes, North America (Baedke and Thompson 2000; Baedke et al. 2004) and from the Dead Sea, Israel (Bookman et al. 2004; Waldmann et al. 2007).

4.1.3.5 Submerged Archaeological Sites

Some coastal archaeological sites are found at present to be submerged below sea level due to the rise of sea level since the Holocene. The dating of those sites enables to reconstruct and to assess the rate of the sea level rise in the historic and pre-historic time span.

Submerged archaeological sites and human installations were described, among others, from offshore northern Israel (Galili and Nir 1993; Galili and Sharvit 1998), from the Black Sea (Coleman and Ballard 2007) and from Italy (Scicchitano et al. 2008).

4.2 Methods to Determine Groundwater Systems' Response to Base-Level Changes

Studies concerning groundwater response to base-level changes, which employ field measurements, are still rare. The following chapter, therefore, describes mainly methods which were employed in the Dead Sea area.

4.2.1 Current Field Measurement

The response of the groundwater system to changes in base-level elevation is expected to be expressed in the field by the following: groundwater level changes, vertical and lateral shift of the fresh–saline water interface in the case of a saline base-level and changes in submarine or sublacustrine groundwater discharge (SGD). Water level measurements and monitoring are carried out employing manual meters, electric devices or pressure transducers at different resolutions and frequencies, depending on the specific objective. An example of groundwater level response to the Dead Sea level changes was described by Yechieli et al. (1995, 2009b) and Kiro et al. (2008) (see also Sect. 11.2.6.3).

The electrical conductivity (EC) profiling and logging of groundwater in boreholes is a known method to detect the fresh–saline water interface. In general, at salinity of up to normal marine values, the EC value correlates satisfactorily with salinity values. The situation is somewhat more complicated at higher salinities but still correlation exists up to a salinity of half of the Dead Sea brine. At a higher salinity, no correlation is found between EC and salinity (Yechieli 2000). The EC profiles are repeatedly conducted for several years in order to examine the response of the interface to changes of base-level elevation. A significant drop of the interface due to changes in base-level elevation was indeed observed in the Dead Sea system (Yechieli 2000; Kiro et al. 2008) (see also Sect. 11.2.6.3). Continuous EC monitoring is also carried out in order to study short term processes. However, the interpretation should be done with cautious due to both artificial effects of the borehole itself and to the tidal effect (e.g., Shalev et al. 2009).

The base-level changes can also be manifested in the amount of submarine groundwater discharge (SGD) to the sea or to a lake. Such changes are expected since a drop of the base-level changes the hydraulic gradient near the shoreline and thus an increase in groundwater flow is expected partly on the expense of the storage. The SGD is estimated by direct measurement with seepage meters (Taniguchi and Iwakawa 2001) which may represent the local situation. An additional way is by sampling and analyzing the seeping water for chemical and isotopic analysis, based on the fact that they differ from the surrounding water body and thus the obtained results are of a more regional significance. The most commonly used measured constituents, in recent studies, are radon (Burnett and Dulaiova 2003) and radium isotopes (Moore 1996), although other parameters, such as nutrients and various pollutants are also used.

The increase of water discharge to the base-level can also be measured on land by in situ velocity meters which are installed in exploration boreholes. Such a device can monitor the change of groundwater flow velocity and direction of both fresh and saline groundwater. A complementary study could be done with artificial tracers such as dyes (e.g., rhodamine) using either the point dilution test, if only one borehole exists, or preferably using an array of monitoring wells if available. Tracers should be chosen with caution as to match the specific requirements, i.e., high salinity (Magal et al. 2008).

4.2.2 Indirect Estimation

Chemical concentrations and ratios, as well as both stable and radioactive isotopes in groundwater, can be used to estimate the groundwater regime between the intake area and the discharge zone and thus its response to base-level changes. Stable isotopes such as ^{18}O, together with noble gas information (Stute et al. 1992), yield an insight as to the temperature that prevailed in the recharge zone, and thus climate and/or altitude of the intake area.

The radio isotopic methods are used, together with the above methods, to determine the age of the groundwater, at certain points along the flow path, from the recharge zone to the discharge area, and thus its flow velocity and residence time. Several radio isotopic methods are used, each with different time scale, depending on their half life time. A general description of these isotopes is given by Phillips and Castro (2003). The most commonly used radio isotopes for groundwater dating are radiocarbon (half life time of ~5,700 years, Munnich 1957) and tritium (half life time of 12.4 years, Bergman and Libby 1957). The radiocarbon method, with the more extended time window, requires several corrections and modification before interpretation, due to its interaction with the rock matrix, especially in carbonate aquifers.

There are several methods of corrections, depending on the specific conditions of the aquifers, some of which are computer aided codes (e.g., Netpath, Plummer et al. 1991). The advantage of tritium is its being part of the water molecule and acting as a conservative parameter. On the other hand, its relative short half life time limits its use to the current short term time window processes. For several decades, the tritium signal was significantly larger due to the fallout of the nuclear testing and therefore a useful tool for groundwater dating. The decreasing tritium values in recent years, due to the cessation of the nuclear tests, limit its usage. Tritium can be, thus, best used together with the analysis of ^{3}He to provide reliable ages of young groundwater (Ekwurzel et al. 1994).

Other less common methods of groundwater dating include several radioisotopes such as ^{36}Cl (half life time of 300,000 years), Noble gases (e.g., ^{39}Ar with half life time of 269 years, Loosli 1983; Loosli et al. 2000), ^{85}Kr (with half life time of

10.76 years), ^{81}Kr (with half life of 229,000 years, Loosli and Oeschger 1969; Lehmann et al. 1991). Depending on the specific half life of each isotope, they are applicable for different processes of different time scales. However, these isotopes were seldom used since their analytical procedure is less available and relatively complicated. The application of the accumulation rate of ^{4}He was suggested to be a qualitative dating tool of old groundwater (Patterson et al. 2005). The Rn content (half life of 3.8 day) can also provide, in several cases, information with regard to groundwater flow rates (i.e., Kafri 2001).

Other methods of groundwater age determination include several pollutants whose concentration in the atmosphere have increased in the twentieth century and are relatively well known (e.g., SF_6, CFC, Busenberg and Plummer 1992). These are, thus, applicable for dating of modern groundwater, younger than 70 years.

Dating of fresh and saline groundwater indicate the travel time of water from the recharge area to the sampling point (monitoring boreholes or discharging springs) or from the sea or lake into the aquifer. A change in base-level is expected to cause a change in travel time of fresh groundwater which may be detected in some systems. Dating of saline groundwater in coastal aquifers indicates the timing of inland seawater or saline lake water intrusion which, in turn, implies on the timing of the sea or lake level rise (i.e., Yechieli et al. 2009a).

The response of coastal aquifers waters to variations in base-level can also be manifested by changes in their chemical composition and ratios, as well as by their isotopic composition, due to changes in the contribution of the different end members to the groundwater. Such changes were attributed, for example, in the receding Dead Sea system to flushing of the brine from the aquifers or to dissolution of evaporites (Yechieli 2006; Kiro et al. 2008).

Chemical changes could be also manifested in the ionic ratio (e.g., Ca/SO_4, Na/Cl) due to dissolution or precipitation of minerals, such as gypsum or halite.

4.2.3 Hydrological Simulations

Hydrological simulations also serve as a tool to analyze the response of all the aspects of the hydrological system to base-level changes by using existing codes such as SUTRA (Voss 1984), SEAWAT (Langevin et al. 2008) and FEFLOW (Diersch and Kolditz 2002). These codes take into account the effect of density driven flows which are important in the case of systems adjacent to saline base-levels. The advantage of hydrological simulations is that they have no time limitation and can be extended to long periods for past situations as well as for future forecast. The simulation can be used to complete missing past records and for forecasting future situation. The problematics of hydrological simulation is its requirement of several hydraulic properties, such as hydraulic conductivity, that are difficult to obtain and thus the simulations yield, in many cases, only rough estimates.

As always, due to the uncertainty of each separate method, it is preferred to use a combination of several methods in order to achieve more confidence in the results.

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