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Research Article

Evidence of submarine groundwater discharge (SGD) along the northern Persian Gulf: Insights from physicochemical profiles and structural geology

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Abstract

Submarine groundwater discharge (SGD) plays a significant role in the hydrological and environmental balance of arid coastal systems like the Persian Gulf. This study investigates the presence of SGD signals along the northern coastline of the Persian Gulf using seawater physicochemical data from the 1992 Mt. Mitchell oceanographic survey—prior to major anthropogenic impacts such as desalination activities. A total of 74 vertical seawater profiles were analyzed, each containing high-resolution measurements of salinity (36.59–43.93 psu), temperature, and dissolved oxygen (1.31–5.85 ppm) from the surface to seabed. The results reveal unusual stratification patterns—such as freshening near the seabed and increased oxygen levels—particularly near the Kazerun-Qatar (KQF), Hendijan-Bahregansar (HBF), and Karehbas (KMF) fault zones. These anomalies strongly suggest offshore freshwater inflow, likely controlled by deep fault systems extending from the Zagros Mountains. By using historical, pre-desalination datasets, this study minimizes confounding from modern effluents and introduces a novel, regional-scale approach for detecting SGD in the Persian Gulf. The findings highlight the possible influence of deep-seated fault zones in offshore SGD, especially in the western basin. These insights offer a novel approach to water resource assessment and SGD monitoring across the Zagros domain.

Keywords: Submarine groundwater discharge, SGD, fault zone, ROPME, Persian Gulf.

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Introduction

In general, wherever the coastal aquifer is hydraulically connected to the sea, terrestrial groundwater may discharge into the sea. Therefore, the submarine groundwater discharge (SGD) is a phenomenon through which water and solutes may be transferred to the surface water bodies (Taniguchi et al, 2002; Burnett et al, 2003). Although this phenomenon has been studied mainly from an environmental point of view, in arid areas, it can make significant amounts of fresh water inaccessible (Moosdorf and Oehler, 2017). So studying the SGD in the coasts of arid regions may also have applications for fresh water management. The water shortage crisis is one of the most critical issues in the Middle East and the arid countries surrounding the Persian Gulf (Qureshi, 2020). The northern coasts of the Persian Gulf are bordered by the Zagros Mountains. Recent droughts, have minimized the streams flow rate, dried up many lakes, and have raised serious alarms not only for drinking water but also for creating major environmental problems (McGirr et al, 2024). This study investigates the presence of SGD signals along the northern coastline of the Persian Gulf using available seawater physicochemical data (Appendix 1).

Ancient climate studies indicate that in the last ice age, the global water level was about 100 to 130 meters lower than the current level, so that until 14,000 years ago, the Persian Gulf was a wide valley (Rose, 2010). The old rivers of the Tigris and Euphrates and other small and large rivers were flowing there. Archaeological evidence also shows that the Persian Gulf basin has been the settlement of human until 8000 years ago (Rose, 2010). Then, the water level rose gradually and submerged the Persian Gulf. In fact, the springs within the Persian Gulf basin could form when the absolute basal level of erosion (sea) was lower than the current level (Milanovic, 2005). The first official submarine groundwater discharge report in the Persian Gulf is related to groundwater artesian springs (Judd and Hovland, 2007). Additionally, fresh submarine groundwater discharge (FSGD) reported from shallow waters of the Bahrain (Farzin, 2017). It has also been said that Bahraini pearl fishermen could spend very long time at sea as they could provide potable water from submarine springs (Chapman, 1981). Farhoudi and Poll (1992) discussed that a significant part of groundwater resources (especially karst water resources) are likely directed to the Persian Gulf from Zagros Mountains, Iran, through large faults. The evidences that Farhoudi and Poll (1992) used to present this theory are as follow: 1) the Persian Gulf has an asymmetric shape, so that the slope of the Iranian side is five times greater than the slope of the southern parts; 2) the northern part of the Persian Gulf receives considerable more rainfall in comparison with the southern parts, but high flow rate springs are emerged at aquifers located south of the Persian Gulf; 3) the aquifers of southern Iran have spread under the Persian Gulf and are expanded to the north of the Arabian homocline; 4) the average depth of the Persian Gulf is ~35 meters and the groundwater can flow into the Persian Gulf from northern aquifers; 5) the water salinity of some Dubai oil reservoirs is eight times less than the Persian Gulf water. The US National Oceanic and Atmospheric Administration (NOAA) surveyed totally 13 logs through the Sea of Oman, Strait of Hormuz, and the Persian Gulf using the Mt Mitchell vessel in 1992 (Reynolds, 1993). Results from this extensive campaign provided several vertical profiles for seawater salinity and temperature which does not indicate any abnormality in the salinity of the Persian Gulf water bed and the water salinity increases gradually with increasing depth. In a latter investigation, Alessi et al. (1999) studied hydrography of the Persian Gulf by using the following data to investigate the physicochemical properties of the waters of the Oman Sea and the Persian Gulf: 1) archived data at the US Naval Oceanographic Office; and 2) the information obtained from the marine scientific surveys of the NOAA research vessel Mt Mitchell. In this research, the area of the Persian Gulf was divided into 7 parts and the depth profiles of salinity and water temperature were plotted. Although the purpose of this research was not to investigate the possibility of submarine groundwater discharge; investigations show that the profiles of Persian Gulf water salinity around the Kazerun-Qatar Fault (KQF) are separated in two distinct groups of graphs. Therefore, although these charts do not confirm the presence of SGD in the desired part; they indicate a kind of abnormality that should be investigated more carefully. Jafari and Fuladi (2024) assessed the potential of water outflow from the folds of Zagros Mountains to the

Persian Gulf by evaluating the relationship between precipitation and elevation in several basins in the Zagros Mountains. They estimated that approximately 110,695 billion cubic meters of water were channeled to the Persian Gulf via the tidal currents of the Zagros Mountains. Rausch and Dirks (2024) did a review on the hydrogeology of the upper mega aquifer system on the Arabian Platform. They highlighted that the Persian Gulf borders the mega aquifer system on the Arabian Platform to the east. They added that the flow to the Persian Gulf is estimated at 12 m3/s (378 MCM/a) for the predevelopment state, but due to the high groundwater abstraction rate in the inflow area, the current discharge rate has reduced to 10 m3/s (315 MCM/a). McGirr et al. (2024) mentioned that the significant reductions in continental hydrology contributions to ocean mass in the Persian Gulf and several other basins were caused by decreased strength in the direct gravitational attraction due to declining terrestrial water storage in Asia since 2002. They added that anthropogenic intervention, such as extraction of groundwater resources, increased far-field manometric sea level, but caused decreased local sea level of up to ∼1 mm/yr in the case which rates of near-field sea-level fall were comparable in magnitude to the longer-term contributions of the polar ice sheets and mountain glaciers, at times masking ∼80% of the sea level increase caused by melting of ice-covered regions. They concluded if this extraction of groundwater ceases, then near-field regions such as the Persian Gulf would see an increase in the rate of local sea-level rise of up to 1 mm/yr. In a recent research conducted by Farzin (2017) and Farzin et al. (2019) on the Bushehr province coastline, Iran, areas with SGD potential were identified. This study was based upon the following data: 1) sea surface temperature (SST) in the vicinity of karst aquifers; 2) the geomorphometric indices of land areas near the studied coastline; and 3) structural geologic features. Although the results of this research showed the possibility of SGD along the studied coastline, there is still no evidence and useful documentation about the deeper parts of the Persian Gulf (along the KQF). Bhandary and Sabarathinam (2020) used the naturally occurring radioactive isotopes to identify and estimate the SGD in the coastal strip of Kuwait along the Persian Gulf. They were able to determine the loss of brackish groundwater from inland of Kuwait. Samani et al. (2021) applied Landsat 8 thermal sensor data to identify potential sites of SGD at a regional scale in the northern coasts of Persian Gulf. They analyzed the relationships between the remotely-sensed sea surface temperature (SST) patterns and geo-environmental variables of upland watersheds using logistic regression model for the first time. They found that the percentage of karstic lithological formation and topographic wetness index were key variables influencing SGD phenomenon in the northern coasts of the Persian Gulf. Heydari et al. (2021) studied temporal and spatial changes of SST and STA in the Persian Gulf to find anomalies occurred in the Bandar Magham, Bandar Nakhiloo, and coasts of Bandar Divan, Bandar Shenas, Bandar Lengeh, and Bandar Kong indicate that these areas have a very high probability of underground aquifers. Meanwhile, the presence of SGD evidence in the deeper parts of the Persian Gulf and along KQF indicates the flow of groundwater from the high areas of the Zagros Mountains under the influence of the bedrock faults in the region (Farzin, 2017). Moreover, the probabilities of SGD occurrence has always been a scientific challenge in Iran and hypothesizes about the possibility of SGD into the Persian Gulf from northern coastline are still unclear. There are several examples around the world that emphasize on the role of fault zone or deep fault zone aquifers in water discharge from coastal zones to the sea (Borisenko, 2001; Shaban et al, 2005; Akawwi, 2006, Akawwi et al, 2008; Peng et al, 2008; Charkin et al, 2017; Cantarero et al, 2019). This research aims to investigate the possibility of SGD in the Persian Gulf by examining the historical data of the seawater physic-chemical properties including salinity, temperature, and dissolved oxygen. The result of this study is very important because it may create a new paradigm to water resources management and water supply projects in the Persian Gulf countries (especially Iran). Additionally, it will create a new scope in the study of the Persian Gulf coral ecosystem by considering the environmental effects of submarine groundwater discharge as a significant phenomenon and source of nutrients.

Study area

The Persian Gulf is the present-day position of the Cenozoic foreland basin that has migrated southwestward in front of the advancing Zagros deformation (Fig. 1) (Hessami et al, 2001; Jahani et al, 2009; Pirouz et al, 2015).

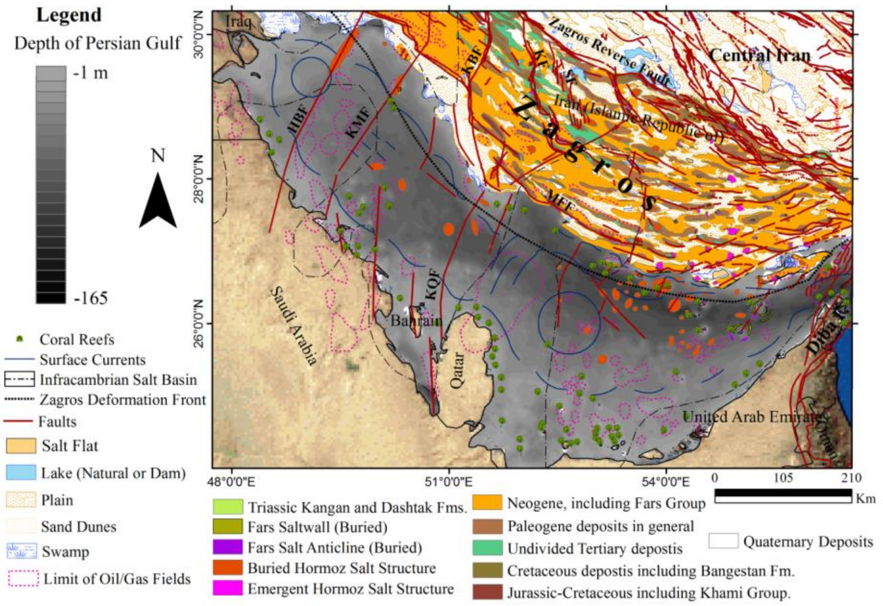

Fig. 1: The map shows main geological features and faults of the Persian Gulf and surrounding area. Fault data are compiled from several references but mainly from Huber (1976), Ross et al. (1986), Nogol-Sadat and Almasian (1993), Hassanpour et al. (2021), Mohammadrezaei et al. (2020). Data of salt structures kindly received from Dr. Hassanpour. Other used references for geology of the area include Haghipour and Aghanabati (1985) and Al-Husseini (2000). Boundary of oil/gas fields are from Soleimany and Sabat (2010) and Mohammadrezaei et al. (2020). Acronyms- MFF: Mountain Front Fault, KBF: Kazerun-Borazjan Fault, KQF: Kazerun-Qatar Fault, KF: Karehbas Fault, SF: Sabzepushan Fault, HBF: Hendijan-Bahregansar Fault. Surface currents adapted from Reynolds (1993).

The Persian Gulf in south of the Southeastern Zagros fold-and-thrust belt and west of the Northern Oman Mountains separates the Makran accretionary wedge in the east from the Arabian Platform in the southwest by Minab-Zendan Transfer Fault. The Southeastern Zagros fold-and-thrust belt and the Persian Gulf comprise a Neoproterozoic to Quaternary sedimentary cover overlying the older crystalline basement. The Zagros orogenic belt resulted from the Arabia–Eurasia convergence and continental collision at the cost of the Neo-Tethys Ocean separating the present-day Zagros from Central Iran (Berberian and King, 1981; Frizon de Lamotte et al, 2011; Agard et al, 2011; Mouthereau et al, 2012). The Persian Gulf Basin is an elongate, margin sag-interior sedimentary basin that is the largest basin with active salt tectonism in the Earth (Edgell, 1996) (Fig. 1). The Persian Gulf is asymmetrical in NE-SW cross section with deposits thickening from 4,500 m near the Arabian Shield to 18,000 m alongside the Main Zagros Reverse Fault (Edgell, 1996; Zaigham et al, 2013). Local coral reefs and especially salt domes are the main visible features of the Persian Gulf (Fig. 1). Halokinesis in the Persian Gulf Basin originates where major intersecting basement faults cut the buoyant salt beds of the Neoproterozoic Hormoz Series and the equivalent Ara Formation of Oman (Edgell, 1996). The intersecting normal faults of the Arabian trend and the lateral strike-slip faults of the Zagros Mountains have provided paths for the upward, buoyant movement of deep-seated salt, where has often produced salt piercements (Edgell, 1996; Bahroudi and Talbot, 2003; Hassanpour et al, 2021; Ehteshami-Moinabadi et al, 2024). The bedding of rock units is relatively horizontal at south of the Zagros deformation front; however, this is not true around the N-S basement faults (Edgell, 1996; Konyuhov and Maleki, 2006; Soleimany and Sàbat, 2010). The Persian Gulf is one of the saltiest open waters in the world, whose salinity sometimes reaches 50 psu in some places (Rochford, 1964). The reason for the high salinity of the Persian Gulf includes the following: 1) dry climate; 2) high surface evaporation rate; 3) the small amount of surface fresh water discharge; and 4) very little exchange of water with the open ocean. In addition, the water flow in the Persian Gulf has the following characteristics (Reynolds, 1993): 1) the circulation regime of the water in the Persian Gulf is mainly caused by the difference in the density of the water in the Oman Sea and the Persian Gulf; 2) the inflow of water from the Oman Sea along the coast of Iran in winter is reduced by the northerly winds; 3) The northern part of the bay is separated from the southern part by a flow resulting from the density difference that is very intense during summer; 4) high surface evaporation of the water of the Persian Gulf has led to the creation of a reverse circulation regime, as a result of which, salty waters from the deep part of the Strait of Hormuz leave the Persian Gulf and are replaced by the surface flow of water with less salinity from the Oman Sea.

Materials and Methods

This study utilizes hydrographic data obtained from the Regional Organization for the Protection of the Marine Environment (ROPME), an intergovernmental body established in 1979 to coordinate environmental monitoring and protection across the Persian Gulf and surrounding countries (Iran, Bahrain, Iraq, Saudi Arabia, Qatar, Oman, Kuwait, and the United Arab Emirates). The monitored marine zone, known as the ROPME Sea Area (RSA), spans from 16°39'N, 53°03'30"E to 25°04'N, 61°25'E. Among the various oceanographic surveys conducted by ROPME, this study focuses on data from the 1992 NOAA Mt. Mitchell oceanographic campaign, which occurred prior to the large-scale operation of desalination plants in the region. This ensures that the measured seawater physicochemical properties reflect natural conditions, unaffected by modern anthropogenic effluents. Specifically, data from four datasets (supplementary material) were used, covering the full width of the Persian Gulf from east to west. A total of 74 vertical hydrographic profiles were analyzed, each consisting of high-resolution measurements of temperature (°C), salinity (psu), and dissolved oxygen (DO, ppm). These profiles include data collected approximately every 70 cm from the surface to the seabed. Instrumental accuracies are reported as ±0.01°C for temperature, ±0.01 psu for salinity, and ±0.01 ppm for DO. Outlier removal was performed using a threshold of three standard deviations from local profile trends, and profiles were cross-checked for consistency with neighboring stations. All data visualization and processing were conducted using MATLAB R2023a and Surfer 24. Complete metadata including station coordinates, sampling dates, depth intervals, and raw measurements are provided in the supplementary Excel files (S1 to S4) to ensure full transparency and reproducibility. The Zagros Mountain range (~2000 km), north of the Persian Gulf, has a high potential for karst water resources, with abundant carbonate formations. Young karst formations in the southern part of Zagros belong to the Cenozoic era; these formations are placed on impermeable layers so that they provide suitable conditions for the creation and development of karstic aquifers (Moghimi, 2013). In the southern border of the country (close to the Persian Gulf and the Oman Sea coastline), many faults in various sizes (perpendicular to the general direction of the Zagros regional structures) have cut the general NW-SE direction of Zagros (Fig. 1). So that, it led to the creation of openings and karstic aquifers are developed within the susceptible formations on the southern slopes of the Zagros Mountain range (Kastning, 1977; Raeisi et al, 1993). Therefore, the coasts of the Persian Gulf and the Sea of Oman are very prone to the occurrence of submarine groundwater discharge, SGD.

Results and Discussion

Results

The collected data in the whole area of the Persian Gulf were first evaluated and validated and outliers were removed. Therefore, totally records of 74 depth profiles (1 profile per ~3200 km^2) were applied for further evaluations. In the mentioned profiles, changes in seawater temperature, salinity, and dissolved oxygen have been measured and recorded for every 70 cm. The accuracy of temperature, salinity, and dissolved oxygen parameters are ±0.01 ºC, ±0.01 psu, and ±0.01 ppm, respectively. In general, dissolved oxygen in the Persian Gulf varies from 1.31 to 5.85 ppm, and water salinity changes from 36.59 to 43.93 psu. The average values for dissolved oxygen and salinity are 4.02 ppm and 39.59 psu, respectively.

Discussion

Although the amount of dissolved oxygen is less than 2 in the water surface in some areas that forms surficial Oxygen Minimum Zones (OMZs), it no uncommon for seabed oxygen concentrations to be below 3.33 ppm in middle depth (Fondriest Environmental, 2013). Regarding the solubility effect (Carpenter, 1966), it is anticipated that the dissolved oxygen concentration in areas with warmer seawater is less than that of cooler waters (Fig. 2). Additionally, the increase of sea surface temperature (SST) has not only reduced the concentration of dissolved oxygen, but has also increased seawater stratification and adversely affected the oxygenation of water in deeper parts (Fig. 3). However, OMZ is not formed at depth (Figs. 3, 4 and 5). These results are not consistent with the findings of other studies conducted in the marine zone off Qatar (Al-Ansari et al, 2015), Bahrain (Supreme Council for Environment, 2016) and Kuwait (Devlin et al, 2015). Considering that the current study is based upon the data obtained in the year 1992, this discrepancy is probably due to the increasingly trend of desalination plants establishment from 1975 in Bahrain (Khalaf and Redha, 2001), from 1982 in Kuwait (Finan and Kazimi, 2023), and from 1998 in Qatar (Lawler et al, 2023). The temperature trend in the Persian Gulf (based upon the current study data set) is a gradual decrease from the sea surface to the depth, but the salinity increases from the surface to the bed (Fig. 3). However, there is no evidence significant relationship between changes in seawater quality characteristics and the buried and/or emergent Hormoz salt structures.

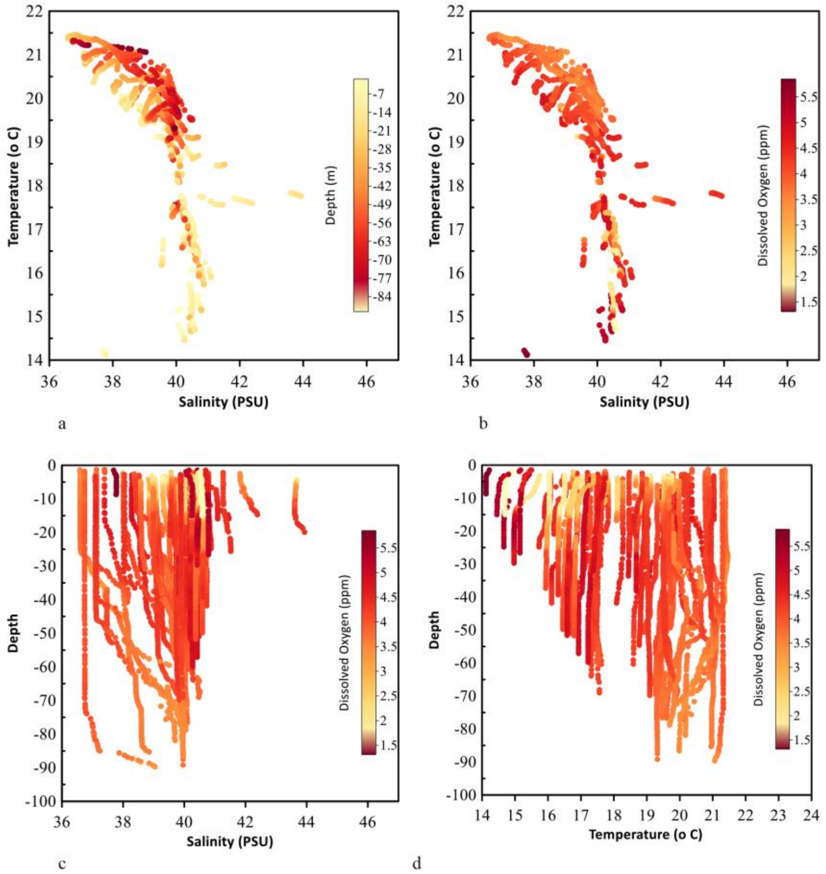

Fig. 2: General plots showing regional trends of seawater salinity, temperature, dissolved oxygen and depth in relation to each other. a: Seawater temperature as a function of salinity and depth. B: Seawater temperature as a function of salinity and dissolved oxygen. c: Seawater salinity and dissolved oxygen changes in different depths. d: Seawater temperature and dissolved oxygen changes in different depths. Plots reveal that dissolved oxygen concentration in warmer waters is less than that of cooler waters. In addition, where the water salinity increase the dissolved oxygen decreases. Therefore, Oxygen Minimum Zones, OMZs (regions with dissolved oxygen less than 2 ppm) mainly formed in benthic parts of the Persian Gulf. However, sea surface warming caused surficial hypoxia layers, especially in shallow areas.

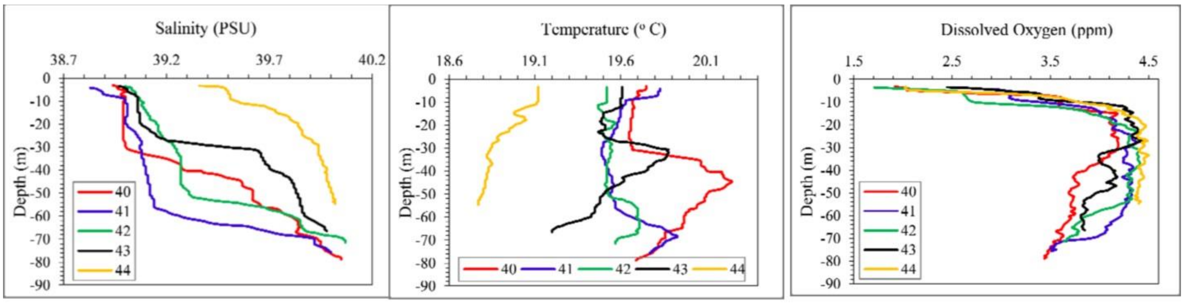

Fig. 3: Representative seawater salinity, temperature, and dissolved oxygen profiles for normally stratified areas. Numbers in the legends refer to profiling points` numbers illustrated in the Persian Gulf study area in figure 6. In these areas, changes in salinity and temperature increase with increasing depth, and as a result, dissolved oxygen naturally decreases. This case shows that the secondary phenomena that cause chaos in the seawater stratification do not exist in these parts

The seawater stratification may alter in some areas under the influence of other phenomena such as sea bottom topography, upward currents, transport of materials through diffusion and convection processes. Generally, profiles that do not have clear stratification (especially in salinity and dissolved oxygen) are located in the western half of the Persian Gulf (Figs. 4 and 6). Due to the uplift of the middle part of the Persian Gulf bed (north of Qatar), the water in the deep parts in the western half is probably less affected by the sea currents and stagnation zone is formed. Therefore, due to phenomena such as diffusion and/or surface evaporation, the seawater stratification has probably decreased over time. In this way, if seawater desalination plants are established in the western half of the Persian Gulf, the environmental impacts of discharging their effluent into the sea might increase dramatically.

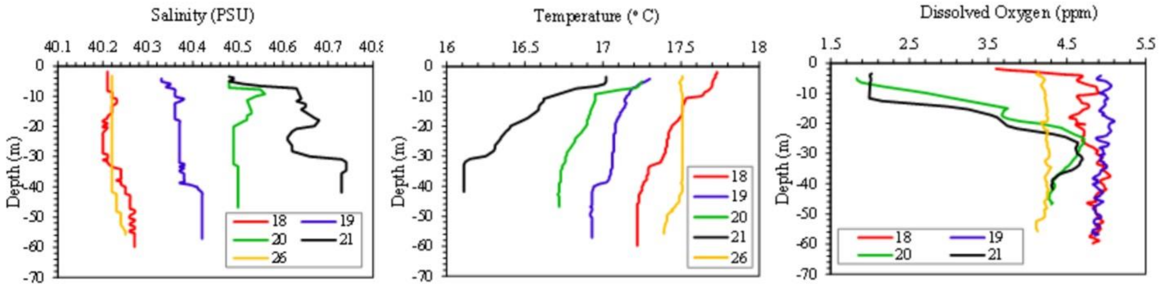

Fig. 4: Representative seawater salinity, temperature, and dissolved oxygen profiles for areas where seawater is not stratified clearly. Numbers in the legends refer to profiling points` numbers illustrated in the Persian Gulf study area in figure 6. The measured parameters in these profiles are almost constant in different depths.

Some seawater profiles in the western half of the Persian Gulf (in the areas adjacent to the fault zones) have adversely stratified (Figs. 5 and 6). Considering that in this part of the study area, the seawater is almost stagnant, the presence of adversely stratification can be a sign of the existence of submarine fresh water flux. In other words, based on existing examples around the world that emphasize on the role of fault zone or deep fault zone aquifers in water discharge from coastal zones to the sea (Borisenko, 2001; Shaban et al, 2005; Akawwi, 2006, Akawwi et al, 2008; Peng et al, 2008; Charkin et al, 2017; Cantarero et al, 2019), we propose that the groundwater is probably directed from the terrestrial areas toward the Persian Gulf by the faults and discharged into the sea. This evidence is largely consistent with Farhoudi & Poll (1992) hypothesis on the possibility of submarine discharge of groundwater originated from karstic aquifers in Zagros Mountains into the Persian Gulf. In addition, in some areas, evidence of SGD can be seen at a depth of about 50 meters (Fig. 5) which requires significant hydraulic head. Therefore, probably the groundwater from the high parts of the Zagros Mountains is directed towards the Persian Gulf by HBF, KMF, and KQF.

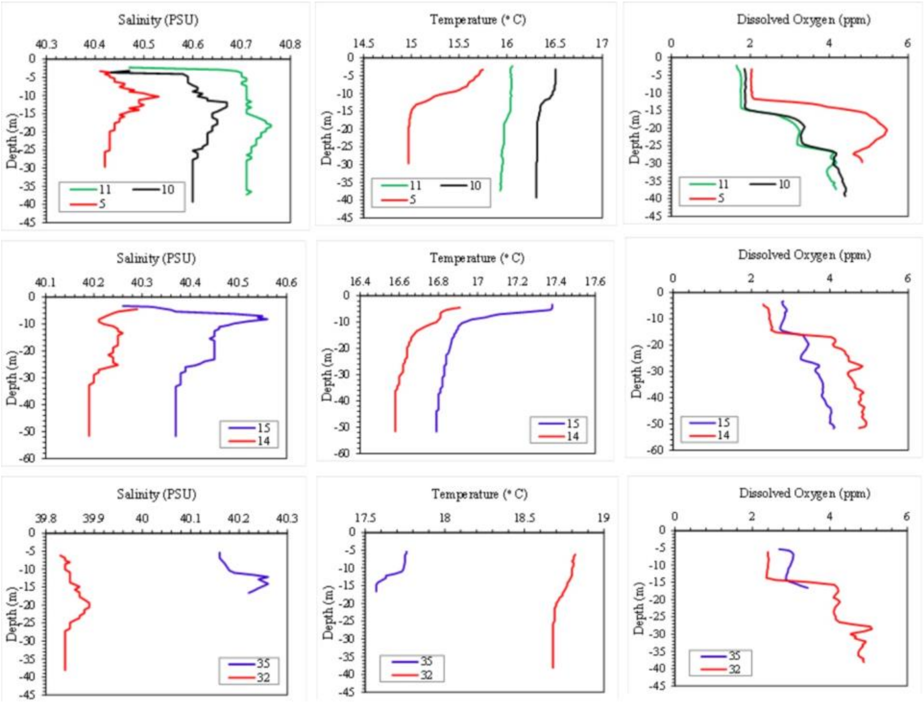

Fig. 5: Seawater salinity, temperature, and dissolved oxygen profiles for areas where submarine groundwater discharge potentially happens. Numbers in the legends refer to profiling points` numbers illustrated in the Persian Gulf study area in figure 6. The seawater salinity has decreased slightly close the sea bottom while the dissolved oxygen increased.

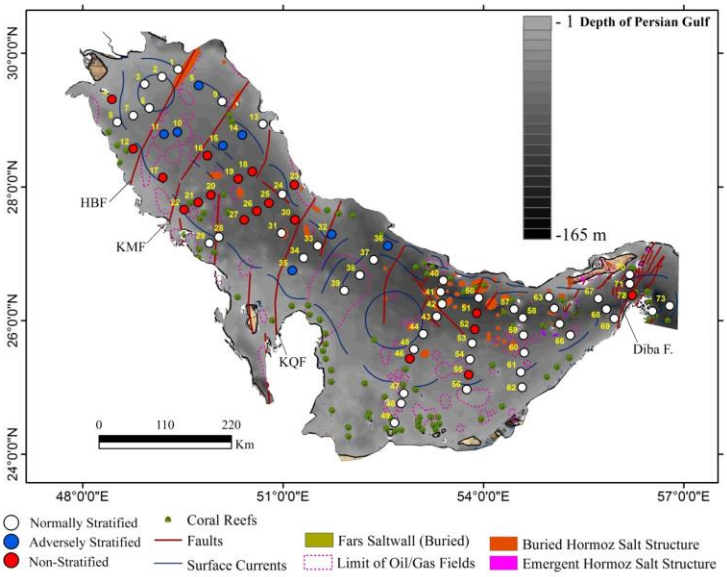

Fig. 6: The map showing the results of the profiles obtained from the Persian Gulf water monitoring.

Conclusion

Analysis of high-resolution hydrographic profiles from the 1992 Mt. Mitchell survey reveals localized anomalies in temperature, salinity, and dissolved oxygen across several areas of the Persian Gulf, particularly near major transverse basement faults such as the Hendijan–Bahregansar (HBF), Karehbas (KMF), and Kazerun–Qatar (KQF) Faults. These anomalies, including near-bottom freshening and elevated DO concentrations, are consistent with the occurrence of submarine groundwater discharge (SGD) from the northern Zagros region toward the Persian Gulf. The spatial correspondence between these hydrographic signals and deep-seated fault zones supports the hypothesis that geological structures play a key role in controlling offshore groundwater fluxes in this arid coastal setting. The findings also highlight the hydro-environmental vulnerability of the western Persian Gulf due to limited water exchange with the open sea and high concentration of anthropogenic activities, such as desalination. While the detected SGD signals are not necessarily associated with recent human influence, given the likely age of discharging groundwater, their full characterization requires further investigation. Future studies should include isotopic analyses, submarine porewater dating, and numerical modeling to better quantify discharge rates and evaluate ecological impacts. These results provide a scientific basis for identifying SGD-prone zones and may serve as a preliminary step for more targeted water resource assessments in the Persian Gulf.

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