Hydrological dynamics of water sources in a Mediterranean lagoon

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Abstract

Lagoons are important ecosystems occupying large coastal areas worldwide. Lagoons contain various mixtures of marine and freshwater sources which are highly dynamic in time. However, it often remains a challenge to identify and quantify dynamic changes of water sources, particularly in heterogeneous lagoon systems like the Köycegiz-Dalyan Lagoon (KDL), which is located at the southwest of Turkey on the Mediterranean Sea coast. The objective of this study was to quantify different contributions of potential water sources i.e. surface water, groundwater and seawater in the lagoon and how these water sources changed over time and space. In the wet and dry season stable isotopes of water, chloride concentration (Cl^-) and salinity were measured in two depths in the lagoon and surrounding water bodies (sea, lake, groundwater). Different components of water sources were quantified with a three component endmember mixing analysis. Differences in Cl^- and stable isotopes over time indicated the dynamic behaviour of the system. Generally, none of the groundwater samples was impacted by water of the Mediterranean Sea. During the wet season, most of the lagoon water (>95%) was influenced by freshwater and vertically well mixed. During the dry season, high Cl^- in the deeper sampling locations indicated a high contribution of marine water throughout the entire lagoon system due to salt water intrusion. However, a distinct layering in the lagoon was obvious from low Cl^- and depleted isotope contents close to the surface supporting freshwater inflow into the system even during the dry season. Besides temporal dynamics also spatial heterogeneities were identified. Changes in water sources were most evident in the main lagoon channel compared to more isolate lagoon lakes, which were influenced by marine water even in the wet season, and compared to side branches indicating slower turnover times. We found that environmental tracers helped to quantify contributions of different water sources in the Köycegiz-Dalyan Lagoon which is a highly dynamic and heterogeneous groundwater dependent ecosystem.

1 Introduction

Lagoons are important ecosystems occupying 13% of the coastal areas worldwide (Barnes, 1980). Along the Mediterranean coastline, more than 100 lagoons are found but only little hydrological and biological data of most of these ecosystems are available (Perez-Ruzafa et al., 2011a). Generally, lagoons are shallow, coastal water bodies with marine water influence. Mostly they have limited connectivity to the open sea through coastal barriers or connecting inlets. Further freshwater input can come from upstream rivers or groundwater. Lagoons are important ecosystems being a habitat for rare species like seagrass, fishes and turtles, and with a high productivity and diversity (Alongi, 1998;Pérez-Ruzafa et al., 2011b;Remane and Schlieper, 1971). Lagoons not only are valued for fauna and flora, but also due to recreational and industrial purposes by society. These societal values are, however, difficult to quantify (Anthony et al., 2009) also due to conflicts of interest in lagoon ecosystems (fishery, aquaculture, tourism) (Perez-Ruzafa et al., 2011a). Particularly in the context of global change lagoon ecosystems require a proper management for a sustainable use and to protect the ecosystem (Kløve et al., 2014;Anthony et al., 2009). Here, management must not impact the quality and quantity of the lagoon water in terms of chemical and ecological status on the one hand. On the other hand, also groundwater management (drinking water/irrigation) must not impact lagoons depending on groundwater and vice versa. For example, pumping of groundwater can influence the quality of the withdrawn drinking/irrigation water due to increased marine water influence or due to the mobilization of groundwater from deeper layers. In addition, groundwater withdrawal can change the fraction of freshwater source in the lagoon water body which strongly would influence its functions as a habitat for species specifically adapted to the environment. This example highlights the vulnerability of lagoon systems. It shows the strong need to protect and manage these ecosystems and to identify seawater intrusions and groundwater dependencies in the lagoon catchment area.

Here, a detailed knowledge about the water sources and water dynamics in lagoon ecosystems is fundamental before studying further ecological and chemical processes. It has been shown that lagoon systems are heterogeneous and dynamic systems. The quality of the water and subsequent seawater quality or adjacent groundwater quality strongly depends on the water flow and origin of water and nutrients (Gattacceca et al., 2009;Niencheski et al., 2007;Santos et al., 2008a;Santos et al., 2008b). Land use can impact the interaction of lagoon with surrounding groundwater resulting in lagoon infiltration processes under pine tree plantations compared to negligible interactions under natural dune vegetation (Schmidt et al., 2011). Such spatial impacts can be identified using environment tracer methods. Further, they can also be used to study temporal dynamics of water sources and hydrological processes like seasonal changes in evaporation and seawater contribution (Lecuyer et al., 2012;Schmidt et al., 2011). Salinity and stable isotopes of water were used to identify spatiotemporal changes of water in the Akyatan lagoon, Turkey (Lecuyer et al., 2012). Assuming two different end members, river and seawater, it was found that in the wet season the contribution of freshwater and seawater was 62% and 38% on average. Throughout spring to autumn, progressively evaporation of lagoon water results in hypersaline conditions with strongly enriched isotope values suggesting limited input of freshwater in the system (Lecuyer et al., 2012). Still, it remains unknown in many lagoon systems what the contribution of different water sources is and how they change not only over time i.e. wet and dry seasons but also over space i.e. both horizontal, spatial locations in the lagoon and vertical, depth locations in the lagoon; the latter is of particular interest in wetland type lagoon systems or lagoons with stratification expecting a not well mixed hydrological systems. Therefore, the objective of the current study was (i) to identify and quantify different water sources in a lagoon, (ii) how they change over time and space, and (iii) thus how heterogeneous and dynamic the hydrology of the lagoon and adjacent groundwater was. We achieved these objectives by applying environmental tracer methods and developing a three component endmember mixing approach. Different sources of water (seawater, groundwater, lake water) were identified at different locations in the lagoon, including top and bottom water column depths, for wet and dry season. Thus, the novelty of this study is to present an environmental tracer method identifying and quantifying both temporal dynamics (wet and dry season) and spatial heterogeneities (depth of the water column and distance to coastline) of water sources in a wetland type lagoon system. With improved, detailed understanding of heterogeneous and dynamic hydrological processes in groundwater dependent lagoon ecosystems, targeted strategies to better manage may be developed.

2 Material and methods

2.1 Study area

Köycegiz-Dalyan Coastal Lagoon is located at the southwest of Turkey on the Mediterranean Sea coast within the province of Mugla (Figure 1a). The geology in this region is mainly composed of allochthonous and authochthounous Flysch and karstic facies overlain by plio-quaternary sediments (Garciansky 1968). Due to tectonic activities, several faults were formed in this area. Details about the geology and more maps can be found in Bayari et al. (1995).

The total area of the watershed of Köycegiz Lake is approximately 830 km^2 and of the lagoon is 130 km^2. The upstream located Köycegiz Lake (2 m asl.) is directly connected through surface water with the lagoon and further to the Mediterranean Sea by the lagoon and its various branches (Figure 1b). The discharge from the Köycegiz Lake is 33 m^3/s on average with up to 110 m^3/s during winter times (Bayari et al. 2001). During winter, most of the branches in the wetland areas in the lagoon are connected. In summer, Köycegiz Lake water level decreases (-0.9 m) reducing the hydraulic gradient to the Mediterranean Sea considerably. The depth of the main Dalyan channel decreases from 5 m upstream near the lake to about 1 m downstream near the Sea. In addition to the Dalyan Channel and its branches, the lagoon also includes the lakes Alagöl and Sülüngür. Maximum depths of these lakes are 4 m and 13 m, respectively. Aquaculture activities are conducted in Sülüngür Lake. Both, Köycegiz Lake and the Köycegiz-Dalyan Coastal Lagoon are part of the area declared as a Special Protection Area in 1988, as it is a unique and important ecosystem with a high diversity of species. It hosts one of the rare breeding and nesting sites for endangered sea turtles, *caretta caretta*, and possesses the ruins of Ancient City of Caunos and 4th century BC Lycian rock tombs that are found near the seaside by the river (Gurel et al. 2005). Groundwater is used as irrigation and drinking water in the area. We expect that the groundwater is mainly recharged locally from the surrounding forested mountains (up to 565 m asl.; Figure 1) of the karstic areas. The main sectors driving the economy in the watershed are agriculture, tourism and forestry. Aquaculture and capture fishing are among the important beneficial uses of the lagoon together with recreational activities.

The area is under the influence of typical Mediterranean climate characteristics, with a hot, dry summer season and a warm, rainy winter season with mean annual air temperatures of 18.3°C and mean annual precipitation of 1083 mm. These data were taken in the study area from the State Meteorology Services of Turkish Republic for Köycegiz Meteorology Station covering the period 1976-2010, and monthly averages are presented in Figure 2. Thus, precipitation usually occurs during the cold winter period and drought condition prevails during the hot summer period.

An environmental isotopic and hydrochemical study was conducted by Bayari et al. (1995) for determination of the dynamics of the upstream Köycegiz Lake. Köycegiz and Sultaniye are the two major basins that comprise Köycegiz Lake. According to their statements the important sources that feed the lake are mainly alluvial groundwater, streamwater (Namnam and Yuvarlakçay), and rain. The main components of outflow from the lake are discharge to Mediterranean Sea through the Dalyan Channel and evaporation from the lake surface. Their environmental isotopic data and chemical data indicate that rainfall and stream flow are low density waters and thermal groundwater is the high density water; complete annual mixing cannot be observed due to the density effects. The main geothermal inflow at the southern lake coast (Sultaniye Basin) is the Sultaniye spring. It is located at a depth of 8-10 m and about 4 km north-west of the lake exit into the Dalyan channel which is shallow (0-6 m) (Bayari et al., 2001); too shallow for receiving any geothermal influenced water from the Sultaniye Basin.

2.2 Conceptual Model

Identifying different water sources in the lagoon we set up a conceptual model distinguishing between dry (Figure 3a) and wet season (Figure 3b). For the dry season our hypothesis was that evaporation results in low water tables in the lagoon favouring both fluxes from Köycegiz Lake and the Sea into the lagoon. However, higher water levels maintain in the main Dalyan channel with freshwater flow from Köycegiz Lake to the Sea. Thus, we expected a density driven layering in the lagoon with (i) freshwater input from the lake in the top layer which is influenced by evaporation and (ii) saltwater input in the bottom layer mixed with groundwater (Figure 3a). We further expected that the seawater influence decreases with distance to the coastline. For the wet season our hypothesis was that freshwater input, mainly from groundwater and lake during baseflow conditions and additionally from precipitation during events, results in high water tables in the lagoon favouring freshwater flow from the lake through the lagoon into the Sea. We expected the lagoon water to be well mixed without distinct density driven layering (Figure 3b). For both season, we excluded any direct influence of the geothermal Sultaniye spring to the lagoon, because the spring’s influence was found only for the bottom layers of the Köycegiz Lake (Bayari et al. 1995) not outflowing into the shallow Dalyan channel and the lagoon but discharging northwards. Still, other unknown geothermal springs in the lagoon cannot be excluded.

2.3 Sampling campaigns

To quantify the different contributions of potential water sources like surface water, groundwater and seawater in the lagoon and how these water sources change over time and space, two sampling campaigns were conducted one representing the dry season (July 2011) and the other one representing the wet season (March 2012). Sampling in both seasons was without major antecedent rain events. Consequently, precipitation as major source in the lagoon can be neglected. Particularly in the wet season, water residence times in the lagoon are short due to high outflow rates from the lake (up to 110 m^3/s; Bayari et al. 2001) and which is also supported by modeling results of Ekdal (2008) indicating residence times <2 days for the wet season in the main lagoon channel.

Water samples were taken in the lagoon along the main channel (L1, L2, L3, L22, L4, L7, L33, L10, L29, L9, L8), surrounding lakes (L5, L13, L14) and their inflow/outflow connections to the lagoon system (L6, L11, L12, L15) as well as in the Köycegiz Lake and Mediterranean Sea in two depths at the top (T), just below the surface, and at the very bottom (B). The samples were taken by boat used for transportation from Dalyan town to Iztuzu Beach, except for Sülüngür Lake. Since aquaculture activities are conducted in this lake boat of the fishing cooperative was used for sampling. Further samples were taken from surrounding groundwater wells. Groundwater samples were taken with the pump of the well, which is used for abstracting water. In total, samples were taken at 18 lagoon, 11 groundwater, 1 sea and 1 lake locations (Figure 1b) which were further analysed for chemical analysis.

2.4 Water isotopes and chemical analysis

Water samples were analysed for $\delta^{18}O$ (± 0.15 ‰) and $\delta^{2}H$ (± 1 ‰) contents without any pre-treatment of the samples using a water isotope analyser (L2120-i, Picarro Inc., Santa Clara, CA, USA). The contents are given in the delta notation as δ-value (‰), which is the relative deviation of the sample from the V-SMOW (Vienna-Standard Mean Ocean Water). The results of the stable water isotope analysis from the observation area were compared to public available isotope contents in precipitation accessible through the IAEA (International Atomic Energy Agency) web database WISER (http://www-naweb.iaea.org/napc/ih/IHS_resources_isohis.html; 2014). Here, Antalya is the closest location of the Global Network of Isotopes in Precipitation (GNIP) having long-term isotope records in precipitation, which is 200 km east of the studied lagoon and 49 m asl. Based on these data, the Local Meteoric Water Line (LMWL; $\delta^{2}H = 8\ \delta^{18}O + 14.3$) and the annual weighed average isotope contents in precipitation ($\delta^{18}O$=-4.9‰; $\delta^{2}H$=-24.9‰) were calculated; monthly long-term weighed averages are shown in Figure 2.

Chloride concentrations (±0.22 mg/L) were measured by using Merck test kits (catalog number 1.14897.0001). NaCl stock solution, which has 1 mg Cl^{-} in 1 mL, was used in order to prepare standard solutions for controlling the reliability of chloride measurements carried out with Merck test kits. Salinity measurements (±0.1 mg/L) were conducted *in-situ* with YSI 6600V2 Multiparameter Water Quality Sonde.

2.5 Endmember mixing analysis

Calculating different water fractions in the lagoon system (top and bottom), three endmembers were defined that differed in isotopic composition and chloride concentrations/salinity: (i) Köycegiz Lake water, (ii) groundwater, and (iii) Mediterranean Seawater. The concentrations (C) of the endmembers were defined for both seasons separately. For lake (C_{LW}) and seawater (C_{SW}), the surface near water samples were taken and for groundwater an average concentration (C_{GW}) was calculated from all groundwater wells without considering GW011 due to increased chloride concentrations compared to other groundwater locations. Thus, the isotope contents (^{18}O) and chloride concentrations (Cl^{-}) or salinity (S) in the lagoon (C_{Lag}) were calculated from the three component mixing analysis:

$$C_{Lag_{18O}} = f_{GW} \cdot C_{GW_{18O}} + f_{LW} \cdot C_{LW_{18O}} + f_{SW} \cdot C_{SW_{18O}} \quad (1)$$

$$C_{Lag_{Cl}} = f_{GW} \cdot C_{GW_{Cl}} + f_{LW} \cdot C_{LW_{Cl}} + f_{SW} \cdot C_{SW_{Cl}} \quad (2)$$

$$C_{Lag_{S}} = f_{GW} \cdot C_{GW_{S}} + f_{LW} \cdot C_{LW_{S}} + f_{SW} \cdot C_{SW_{S}} \quad (3)$$

$$1 = f_{GW} + f_{LW} + f_{SW} \quad (4)$$

where f refers to the fraction of groundwater (GW), lake water (LW), and seawater (SW), respectively. Getting information about the uncertainty of the method, we calculated the mixing ratios based on two different approaches considering simultaneously δ^{18}O (Eq.1) and Cl$^-$ (Eq.2) or δ^{18}O (Eq.1) and salinity (Eq.3), both in combination with Eq.4.

3 Results

3.1 Stable isotopes of water

Results of stable isotope analysis are presented in Table 1. All analysed water samples plotted close or below the LMWL for both the dry (Figure 4a) and wet season (Figure 4b). Groundwater samples were the most depleted samples ranging from -6.2 to -5.7‰ for δ^{18}O, and were even lower compared to average precipitation contents (-4.9‰ for δ^{18}O). Assuming only negligible differences in isotopic composition of precipitation between Antalya and our observation area due to close proximity and similar location on the Mediterranean Sea, these differences support our assumption of higher altitude precipitation from surrounding mountains as major recharge source of groundwater. Average differences in elevation (400 m) and isotope contents (1.17‰ for δ^{18}O; 9.9‰ for δ^{2}H) give an altitude gradient of 0.29‰/100 m for δ^{18}O (2.5‰/100 m for δ^{2}H). These gradients are in accordance with values reported for Southern Adriatic region (0.24‰/100 m; Vreca et a. 2006), the global and Italian gradients (0.2‰/100 m; Bowen and Wilkison 2002, Longinelli and Selmo 2003) and simulated values for the Mediterranean Sea region (Lykoudis and Argiriou 2007).

In groundwater, more depleted contents were generally observed in the wet season compared to the dry season; however, absolute differences between seasons were small (0.21‰ for δ^{18}O; 2.8‰ for δ^{2}H). These differences can either result from a fraction of local seepage water with short residence times, from influence of seawater or from uncertainties of groundwater sampling. Well screening depths were unknown and therefore we expected some minor uncertainties when taking groundwater samples, i.e. water from same depths and taken with same flow rates during sampling.

Isotope contents of seawater were positive with more enriched contents in dry (1.5‰ for $\delta^{18}O$) compared to wet seasons (0.5‰ for $\delta^{18}O$). All Köycegiz Lake water samples plotted below the LMWL (Figure 4) indicating enrichment due to evaporation and potential geothermal water origin as found in previous studies (Bayari et al. 1995; 2001). When considering isotope contents of reported geothermal origin in the area (-0.81‰, -4.87‰, -4-76‰ and -2.9‰, -30.0‰, -27.2‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively; Bayari et al. 1995), it is evident that the geothermal origin is hidden in the evaporation signal and therefore these two sources cannot be distinguished considering isotope contents only. Additionally, a Local Evaporation Line (LEL) was determined considering the top lake samples for both seasons only. The resulting LEL ($\delta^{2}H = 5.40\ \delta^{18}O - 0.3$) is similar to another Turkish lagoon ($\delta^{2}H = 5.29\ \delta^{18}O - 0.55$; Lecuyer et al. 2012). It intersects the LWML in -5.85‰ $\delta^{18}O$ (-31.9‰ $\delta^{2}H$) which is also close to the average groundwater contents (-6.08‰ $\delta^{18}O$ and -34.84‰ $\delta^{2}H$) supporting assumption of higher elevation recharge area for the catchment.

Water samples from the lagoon mainly plotted on/below the LMWL and between groundwater and seawater samples. Distinct differences in isotopic contents were found (i) for the dry (Figure 4a) and wet season (Figure 4b) indicating a seasonally dynamic water body and (ii) for samples close to the surface (open squares, Figure 4) and the bottom of the lagoon (closed square, Figure 4) indicating a layered vs well mixed system in the dry and wet season, respectively. Particularly in the dry season, differences between top and bottom lagoon samples were obvious. Here, most interestingly, water samples at the bottom of the lagoon were more enriched compared to top water samples. This clearly indicates that the enrichment was not caused by evaporation but rather by mixing with enriched seawater which is more pronounced at the bottom due to salt water density effects. In the wet season, similar isotope contents were found for top and bottom samples except for samples from Alagöl (L5; -2.7‰, $\delta^{18}O$) and Sülüngür Lake (L13, L14; +0.64-0.68‰, $\delta^{18}O$) which had more enriched isotope contents at the bottom only. Here, top water samples showed similar ranges in isotope contents (-4.5 to -4.0 ‰, $\delta^{18}O$) compared to other lagoon samples (-5.0 to -4.0‰, $\delta^{18}O$).

3.2 Chloride vs. stable isotopes of water

Results of geochemical analysis are given in Table 1. Chloride and salinity showed similar spatiotemporal results and therefore, chloride results are discussed in more detail only. Chloride concentrations were in line with the results of stable isotope of water. Chloride was lowest in groundwater samples for both sampling times suggesting no or negligible seawater influence for most of these groundwater locations. Only one sampling site (GW11) showed increased chloride concentrations (460 mg/L in wet season and 2300 mg/L in dry season), which was also accompanied by higher water isotope contents in the dry compared to the wet season (Table 1). If this was caused by mixing with seawater, it would result in an increased seawater contribution of 7±5% for the dry season in GW11. Another reason could be short residence times of recharge from the unsaturated zone. Consequently, chloride originating from agricultural activities (irrigation, pomegranates) would be leached and diluted by winter precipitation with low isotope contents in the wet season.

Chloride concentrations were similar during both sampling campaigns in the dry and wet season at the bottom of the Köycegiz Lake (4500 and 4800 mg/L), but differences were measured at the top (2200 and 920 mg/L). High chloride concentrations were measured in seawater with 21700 mg/L and 20800 mg/L during the wet and dry season, respectively.

In the lagoon, chloride concentrations were generally higher in the dry season compared to the wet season (Figure 5, Table 1). In the dry season, a clear layering was also supported by the chloride concentrations which were higher at the bottom of the lagoon compared to its top. When looking at the chloride isotope relationship, lagoon samples were mainly plotting in the triangle of groundwater, Köycegiz Lake water and seawater samples suggesting three main endmembers in the system (Figure 5a). In the wet season, high chloride concentrations were only measured in the lagoon lake systems that also had enriched isotope contents (Figure 5b). All other lagoon samples had chloride concentrations lower than 5000 mg/L plotting in the triangle of groundwater, Köycegiz Lake water and seawater samples suggesting three main endmembers in the system (Figure 5b).

3.3 Endmember mixing analysis

The three component endmember mixing analysis was calculated for (i) the wet and dry season and (ii) for the top and bottom layer. The selected endmembers are given in Table 1 (asterisks) and the resulting source fractions for each location and season are given in Table 2.

For the wet season, average fractions of water sources were similar in the top and bottom of the lagoon (Figure 6b). The arithmetic average (median) of groundwater, lake and seawater contribution was 0.24 (0.25), 0.72 (0.73) and 0.04 (0.04) for the top and 0.21 (0.22), 0.62 (0.74), and 0.17 (0.02) for the bottom layer, respectively. Thus, the entire lagoon contained little seawater, and the main source was freshwater, either from the Köycegiz Lake or the groundwater. Certainly, we cannot exclude direct influence from precipitation having similar chemical composition compared to groundwater which will be further discussed below. High fractions of seawater were mainly found in the bottom of the lagoon lake systems (Figure 7d, Table 2). The more shallow Alagöl lake (L5; 3.3 m) contained about 34% seawater and 98% seawater were calculated for the deeper Sülüngür lake (L13, L14; 3.6-5.4 m) (Table 2). The branches of the lagoon showed slightly increased salt water contributions (9% top layer, 10% bottom layer) compared the Dalyan channel locations (2% top layer, 3% bottom layer) (Figure 7c,d). Besides, no variability in seawater and freshwater contribution was found with distance from the shore line (Figure 7c,d); the error bars in Figure 7 indicate the variability of the results when using $\delta^{18}O$ and Cl^- or $\delta^{18}O$ and salinity as signatures for the endmember mixing analysis.

For the dry season, average fractions of water sources were different compared to the wet season, and more variability was found within the lagoon and when comparing top and bottom of the lagoon (Figure 6a). The arithmetic average (median) of groundwater, lake and seawater contribution was 0.03 (0.01), 0.54 (0.43) and 0.43 (0.57) for the top and 0.09 (0.00), 0.20 (0.18), and 0.71 (0.83) for the bottom layer, respectively. Particularly the contribution of groundwater was little during the dry season (Table 2, Figure 6a). The lagoon contained more seawater in the dry season compared to the wet season and at the bottom compared to the top layers. Further, there was a gradient of salt water contribution in the lagoon with nearest distance to the shoreline (Figure 7a,b). The closer to the sea, the higher is the fraction of seawater. Still, the lagoon lake systems contained on average higher fractions of salt water (60%, top; 88%, bottom) compared to the Dalyan channel locations (35%, top; 69%, bottom) (Figure 7a). The branches of the lagoon seem to be more mixed compared to lake and channel locations (Figure 7a,b) containing on average 51% and 67% of seawater on top and bottom, respectively.

4 Discussion

The results clearly indicated differences in contribution of various water sources in the dry and wet season. We proved that it is an extremely dynamic system dominated by seawater in the dry season (>55%) and freshwater in the wet season (>95%). Lecuyer et al. (2012) also found higher contribution of freshwater (62%) compared to seawater (38%) in winter (wet season) assuming seawater and stream water as sole endmembers. Still, their open water lagoon on the Turkish coast was generally more dominated by seawater throughout the rest of the year; particularly in summer and autumn freshwater contribution seemed to be mostly absent and hypersaline conditions formed due to evaporation of seawater. In contrast, our study site had freshwater influence even in the dry season. Here, the freshwater mainly came from the upstream lake and groundwater contribution was minor. Thus, the lagoon is groundwater dependent only in the wet season. In addition, we cannot exclude direct precipitation as additional water source for the wet season; due to little precipitation in summer (3 mm in average) its influence during the dry season was assumed to be negligible. We expect that winter precipitation has similar isotopic composition compared to the local groundwater and therefore, any contribution of direct precipitation was hidden in the groundwater term. However, this hidden precipitation is suggested to be little when looking at the upstream Köycegiz Lake water balance and the size of the entire catchment (960 km²) compared to the lagoon size (130 km²). In the Köycegiz Lake precipitation is for example more than 15 times smaller compared to its outflow into the lagoon (Bayari et al., 1995). Additionally, we sampled during a period without precipitation and therefore, our results are representative for base flow conditions in the lagoon system.

We found different dynamics for the bottom and top layers and also for the different locations in the lagoon. Particular seasonal changes were dramatic in the main Dalyan channel closer to the coast and at its bottom (Figure 7b,d). We assume that the terrestrial water levels (groundwater, lake, lagoon) declined in the dry season influencing the hydraulic gradients and also density driven flow of the seawater further inland. Here, the intrusion reached up to 4 km inland at the bottom of the lagoon. A 50:50 mixing of salt and freshwater is expected for bottom layers at 4.9 km distance from the coast (Figure 7b) and for top layer at 1 km. The freshwater (seawater) mixing relationship with distance from the shoreline was best approximated by logarithmic (exponential) function (Figure 7). Still, the salt water intrusion was mainly restricted to the lagoon system itself as the groundwater wells were unaffected by seawater influence in the dry season. Our findings are in agreement with previous studies on hydrodynamic modelling in this area (Ekdal et al., 2005;Erturk et al., 2003;Gönenc et al., 2004). In these studies, similar spatial and temporal dynamics were obtained concluding that intrusion causes strong stratification throughout almost the entire lagoon especially in the dry season. The flow direction in the upper layer was from Köycegiz Lake towards the Mediterranean Sea, while flow in the bottom layer was from the Mediterranean Sea towards the Köycegiz Lake. Barotrophy was found to be the driving force of the surface flow, whereas the bottom flow was baroclinic (Gönenc et al. 2004).

In the present study, the endmember mixing analysis yielded lower uncertainties in the wet compared to the dry season (Figure 7), which is also obvious when looking at the endmember mixing triangles in Figure 5. For the wet season, the composition of the seawater endmember was adequate (Figure 5b). For the dry season though, higher chloride concentration as well as more enriched $\delta^{18}O$ were expected (Figure 5a) and thus, samples plot outside of the mixing triangle. This indicates that either the endmember was chosen wrongly or/and evaporation is crucial. Evaporation of surface water explains an increase in salt concentrations and isotopic enrichment like observed in a close-by lagoon (Lecuyer et al., 2012). Even though evaporation was actually considered indirectly by the lake endmember, evaporation of lagoon water could be higher due to the smaller water volume compared to the lake. Therefore, a stronger enrichment of stable isotopes explains the deviations of top surface water samples located outside of the mixing triangle in the dry season (Figure 5a). However, also enrichment of bottom samples was found in the dry season which is unusual and cannot be explained by evaporation only. Even hypersaline conditions in some of the bottom samples were found (compared to the Seawater sample). Interestingly, the slope of the Cl^--$\delta^{18}O$ relationship was steeper for bottom compared to top lagoon samples. It remained unknown whether an additional water source in the system has to be considered which was of geothermal origin as found for Köycegiz Lake (Bayari et al., 1995) and as common in this area due to geology and tectonic activity (Mutlu and Gülec, 1998).

Further assessing the two discussed uncertainties (i.e. choice of endmember and evaporation) and neglecting the small contributions of groundwater to the lagoon, a two component endmember mixing analysis was additionally conducted after correction of the data due to evaporation (Figure 5a; 2 EMMA mixing line). First, the seawater surface sample was replaced by the deep lagoon sample at the very end of the Dalyan Channel exiting into the Sea

(L08B). Here, chloride concentrations and also isotopes were even higher compared to the seawater sample. It was measured in the depth and we expect it to be representative to the actual seawater not influenced by any freshwater compared to the actual seawater sample from the surface. Therefore, L08B could be used as endmember for the dry season being representative for seawater too. Second, all lagoon samples were forced onto the mixing line accounting for enrichment due to evaporation. Therefore, an Evaporation Line was calculated considering the top lake sample for both seasons only ($Cl^- = 670\ \delta^{18}O + 4000$). Here, 10% increase in chloride was accompanied by 3.4% increase in $\delta^{18}O$. This regression was used to correct the lagoon data back to the mixing line. Similar procedures were done with salinity and isotope data (data not shown). The difference between measured and corrected chloride concentrations (salinity) was further used to do a mass balance calculation. Thus, relative, average evaporation were estimated at all sites (Table 3); they have to be seen as relative because the actual surface Köycegiz Lake water already comprised evaporation which was estimated to 6.8% (Bayari et al. 1995). The calculated evaporation in the lagoon ranged from 0 to 7%. There was only one outliner L2B (Figure 5a) with high chloride concentrations resulting in 54% evaporation based on chloride data; but with 0.2% evaporation based on salinity data. We attributed it to erroneous chloride analysis rather than to water influenced by geothermal origin because of differences in chemical and isotope characteristics compared to geothermal springs in this area (Bayari et al., 1995). The results of the two component endmember mixing approach yielded similar fractions of freshwater and marine water as the three component approach (Figure 8, Table 3). Considering uncertainties of the methods (Figure 7), no distinct differences in freshwater or saltwater sources were found hence. This suggested that for the dry season both groundwater and evaporation could be neglected in the system. Still, the correction of the data due to evaporation is kind of arbitrary forcing all values onto the mixing line. Only knowing the actual evaporation at individual locations and in the lake would help to adequately correct the data which even might push some results into the 3 endmember mixing triangle. Hence, fractions of groundwater even in the dry season would be underestimated by the current procedure of data correction.

Independent on the mixing approach, there were not only spatial differences in top and bottom layers for the main Dalyan channel, but also differences between different locations within the lagoon. The main channel responded quickly to changes and showed seasonal dynamics. The lake structures in the lagoon system were, however, responding differently. Here, the salt water was found in the bottom layer even in the wet season indicating maintenance of stratification; particularly in the larger and deeper Sülüngür Lake. A partial mixing was found for the smaller and shallower Alagöl Lake where salt water contribution was 34% (±20%). Also the side branches of the lagoon had less extreme changes as the main channel indicating higher water transit times in these areas and thus slower renewal. Particularly in the dry season, the contribution of fresh and salt water was about equal for the top layer and 2/3 to 1/3 for the bottom layer and independent on the distance to the coastline. These findings are in agreement with residence time calculations of a previous study (Ekdal, 2008) using the Water Quality Analysis Simulation Model. Average residence times of Sülüngür Lake (especially deeper parts of the lake) were considerably higher (16-700 d) when compared to other parts of the system (>16 d). The residence time in Alagöl (5-16 d) was also high when compared to the main channel. The main channel had a low residence time (<5 d), which showed the dynamic characteristics of the lagoon, and which is in agreement with the results of this study.

5 Conclusion

We showed that environmental tracers can be used not only to identify but also to quantify different water sources in a lagoon ecosystem. Freshwater and marine water sources were strongly dynamic and heterogeneous in time and space. We found different water sources and mixing ratios for dry and wet seasons and for top and bottom layers in the lagoon. In the wet season, freshwater was found in all locations and all depths except at the bottom of a larger lagoon lake. Generally, the freshwater was a mixture of upstream lake water and groundwater. The groundwater dependence was, however, mainly restricted to the wet season and almost absent in the dry season. It was assumed that water levels decline and the input of seawater in the lagoon gets more pronounced; particularly in the main flow channel of the lagoon. Here, a clear stratification was observed in the dry season only, with higher salt water contributions at the lagoon bottom compared to its top. At some of these locations, the lagoon changed from a complete freshwater system to a complete salt water system which certainly has implications for the ecosystem which has to be highly adapted to such dynamic conditions. At side branches and lake structures in this wetland type lagoon, changes in water sources were less extreme and variable. From these findings, we conclude that the lagoon and the groundwater could be vulnerable to certain global change scenarios like sea level rise and decrease in precipitation. Consequently, water levels in the groundwater and lake would drop and the seawater influence would increase in the lagoon system affecting its ecosystem functions and probably also affecting the groundwater quality. In future, it needs to be analysed how the ecosystem itself reacts to changes of water sources to investigate the vulnerability of the ecosystem functions.

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Table 1. Chemical analysis of water samples for the dry and wet season; asterisks indicate values used for endmember mixing analysis using either a three (3EMMA) or two (2EMMA) mixing approach.

	dry season					wet season				
Location	Depth (m)	Chloride (mg/l)	Salinity (g/l)	δ^{18}O (‰)	δ^{2}H (‰)	Depth (m)	Chloride (mg/l)	Salinity (g/l)	δ^{18}O (‰)	δ^{2}H (‰)
L01T	0.1	2400	3.8	-2.90	-16.4	0.1	930	3.1	-4.70	-24.9
L02T	0.1	2600	3.8	-2.87	-16.0	0.1	930	3.1	-4.51	-26.3
L03T	0.1	2800	4.0	-2.97	-16.4	0.1	930	3.2	-4.78	-24.8
L04T	0.1	3700	7.0	-2.71	-14.9	0.1	940	3.0	-4.93	-25.4
L05T	0.1	11400	23.6	-0.15	-1.3	0.1	2350	4.6	-4.50	-22.5
L06T	0.1	14900	22.3	-0.16	-0.7	0.1	1500	4.2	-4.72	-22.8
L07T	0.1	7800	16.1	-1.86	-10.8	0.1	1050	3.2	-4.68	-24.8
L08T	0.1	18600	37.9	1.45	9.2	0.1	1300	4.2	-4.74	-23.3
L09T	0.1	14700	29.3	0.59	3.3	0.1	1300	4.5	-4.44	-24.5
L10T	0.1	14700	27.6	0.47	2.2	0.1	840	3.4	-4.76	-24.7
L11T	0.1	15800	27.6	0.30	2.4	0.1	2150	5.9	-4.95	-27.8
L12T	0.1	13200	25.7	0.20	0.6	0.1	2500	6.9	-4.28	-22.9
L13T	0.1	18200	30.6	1.00	4.2	0.1	1400	7.6	-4.17	-21.9
L14T	0.1	17400	30.6	0.95	-0.6	0.1	1350	7.6	-3.97	-21.0
L15T	0.1	13900	-	-0.33	-1.3	0.1	1200	7.3	-4.43	-22.5
L22T	0.1	8700	16.7	-1.51	-8.8	0.1	950	3.2	-4.73	-24.4
L29T	0.1	13700	29.3	0.50	3.2	0.1	750	3.3	-4.62	-25.0
L33T	0.1	12000	25.0	-0.56	-2.9	0.1	950	3.4	-4.76	-23.8
L01B	3.8	3300	26.3	-2.86	-16.4	3.8	940	3.1	-4.73	-24.7
L02B	4.4	3600	27.8	-0.12	-0.8	4.4	940	3.2	-4.7	-24.4
L03B	2.5	3700	31.8	-2.90	-16.6	2.4	950	3.2	-4.7	-24.8
L04B	2.1	20000	32.7	0.73	4.3	2.0	970	3.1	-5.01	-27.0
L05B	3.3	22300	38.2	1.43	8.1	3.2	7100	19.4	-2.7	-12.3
L06B	1.4	12800	32.1	-0.09	-0.9	1.7	1600	4.7	-4.58	-23.1
L07B	2.0	21400	35.8	1.13	7.5	1.9	1100	3.1	-4.90	-23.8
L08B*$^{, 2EMMA}$	1.1	23800	39.7	1.16	7.4	1.1	1300	4.3	-4.44	-23.9
L09B	1.3	24200	39.0	1.35	7.9	1.2	1700	5.4	-4.33	-23.4
L10B	1.1	21800	33.8	1.30	7.1	1.3	930	3.4	-4.78	-24.0
L11B	1.5	17100	31.2	1.02	4.4	1.5	3500	7.5	-4.34	-21.3
L12B	1.5	14300	34.6	0.66	2.4	1.5	3600	7.3	-4.31	-21.4
L13B	3.4	18300	36.5	1.07	4.6	3.6	21600	41.2	0.64	4.9
L14B	5.4	18100	36.9	0.76	4.3	5.4	21000	41.2	0.68	3.0
L15B	1.6	16400	-	0.65	4.0	1.6	1320	8.0	-4.05	-21.9
L22B	3.0	22100	35.9	0.97	5.9	3.0	980	3.3	-4.66	-24.8
L29B	1.8	17500	35.5	0.93	5.5	1.8	850	3.3	-4.58	-24.8
L33B	3.8	19800	38.8	1.11	7.0	3.8	3400	11.3	-3.71	-18.5
GW03	-	132	0.4	-5.27	-25.8	-	-	-	-	-
GW04	-	117	0.4	-6.10	-34.7	-	111	0.4	-6.08	-34.1
GW05	-	146	0.5	-6.03	-34.3	-	88	0.4	-6.25	-34.8
GW11	-	2300	1.3	-6.39	-36.1	-	460	1.1	-6.66	-43.4
GW14	-	69	0.3	-6.35	-35.5	-	41	0.3	-6.46	-38.3
GW15	-	41	0.3	-6.32	-36.0	-	40	0.3	-6.22	-36.6
GW18	-	42	0.4	-6.02	-32.9	-	16	0.5	-5.62	-35.2
GW19	-	25	0.3	-6.63	-37.6	-	-	0.3	-6.55	-38.9
GW20	-	56	0.4	-5.77	-30.0	-	18	0.2	-6.60	-39.5
GW25	-	57	0.6	-5.24	-29.0	-	50	0.5	-5.25	-31.0
GW29	-	46	0.4	-5.87	-33.5	-	26	0.4	-6.00	-34.1
GW*	-	73	0.4	-6.00	-32.9	-	49	0.4	-6.17	-36.6
Sea*$^{, 3EMMA}$	0.1	20800	40.0	1.45	9.1	0.1	21700	39.2	0.49	1.1
Lake*	0.1	2200	3.7	-2.88	-15.9	0.1	920	3.2	-4.38	-23.4
Lake	12.8	4500	11.2	-2.26	-11.5	12.7	4800	13.6	-2.27	-12.0

Table 2. Average results of the three component endmember mixing analysis giving the contributions of groundwater (f_{GW}), lake water (f_{LW}) and seawater (f_{SW}) in the lagoon top and bottom for dry and wet season.

	dry season			wet season		
	f_{GW}	f_{LW}	f_{SW}	f_{GW}	f_{LW}	f_{SW}
Location -TOP						
L01	0.020	0.975	0.005	0.210	0.780	0.010
L02	0.015	0.970	0.015	0.080	0.915	0.005
L03	0.070	0.905	0.025	0.265	0.720	0.015
L04	0.075	0.830	0.095	0.360	0.620	0.020
L05	0.000	0.559	0.441	0.255	0.675	0.070
L06	0.045	0.400	0.551	0.320	0.630	0.050
L07	0.140	0.530	0.335	0.210	0.775	0.015
L08	0.000	0.189	0.811	0.320	0.640	0.040
L09	0.000	0.431	0.569	0.130	0.835	0.035
L10	0.000	0.447	0.549	0.260	0.730	0.010
L11	0.000	0.335	0.665	0.605	0.290	0.105
L12	0.000	0.513	0.488	0.230	0.665	0.105
L13	0.000	0.307	0.693	0.135	0.790	0.070
L14	0.000	0.332	0.668	0.065	0.825	0.110
L15	0.030	0.650	0.320	0.250	0.665	0.085
L22	0.055	0.580	0.360	0.240	0.745	0.015
L29	0.000	0.468	0.532	0.150	0.840	0.010
L33	0.040	0.400	0.560	0.265	0.720	0.015
Location - BOTTOM						
L01	0.335	0.420	0.245	0.225	0.765	0.010
L02	0.020	0.645	0.335	0.220	0.775	0.005
L03	0.360	0.380	0.258	0.235	0.760	0.005
L04	0.088	0.140	0.772	0.425	0.555	0.020
L05	0.056	0.050	0.894	0.200	0.460	0.340
L06	0.100	0.250	0.650	0.250	0.695	0.050
L07	0.073	0.075	0.852	0.355	0.630	0.015
L08	0.145	0.000	0.855	0.115	0.865	0.020
L09	0.108	0.015	0.874	0.130	0.815	0.060
L10	0.061	0.168	0.770	0.280	0.705	0.015
L11	0.000	0.349	0.651	0.375	0.480	0.145
L12	0.030	0.305	0.674	0.350	0.505	0.145
L13	0.000	0.150	0.850	0.025	0.000	0.975
L14	0.060	0.060	0.880	0.025	0.000	0.975
L15	0.000	0.300	0.700	0.110	0.815	0.075
L22	0.107	0.055	0.838	0.205	0.785	0.010
L29	0.000	0.175	0.825	0.135	0.855	0.010
L33	0.045	0.005	0.950	0.150	0.675	0.175

Table 3. Average results of 2 component endmember mixing analysis giving the contributions of lake water (f_{LW}) and seawater (f_{SW}) in the lagoon top and bottom for the dry season; average relative percentages of evaporation calculated for dry season based on data correction (details given in text).

	f_{LW}	f_{SW}	evaporation (%)
Location -TOP			
L01T	0.993	0.007	-
L02T	0.989	0.011	0.1
L03T	0.975	0.025	-
L04T	0.913	0.087	-
L05T	0.540	0.460	5.3
L06T	0.469	0.531	3.3
L07T	0.689	0.311	-
L08T	0.179	0.821	3.7
L09T	0.389	0.611	4.7
L10T	0.412	0.588	4.7
L11T	0.376	0.624	3.1
L12T	0.472	0.528	5.0
L13T	0.292	0.708	4.3
L14T	0.312	0.688	4.5
L15T	0.472	0.528	2.1
L22T	0.671	0.329	0.7
L29T	0.413	0.587	5.0
L33T	0.483	0.517	1.6
Location - BOTTOM			
L01B	0.598	0.402	-
L02B	0.667	0.333	0.2
L03B	0.494	0.506	-
L04B	0.198	0.802	1.4
L05B	0.075	0.925	1.9
L06B	0.365	0.635	2.4
L07B	0.126	0.874	1.7
L08B	0.000	1.000	-
L09B	0.016	0.984	0.8
L10B	0.156	0.844	2.9
L11B	0.312	0.688	4.8
L12B	0.315	0.685	3.6
L13B	0.194	0.806	2.6
L14B	0.181	0.819	1.4
L15B	0.374	0.626	4.2
L22B	0.100	0.900	0.8
L29B	0.226	0.774	2.7
L33B	0.118	0.882	1.5

Figure Captions

Figure 1. Geographic location of the Köycegiz-Dalyan Coastal Lagoon (a) and sampling locations (b); source of modified satellite picture was Google Earth (2014).

Figure 2. Long-term monthly data of average precipitation (grey bars) and air temperature (solid line) from Köycegiz meteorology station (1976-2010) and isotopic composition of precipitation in Antalya (dashed line). Data from Antalya are available at the IAEA database WISER (http://www-naweb.iaea.org/napc/ih/index.html; accessed 19.05.2014).

Figure 3. Conceptual model of flow connections between the lagoon and surrounding water bodies for (a) the dry and (b) wet season.

Figure 4. Dual isotope plot for (a) dry season and (b) wet season sampling campaign; LMWL and average precipitation taken from closest station of the GNIP data base i.e. Antalya. Figure 5. Chloride concentrations and δ^{18}O ratios for (a) dry season and (b) wet season sampling campaign; the dashed lines connect the three (bold) or two (light) endmembers used for the three component mixing analysis.

Figure 6. Fractions of different sources of the lagoon water for (a) dry and (b) wet season sampling campaign.

Figure 7. Changing fractions of freshwater (circles) and marine water (triangles) with distance from the coastline for (a) the top layer in the dry season, (b) bottom layer in the dry season, (c) top layer in the wet season, (d) bottom layer in the wet season; closed dark symbols indicate locations at the main lagoon channel, open symbols indicate surrounding lake locations and closed light symbols indicate their inflow/outflow connections to the lagoon system; error bars were determined from variability of endmember mixing analysis using salinity and chloride data individually in combination with δ^{18}O.

Figure 8. Fractions of freshwater (a) and seawater (b) contributions in the top and bottom lagoon samples calculated from two and three endmember mixing approaches; dashed line gives 1:1 line.

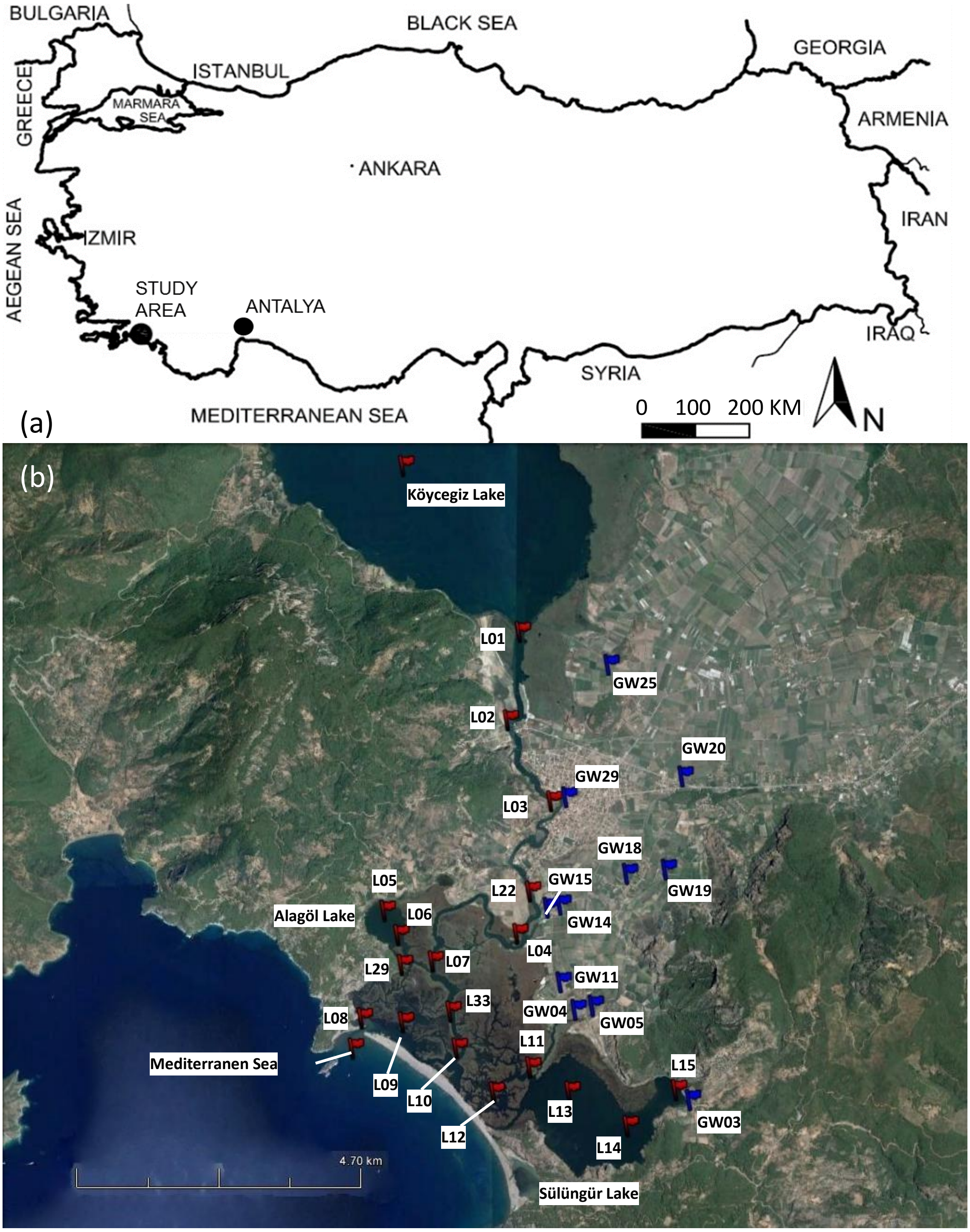
(a)
BULGARIA
BLACK SEA
GEORGIA
GREECE
ISTANBUL
MARMARA SEA
ARMENIA
ANKARA
IRAN
AEGEAN SEA
IZMIR
STUDY AREA
ANTALYA
IRAQ
SYRIA
MEDITERRANEAN SEA
0 100 200 KM
N
(b)
Köycegiz Lake
L01
GW25
L02
GW20
GW29
L03
GW18
GW19
L05
L22
GW15
GW14
Alagöl Lake
L06
L04
L29
L07
GW11
L33
GW04
GW05
L08
L11
Mediterranen Sea
L09
L10
L15
L13
GW03
L12
L14
4.70 km
Sülüngür Lake

Figure 1

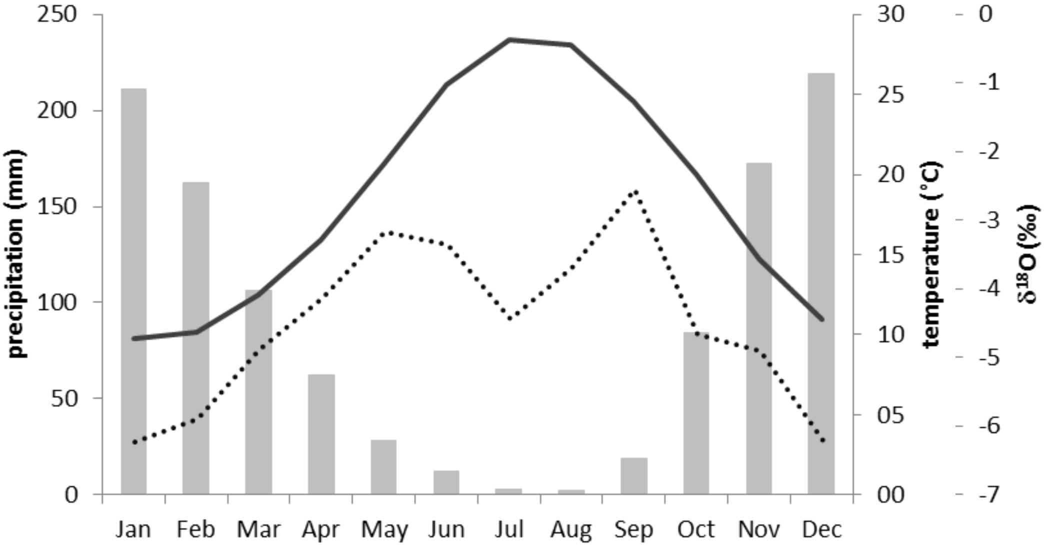
precipitation (mm)
250
200
150
100
50
0
temperature (°C)
30
25
20
15
10
05
00
$\delta^{18}O$ (‰)
0
-1
-2
-3
-4
-5
-6
-7
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 2

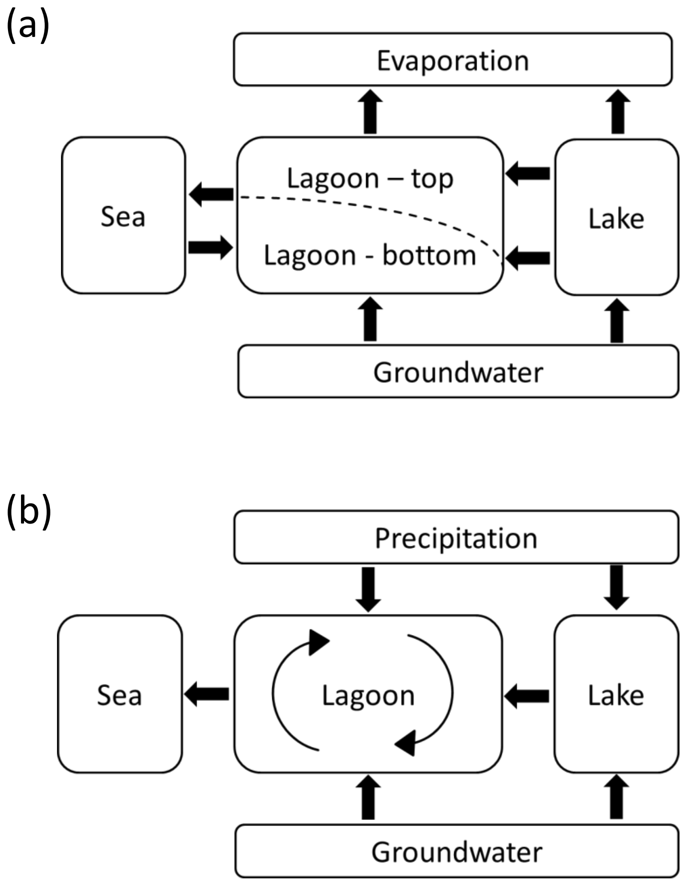
(a)
Evaporation
Sea
Lagoon – top
Lagoon - bottom
Lake
Groundwater
(b)
Precipitation
Sea
Lagoon
Lake
Groundwater

Figure 3

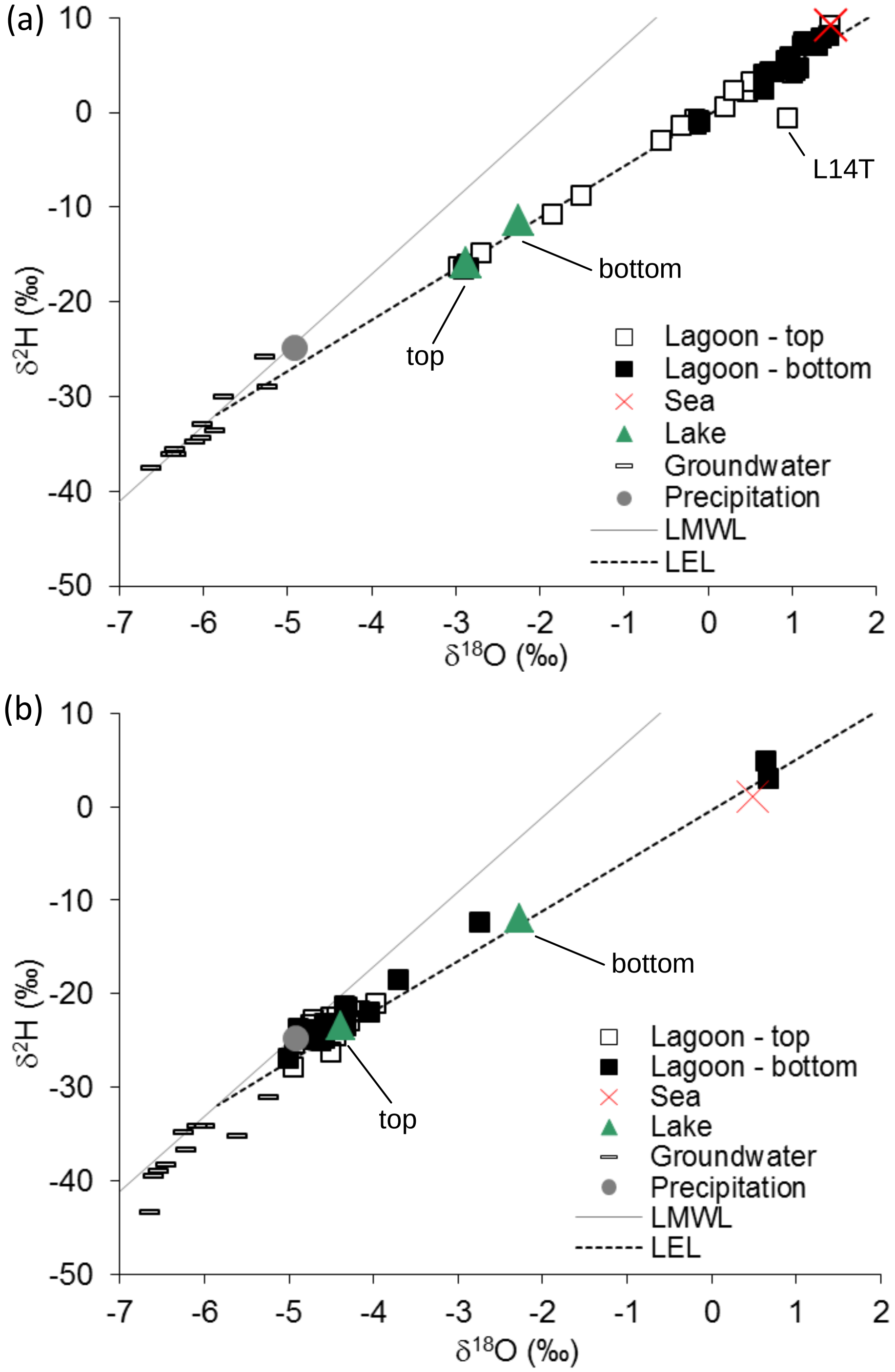
(a)
10
0
-10
-20
-30
-40
-50
δ²H (‰)
-7
-6
-5
-4
-3
-2
-1
0
1
2
δ¹⁸O (‰)
L14T
bottom
top
□ Lagoon - top
■ Lagoon - bottom
× Sea
▲ Lake
▭ Groundwater
● Precipitation
LMWL
LEL
(b)
10
0
-10
-20
-30
-40
-50
δ²H (‰)
-7
-6
-5
-4
-3
-2
-1
0
1
2
δ¹⁸O (‰)
bottom
top
□ Lagoon - top
■ Lagoon - bottom
× Sea
▲ Lake
▭ Groundwater
● Precipitation
LMWL
LEL

Figure 4

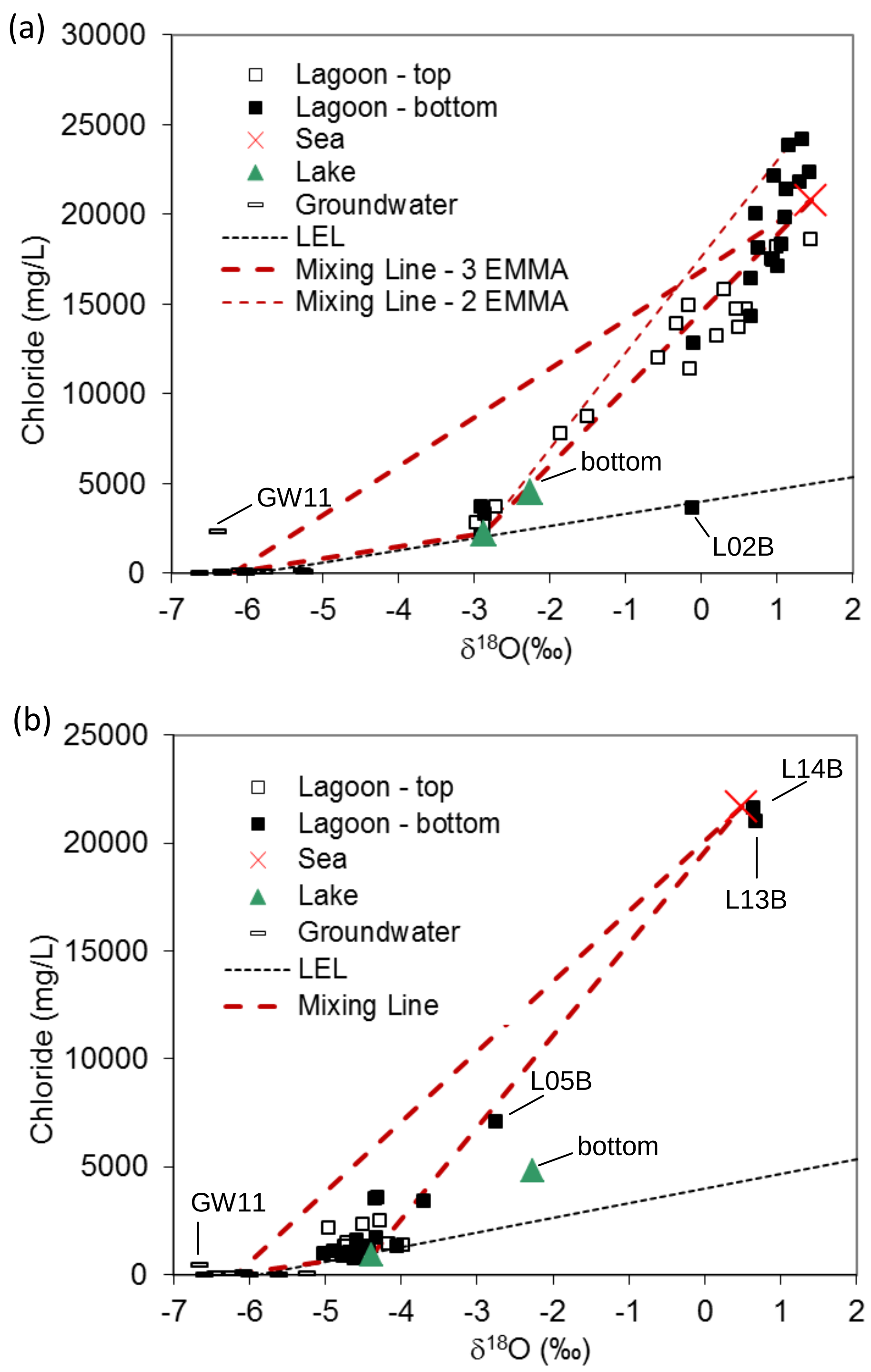
(a)
30000
25000
20000
15000
10000
5000
0
Chloride (mg/L)
-7
-6
-5
-4
-3
-2
-1
0
1
2
δ18O(‰)
Lagoon - top
Lagoon - bottom
Sea
Lake
Groundwater
LEL
Mixing Line - 3 EMMA
Mixing Line - 2 EMMA
GW11
bottom
L02B
(b)
25000
20000
15000
10000
5000
0
Chloride (mg/L)
-7
-6
-5
-4
-3
-2
-1
0
1
2
δ18O (‰)
Lagoon - top
Lagoon - bottom
Sea
Lake
Groundwater
LEL
Mixing Line
L14B
L13B
L05B
bottom
GW11

Figure 5

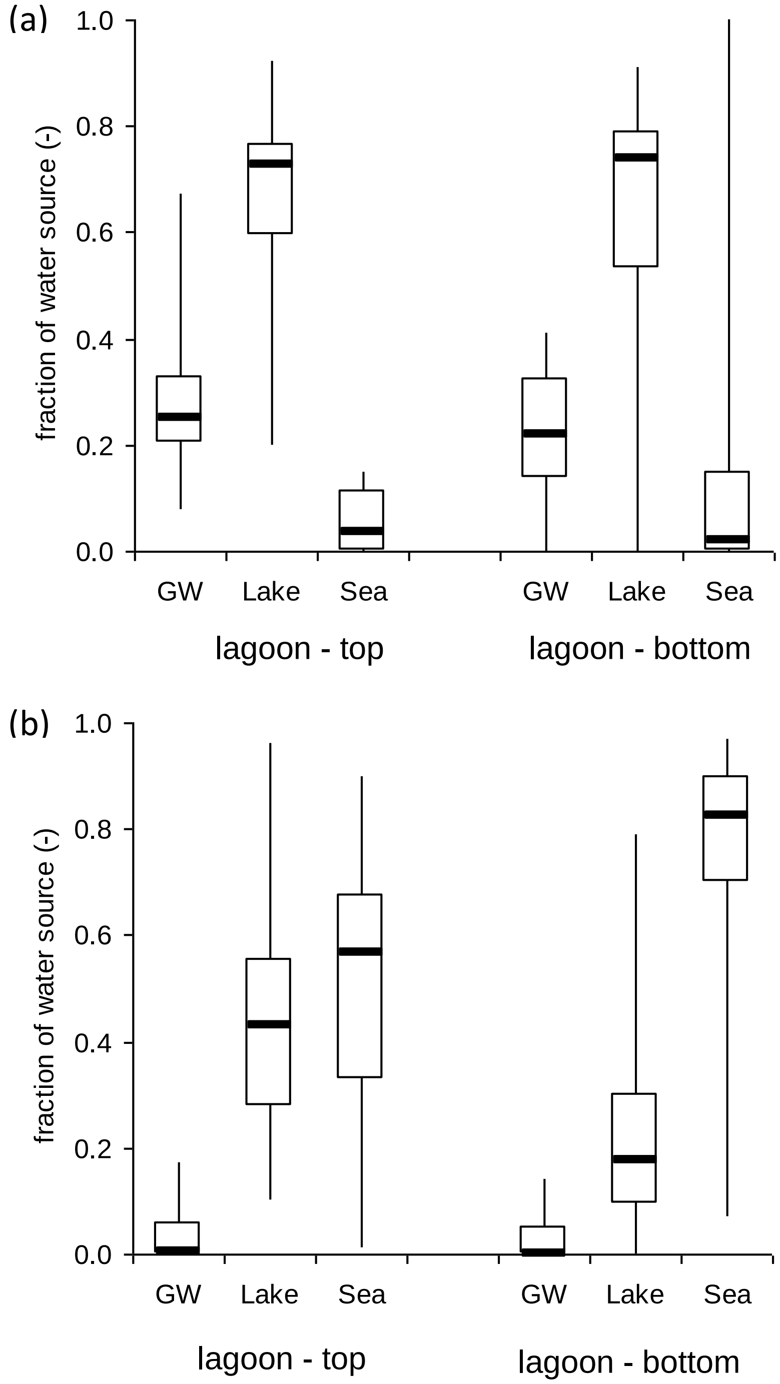
(a)
1.0
0.8
0.6
0.4
0.2
0.0
fraction of water source (-)
GW
Lake
Sea
GW
Lake
Sea
lagoon - top
lagoon - bottom
(b)
1.0
0.8
0.6
0.4
0.2
0.0
fraction of water source (-)
GW
Lake
Sea
GW
Lake
Sea
lagoon - top
lagoon - bottom

Figure 6

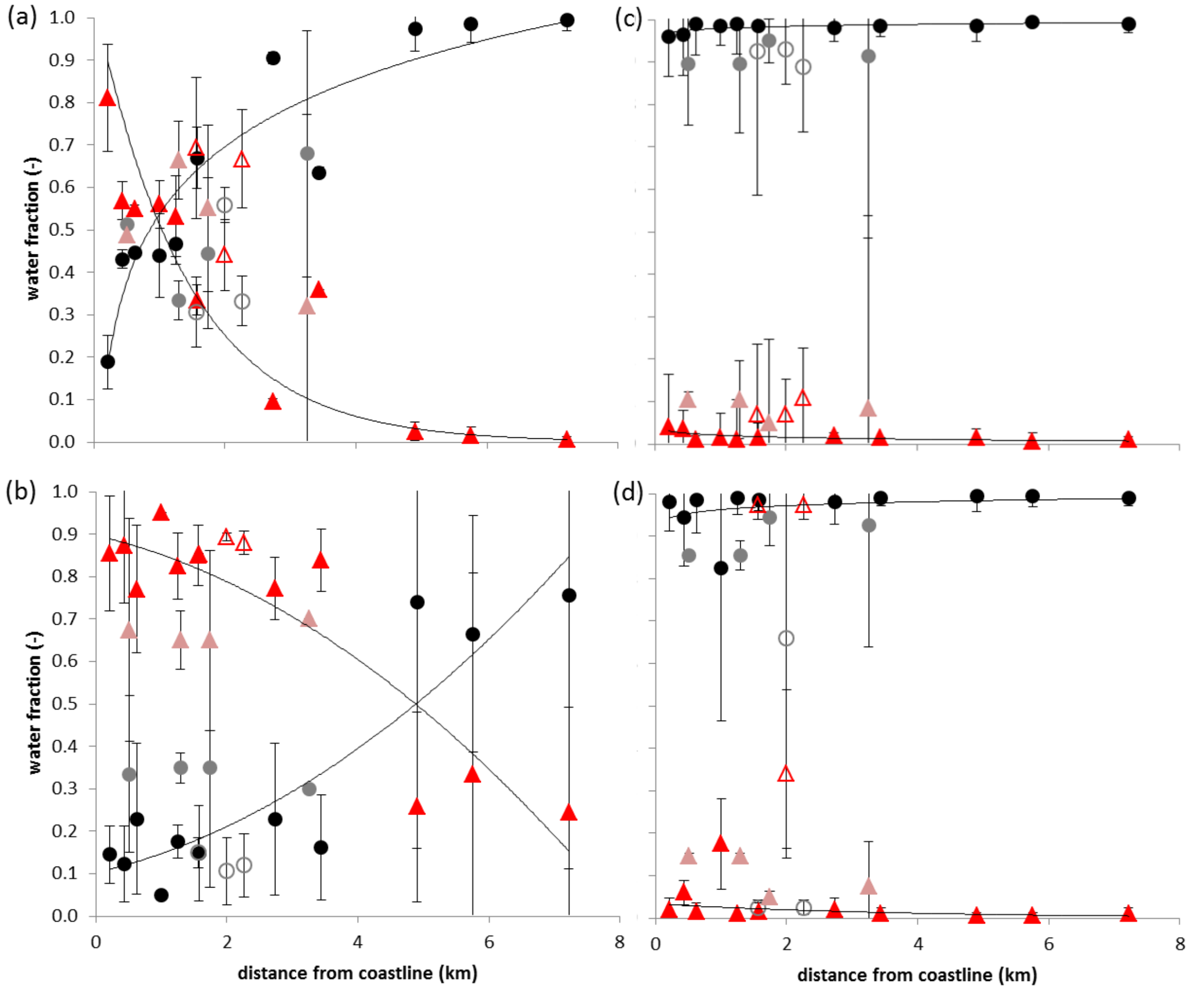
(a)
(b)
(c)
(d)
water fraction (-)
water fraction (-)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
distance from coastline (km)
distance from coastline (km)

Figure 7

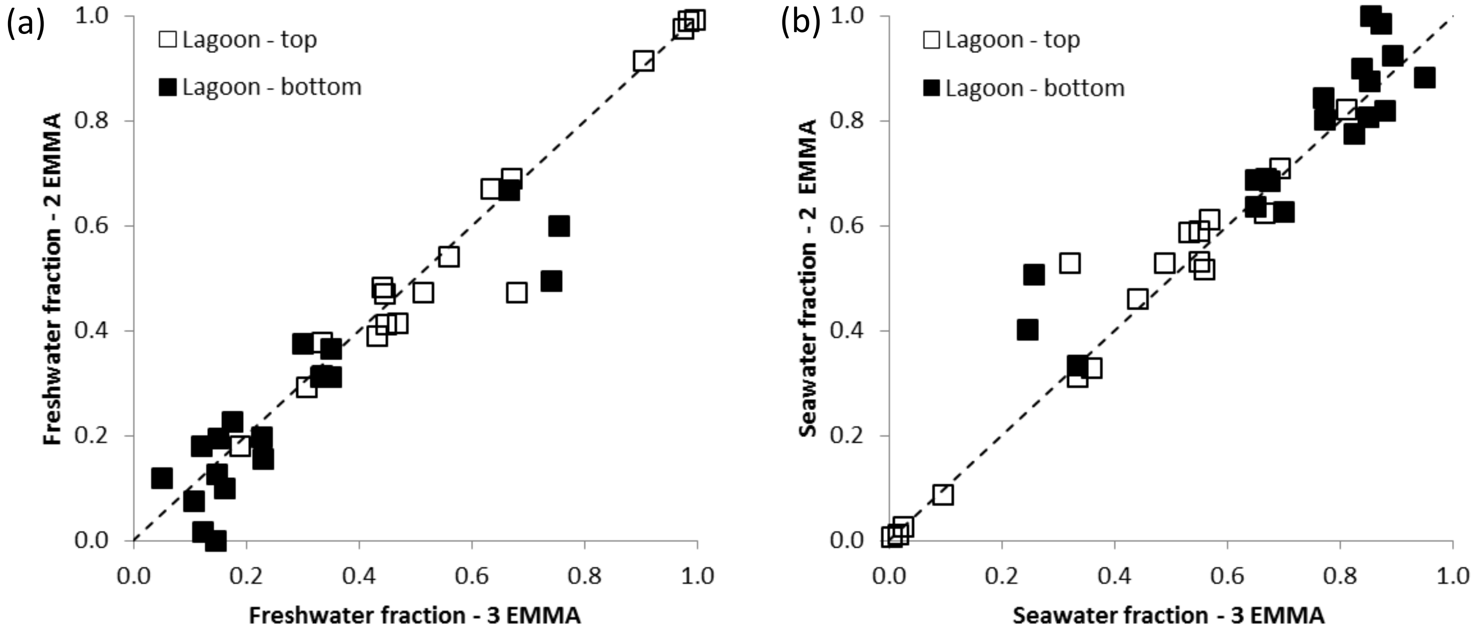
(a)
☐ Lagoon - top
■ Lagoon - bottom
Freshwater fraction - 2 EMMA
Freshwater fraction - 3 EMMA
0.0
0.2
0.4
0.6
0.8
1.0
(b)
☐ Lagoon - top
■ Lagoon - bottom
Seawater fraction - 2 EMMA
Seawater fraction - 3 EMMA

Figure 8