

Analysis of drivers governing temporal salinity and temperature variations in groundwater discharge from Altug Submarine Karst Cave (Kas-Turkey)

N. Nur Ozyurt

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Abstract Salinity and temperature variations in groundwater discharge from the Altug submarine karst cave have been observed at 28 m below sea level for every 10 min between November 2004 and August 2005 to determine the drivers that govern the salinization. Comparisons between temporal trends of salinity and temperature with those of precipitation, air pressure, sea level and wind velocity revealed an apparent dominance of precipitation regime on the salinity and temperature variations. Spectral analyses applied to observations showed that the air pressure and sea level oscillations are affected by sun and moon tides which do not have an appreciable impact on the salinity and temperature variations. Annual rate of salinization in Altug cave seems inversely related to the inland groundwater head so that the maximum and minimum fresh water contributions occur at mid-spring and late-summer, respectively.

Keywords Karst · Submarine · Cave · Salinity · Temperature · Turkey

Introduction

With their high infiltration and transmission capacity, the karst aquifers are among the most productive aquifers that constitute water supply for about one quarter of the world's population (Ford and Williams 1989). However, when these aquifers are in contact with sea, as in the case of many countries in the Mediterranean Sea basin, considerable

amount of water discharges naturally into the sea in the form of coastal and submarine groundwater discharges (SGD) (Mijatovic 2007; Bayari and Kurttas 2002; Gunay 1971; Khout 1977). Furthermore, increasing demand for potable water during the hot and dry summer months increases the severity of water scarcity problem in these countries. Proper utilization of karst groundwater in coastal setting requires information on the location and discharge dynamics of these SGDs. Several drivers such as, inland hydraulic head, sea level change, storm surge, air pressure and ocean loading determine the spatio-temporal discharge dynamics of SGDs along the karstic coast line. Thus, a proper assessment of the salinization of karstic SGD requires long-term observations in order to understand the dominant processes.

In the Mediterranean Riviera of southwest Turkey, the karst aquifer constituting the only water supply occupies the entire coastline along which considerable amount of groundwater is lost to sea at numerous sites. Previous hydrogeological studies (e.g. Elhatip 1992; Elhatip and Gunay 1998; DSI 1974) indicated that the accessible groundwater in karst aquifer is limited and the possibility of recovering karstic SGD must be investigated to meet the future water demand. A systematic survey carried out by Bayari et al. (2007) revealed that most of the groundwater discharge to the sea occurs through the fracture systems, which are widely scattered along the entire coastline and the point-wise SGD through 15 coastal and submarine caves appears to be the only potential source of recoverable groundwater. Future development of recovery technologies in individual discharges requires sound information on temporal dynamics of salinization. The aim of this study is to determine the factors affecting the temporal salinization dynamics in Altug submarine cave, as an example of high salinity SGD points in the study area. For this purpose, temporal salinity and temperature dynamics have been

N. N. Ozyurt (✉)
Department of Geological Engineering,
Hacettepe University,
Beytepe, Ankara 06800, Turkey
e-mail: nozyurt@hacettepe.edu.tr

observed between November 2004 and August 2005 with a submersible mini data logger and the observations were compared to potential drivers that could affect salinity variations.

Study Area

The study area is located near the Kas town, southwest of Turkey. Along the coastline, steeply rising mountain flank morphology made up of extremely karstified carbonate rocks, characterize the scenery (Fig. 1). The geology of aquifer is dominated by autochthonous Beydaglari carbonate rocks of Mesozoic and Tertiary periods whereas the Lycian and Antalya nappes bound the aquifer from west and east, respectively. Plio-quaternary units are observed mostly in coastal and intramountain plains. A morphology that is abound with karst plains, uvalas, sinkholes and naked rock surfaces is observed throughout the land extending between the Altug cave and mountain flank. Groundwater is scarce in this extreme karst setting and can only be found in a few fracture zones that extend to the sea. Mediterranean type climate with mild-humid winters and hot-dry summers prevail in the region. Long-term mean annual precipitation and temperature is estimated to be 850 mm and 19.5°C, respectively. Details of regional hydrogeologic structure, coastal and submarine karst discharges can be found in previous studies (e.g. Elhatip 1992; Bayari et al. 2007, Oztan 2004; Coskun 1978).

Altug submarine karst cave, developed in Late Cretaceous limestone, is located roughly 10 km to the southeast of Kas town, at 36°08'50"N and 29°40'00"E coordinates. The entrance of the cave, which is located at 12 m below mean sea level (bsl), is in the form of a vertically extending pit with an average diameter of 2 m (Fig. 2). After 40 m bsl, the cave steadily enlarges toward north until the bottom is reached at 63 m bsl. At the bottom, an impenetrable conduit continues northward. Groundwater seeping from the conduit follows the ceiling due to its lower density and floats up to the surface through the entrance pit. Summer time SGD rate through the pit is estimated to be ca. 10 l s^{-1} . Groundwater flow through the cave is recognized both by the temperature difference during summer months and by the presence of a halocline that partly affects the visibility. Overall morphology implies an epikarstic origin so that the cave should probably have formed as a sinkhole in the beginning. The large chamber at the bottom part seems to have developed due to ceiling collapse under subcutaneous zone conditions. The initial formation of cave should have dated back to Plio-quaternary glaciation period when the Mediterranean Sea level fell more than 100 m. Present submerged condition appears to be a result of sea level rise after Late Glacial Maximum (ca. 18,000 years BP). Because the remains of prehistorical settlements of Lycian civilization (ca. 10,000 BP), located 15 km to the east, are found up to 5 m under the present sea level, the submergence of the cave may also be associated with a regional down lift.

Fig. 1 Location and simplified geologic map (modified after Senel 1997) of the study area

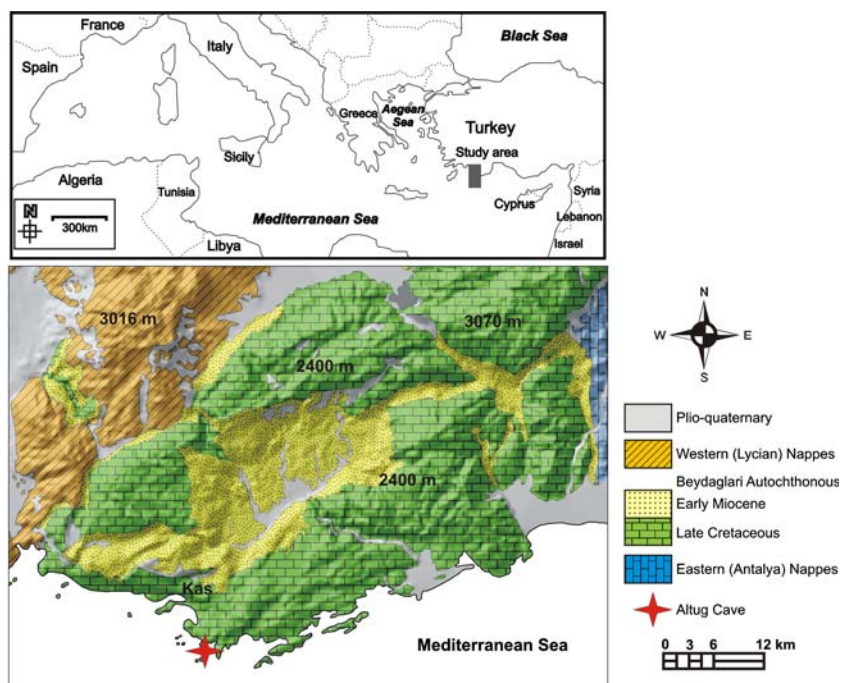
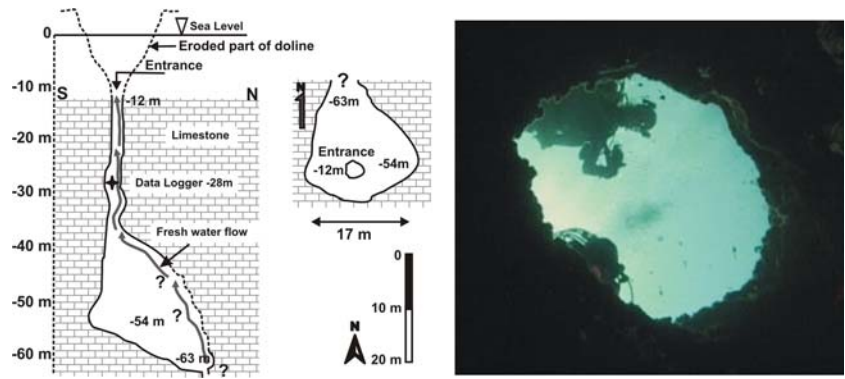


Fig. 2 Plan, extended cross-section and upward entrance view of Altug submarine cave

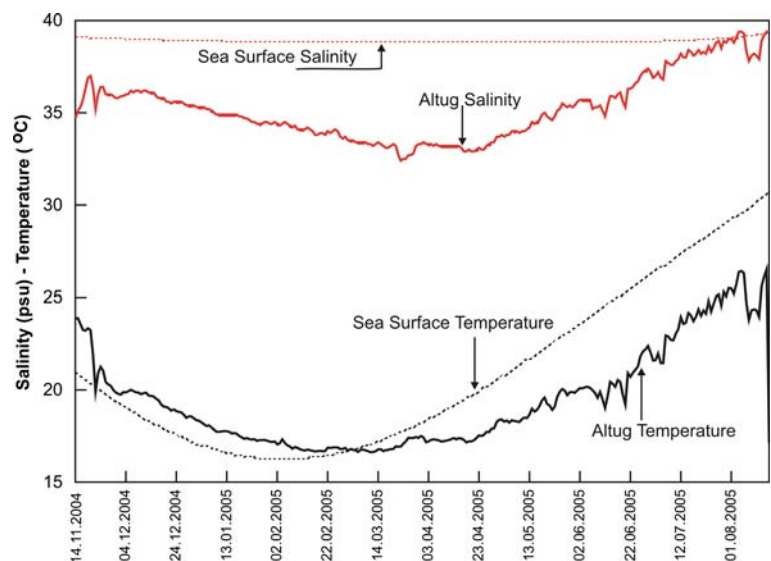


Materials and methods

A mini submersible data logger (Star-Oddi, 2006) has been used in this study to monitor salinity and temperature of SGD in Altug cave between November 2004 and August 2005. The instrument is capable of measuring the electrical conductivity and temperature within the respective ranges of 10–50 ms/cm and –1 to 40°C. Respective accuracies of conductivity and temperature measurements are ±0.8 ms/cm and ±0.1°C and the accuracy of salinity data derived from measurements is ±0.75 psu. The logger, set to collect data for every 10 min, was fixed at an appropriate position of 28 m bsl where continuous contact of uprising groundwater with the instrument is assured. To ease comparison with other data sets, raw SGD observations were converted to daily averages. Equations of the International Equation of State of sea water (UNESCO, 1983) have been used to convert original electrical conductivity data to salinity values used in the study. Monthly sea surface salinity (SSS)

and sea surface temperature (SST) data were taken from MFSTEP (2005) records which are based on a complex combination of in-situ and satellite-derived data having daily to weekly time resolutions. Accuracy of MFSTEP’s SST and SSS data is believed to be in the order of ±0.25°C and ±0.25 psu, respectively. The monthly SSS and SST records were found to be in agreement with the nonperiodic SSS and SST measurements that have been carried out at several kilometers offshore of the Altug Cave in every season. Appropriate polynomial equations fitted to monthly SSS and SST data were used to produce daily values that are used in this work (Fig. 3). Daily sea level data, accurate to ±1 mm, were determined from the hourly records of Antalya mareograph station located 100 km to the east and were found to be the representative of local conditions based on nonperiodic, short-term observations. Daily total precipitation (accurate to ±1 mm), daily mean of hourly air pressure (accurate to ±0.1 mbar) and daily mean of hourly wind velocity (accurate to ±0.1 m/s) data were taken from

Fig. 3 Temporal SGD and sea surface salinity and temperature variation



Kas meteorological located 10 km to the north of the cave. The moon phase data were obtained from NOAA/NOS (2007).

Results

Temporal salinity and temperature trend

Temporal salinity and temperature variation in the Altug cave forms parallel and concave curves with minima around spring months (see Fig. 3). The SSS varies slightly between 38.86 and 39.33 psu (practical salinity unit). A negligible decline in SSS occurs around spring season probably because of the slight dilution of sea water by the stream flow input into the Mediterranean Sea. The SST seems to have been determined by the seasonal atmospheric heat flux so that the minimum and maximum SSTs are observed in winter and summer seasons, respectively.

Salinity of SGD decreases from ca. 35 psu in November to ca. 33 psu in March–April and then it tends to rise toward sea water's salinity value which is almost stable around 39 psu. Because the freshwater's salinity is constant around 0.1 psu, the observed variation indicates a temporally varying fresh groundwater contribution to SGD. Obviously, the amount of fresh groundwater contribution rises from late autumn to mid-spring months, a period in which almost all of the annual precipitation falls. A sudden fall was observed in the SGDs salinity and temperature in mid-August when no accountable precipitation occurred in the study area. This and similar variations observed in spring and summer months are thought to have link with small magnitude earthquakes that frequently occurs in this region. Crustal dilatations caused by earthquakes are known to increase or decrease groundwater discharge by compressing or expanding the aquifer (e.g. Bayari et al. 2007). An earthquake leading to compression of aquifer is

expected to decrease the observed salinity and temperature in Altug Cave because the associated dilatation should increase the discharge of groundwater, with lower temperature and salinity, into the sea. A reverse process is expected in the case of an aquifer expansion due to earthquake. However, a direct relationship between the timings of available earthquake records and these anomalies could not be established.

Effect of rainfall on SGD salinity

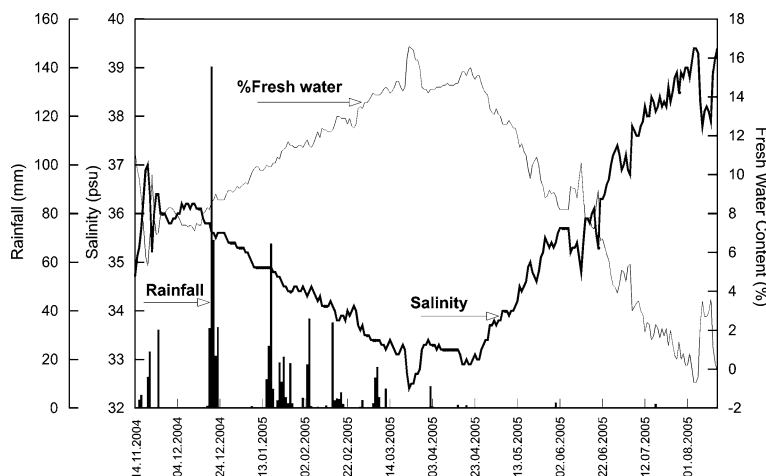
A comparison between the temporal spread of individual rainfall magnitudes and the SGD salinity variation suggests a fresh water discharge mechanism that is driven by the hydraulic head gradient between the aquifer and sea (Fig. 4). It appears that the precipitation events prior to the beginning of observation period have already decreased the SGD salinity around 35 psu. This trend of lowering salinity is maintained by the rising head in aquifer due to continuing precipitation events in the early observation period (i.e. from November to March). The fresh water content in SGD is described by

$$\% \text{Fresh Water} = 100 - \left[\left(\frac{\text{Salinity_Altug} - \text{Salinity_groundwater}}{\text{SSS} - \text{Salinity_groundwater}} \right) \times 100 \right] \quad (1)$$

where fresh groundwater's salinity (i.e. Salinity_groundwater) is assumed to be 0.1 psu.

The increasing % fresh water during this period indicates that the maximum hydraulic gradient is achieved around mid-March when the bulk of the recharge to aquifer terminates (see Fig. 4). In other words, magnitude of fresh water contribution to SGD is controlled by the magnitude of the hydraulic head which is determined by the cumulative effect of past precipitation events. In fact, the same effect is also observed on the flow rates of streams which

Fig. 4 Relationship among SGD salinity, percent fresh water content, and rainfall



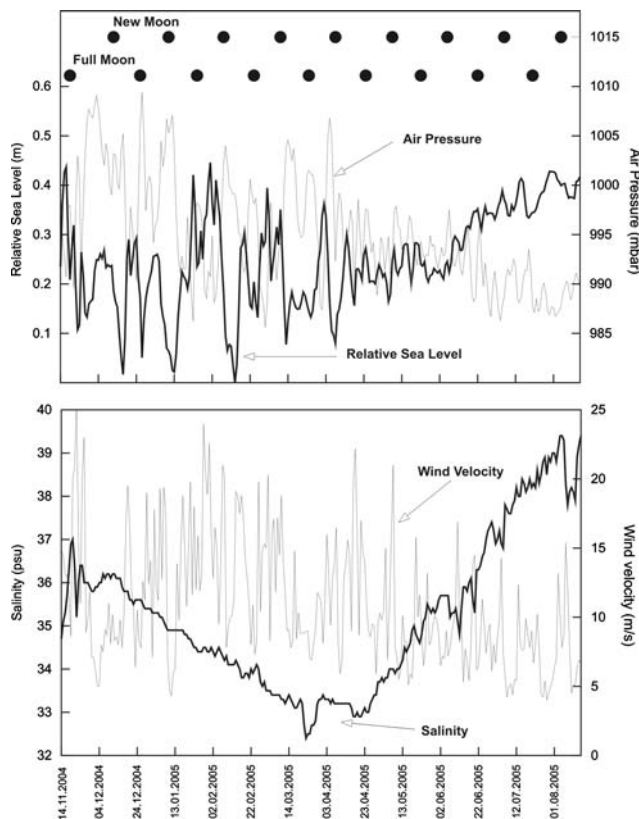


Fig. 5 Comparison of temporal variations of SGD salinity, wind velocity, air pressure and relative sea level

are located around the study area. All streams fed by the same karst aquifer reach their maximum discharge around April after which a steady recession period starts (Bayari et al. 2007; DSI 1974).

Effect of sea level, atmospheric pressure on SGD salinity

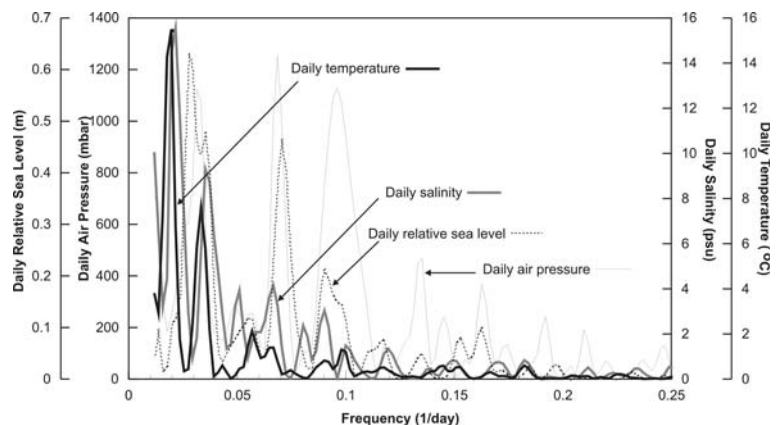
The short-term salinity oscillations observed particularly in the dry period after April suggests that other drivers such

as, sea level and atmospheric pressure oscillations could also have an effect on the SGD salinity. Previous studies (e.g. SCOR and LOICZ 2006) indicate that sea level changes due to moon tides, atmospheric pressure variations and wind effect may influence the SGD salinity by changing the gradient between groundwater and sea levels. Rising air pressure has also been shown to raise head gradient in confined aquifers by means of the pressure load exerted over the aquifer (Rojstaczer and Riley 1990). Therefore, the relationships between the temporal salinity variations and the sea level, atmospheric pressure, wind speed and moon tides have been investigated to determine the potential effect of these gradient drivers (Fig. 5).

A visual analysis of these variables suggests an inverse relationship between the sea level and air pressure. The sea level seems to be controlled primarily by atmospheric pressure variations via ‘inverted barometer’ effect which is the depression of sea level by increasing air pressure. Moreover, the storm surges that occur mainly as a result of strong winter winds also cause episodic changes in sea level. Steady sea level rise that occurs after April seems to be associated with a low air pressure system that regularly settles over the eastern Mediterranean in this period of the year. Absence of correlation between air pressure and salinity time series indicates the dominance of a unconfined flow system within the aquifer that feeds Altug SGD. Moon tides that cause sea level rise during the full and new moon periods do not have a visually discernible effect neither on sea level nor on the salinity of SGD.

Power spectral density (PSD) analyses have also been applied to the above variables to determine any potential resemblance among their periodicity that may not be visually discernible (Fig. 6). The PSD analyses revealed that the temporal variation of sea level and atmospheric pressure are influenced by principal lunar (M2 0.518 days), principal solar (S2 0.500 days), monthly lunar (MM 27.555 days) and lunar fortnightly (MF 13.661 days) harmonics of the gravitational forces exerted by moon and sun

Fig. 6 Power spectral density graphs of daily SGD salinity, SGD temperature, air pressure and relative sea level



(NOAA/NOS CO-OPS, 2007). However, temporal salinity and temperature variations in SGD were found to be not affected by these periodic sea level and atmospheric pressure changes. SGD's salinity and temperature indicate very weak periodic signals with periodicities around 50 and 28 days. These variations seem to be linked with the sea level changes that are driven by the superposition of sun-moon tidal sea level oscillations with MM and MF harmonics. The effect of the superposition of gravitational tidal signals on SGD's temperature and salinity also seems to be partly masked by other factors that affect sea level (i.e. wind surge and atmospheric pressure). Overall, the salinity and temperature variations in Altug submarine cave seem to have link with the hydraulic gradient changes which are governed by the recharge of aquifer and by the seasonal sea level change.

Discussion and conclusions

This study shows that the long-term high temporal resolution observations reveal important information on the processes that govern the salinity variation in karstic SGDs. In the present case, salinity and temperature variations were found to be controlled essentially by the head changes in the aquifer that depends on the precipitation regime. When the head in aquifer declines considerably in dry period, sea level oscillations start to be more explicit on SGD's salinity and temperature variations. While similar responses have also been observed in other comparable karst settings (e.g. Bakalowicz 2005), effects of other drivers like sea tides, atmospheric pressure and storm surge were reported from karstic and non-karstic SGDs elsewhere in the world (e.g. SCOR and LOICZ 2006). Temporal variations observed in Altug SGD also implies that any isotopic and chemical signal to be extracted from SGD samples may depend very much on the sampling season so that a sampling scheme that spreads various seasons in a year is essential to properly characterize the temporal behavior of karstic SGDs. While, previous studies (e.g. Elhatip 1992) suggest the recovery of karstic SGD as future water supply, the level of salinity observed in Altug does not allow the direct use this SGD as a potable water resource in neither period of the year. However, it may still be regarded as a better supply of water compared to desalination of sea water, if this process would be the only solution for local water need in the future.

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