



THE IMPACTS OF BRINE INFLUX FROM ZWARA DESALINATION PLANT ON THE MARINE ENVIRONMENT

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تأثير تدفق المياه المالحة المركزة من محطة تحلية زوارة على البيئة البحرية

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Abstract

This study investigates the environmental impacts of brine discharge from Zwara Desalination Plant (ZDP) on the surrounding marine ecosystem along the Libyan coastline. Field data were collected from nineteen sampling stations near the plant outfall to assess variations in physicochemical parameters of seawater, sediment characteristics, and benthic community composition. Key parameters analyzed included salinity, temperature, pH, dissolved oxygen, major ions, and nutrient concentrations, alongside sediment grain size and organic content.

Results revealed significant spatial variations in physicochemical properties, with elevated salinity (up to 47 psu), temperature, and ion concentrations (e.g., Na⁺, Cl⁻, Mg²⁺, SO₄²⁻) detected near the discharge point. These changes were associated with reduced dissolved oxygen levels and altered seawater chemistry. Principal Component Analysis (PCA) indicated that total hardness, ion concentrations, and temperature were the dominant factors influencing environmental variability. Biological analysis identified notable shifts in benthic community composition, with sensitive seagrass species such as *Posidonia oceanica* showing strong spatial dependence and significant correlations with environmental parameters and sediment organic content.

The findings demonstrate that brine discharge from thermal desalination processes can significantly alter marine environmental conditions, potentially affecting biodiversity, especially seagrass ecosystems. The study highlights the need for sustainable brine management strategies, such as improved dilution, alternative disposal techniques, and implementation of environmentally responsible practices like Zero Liquid Discharge (ZLD), to mitigate ecological impacts and ensure long-term sustainability of desalination activities.

Keywords: Desalination, brine discharge, physicochemical parameters, marine ecosystem.

الملخص

تهدف هذه الدراسة إلى تقييم التأثيرات البيئية لتصريف المحلول الملحي الناتج عن محطة تحلية المياه الحرارية في زوارة على النظام البيئي البحري على الساحل الليبي. تم جمع البيانات الميدانية من تسع عشرة موقع بالقرب من نقطة التصريف المحلول الملحي لتحليل التغيرات في الخصائص الفيزيائية والكيميائية لمياه البحر، وخصائص الرواسب، وتركيب المجتمعات القاعية. شملت القياسات الرئيسية للملوحة، ودرجة الحرارة، والرقم الهيدروجيني، والأكسجين الذائب، وتركيزات الأيونات الرئيسية والعناصر الغذائية، بالإضافة إلى حجم حبيبات الرواسب ومحتواها من المادة العضوية.

أظهرت النتائج وجود تباينات مكانية ملحوظة في الخصائص الفيزيائية والكيميائية، حيث سُجلت مستويات مرتفعة من الملوحة (تصل إلى 47 جزءاً في الألف)، ودرجة الحرارة، وتركيزات الأيونات مثل الصوديوم والكلوريد والمغنيسيوم والكبريتات بالقرب من موقع التصريف. كما ارتبطت هذه التغيرات بانخفاض مستويات الأكسجين الذائب وتغير في كيمياء مياه البحر. وأظهر تحليل المكونات الرئيسية (PCA) أن العسرة الكلية، وتركيزات الأيونات، ودرجة الحرارة تمثل العوامل الرئيسية المؤثرة في التباين البيئي.

من الناحية البيولوجية، لوحظت تغيرات واضحة في تركيب المجتمعات القاعية، حيث أظهرت الأعشاب البحرية الحساسة مثل *Posidonia oceanica* ارتباطاً مكانياً قوياً مع العوامل البيئية، إضافة إلى وجود علاقات ارتباط معنوية مع خصائص الرواسب، خاصة المحتوى العضوي.

تشير هذه النتائج إلى أن تصريف المحلول الملحي الناتج عن عمليات التحلية الحرارية قد يؤدي إلى تغييرات ملحوظة في البيئة البحرية، مما قد يؤثر سلباً على التنوع الحيوي، وخاصة النظم البيئية للأعشاب البحرية. وتؤكد الدراسة على أهمية تطبيق استراتيجيات مستدامة لإدارة المحلول الملحي، مثل تحسين التخفيف، واستخدام تقنيات تصريف بديلة، وتبني ممارسات بيئية متقدمة مثل نظام التصريف الصفري (ZLD)، للحد من التأثيرات البيئية وضمان استدامة عمليات التحلية على المدى الطويل.

الكلمات المفتاحية: تحلية المياه ، تصريف المحلول الملحي، الخصائص الفيزيائية والكيميائية، النظام البيئي البحري.

1. Introduction

The critical shortage of water in many Mediterranean and Gulf countries has led to increased reliance on seawater desalination, raising environmental concerns that were previously overlooked, particularly those associated with brine discharge during freshwater production (Gacia et al., 2007; Einav and Lokiec, 2003). Despite the rapid expansion of desalination technologies, there remains limited information on the impacts of effluent desalination on marine ecosystems (Safrai and Zask, 2008), especially for large-scale reverse osmosis (RO) plants (Moreno et al., 2014; Torquemada et al., 2005). In Europe, approximately 92% of new installations utilize membrane technologies, primarily seawater reverse osmosis (SWRO), due to their economic and operational efficiency (Trancki et al., 2012; Pagès et al., 2010). Thermal desalination methods such as multi-effect distillation (MED) and MED with thermal vapor compression (MED-TVC) also remain widely used due to their reliability and production capacity.

Ocean disposal is the most common method for brine discharge because of its cost-effectiveness and efficiency (Torquemada et al., 2005; Ahmed et al., 2001). However, the sensitivity of marine ecosystems to changes in physicochemical conditions challenges the sustainability of this practice (Einav and Lokiec, 2003). Brine effluents are typically characterized by high salinity (up to 69,000 psu), elevated temperatures (often exceeding ambient seawater by up to 10°C), and the presence of chemical additives such as antiscalants, antifouling agents, and corrosion inhibitors (Pagès et al., 2010; Darwish et al., 2013). These discharges can degrade seawater and sediment quality,

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affecting marine organisms, particularly benthic communities (Naser, 2013; Lattemann and Höpner, 2002; Sadhwani et al., 2005).

Alterations in salinity, temperature, pH, and dissolved oxygen can significantly impact marine biodiversity. Elevated salinity can cause osmotic stress, reducing growth, reproduction, and survival rates of marine species (Yolanda and Luis, 2006). Seagrass meadows, which are widely distributed in coastal ecosystems, are particularly sensitive to such changes (Moreno et al., 2014). For instance, *Posidonia oceanica* shows reduced growth at 38 psu, mortality at 45 psu, and complete mortality at 50 psu (Latorre, 2005; Torquemada and Lizaso, 2005), while *Cymodocea nodosa* exhibits significant mortality outside the salinity range of 17–41 psu (Sandoval et al., 2012; Yolanda and Luis, 2006). Similarly, increased salinity has been associated with reduced fish size and survival rates (Ahmed and Anwar, 2012; Parry, 1960).

Temperature is another critical factor influencing marine life. Thermal discharges from desalination plants can elevate seawater temperatures, potentially disrupting metabolic processes and causing mortality under prolonged exposure (Marsh et al., 1986; Hiscock et al., 2004; Lattemann and Höpner, 2008). Additionally, increased temperature and salinity reduce oxygen solubility, leading to lower dissolved oxygen levels and limiting respiration in marine organisms (Tonner, 2006; Ahmed and Anwar, 2012). Changes in pH also affect carbonate chemistry, influencing photosynthesis and primary productivity in marine plants (Torquemada et al., 2005; Beer and Waisel, 1979; Invers et al., 1997).

Desalination processes are also energy-intensive and contribute to CO₂ emissions, primarily due to reliance on fossil fuels (Tzen, 2014). The dissolution of CO₂ in seawater leads to ocean acidification, altering carbonate equilibrium and negatively affecting calcifying organisms and overall ecosystem functioning (Fabry et al., 2008; Royal Society, 2005).

Although several studies have investigated the environmental impacts of desalination in regions such as the Mediterranean Sea, Arabian Gulf, Red Sea, and Australia (Moreno et al., 2014; Torquemada and Lizaso, 2005; Hashim and Hajjaj, 2005; Naser, 2014; Uddin, 2014; Dupavillon and Gillanders, 2009), most have been conducted under controlled experimental conditions. In situ studies remain limited, and many lack sufficient quantitative data (Gacia et al., 2007; Ruíz et al., 2009; Roberts et al., 2012).

Despite plans for further desalination development along the Libyan coastline, there is a lack of scientific research assessing its environmental implications (Elhassadi, 2013). Therefore, this study aims to evaluate the physicochemical effects of brine discharge from the Zwara thermal desalination plant and assess its potential impact on the marine ecosystem along the Libyan coast.

2. The Research Site

This study was conducted along the Libyan coastline in the vicinity of the Zwara Desalination Plant (ZDP) (Figure 1). The plant, commissioned in 2006, is located west of the city of Tripoli (32°53'N/10°12 'E). Freshwater at this facility is produced using multi-effect distillation (MED), a thermal desalination process in which seawater is heated to generate distilled water, leaving behind a concentrated brine stream that is discharged back into the marine environment. The ZDP releases approximately 40,000 m³/day of effluent, of which about 26,666.7 m³/day consists of brine.

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Figure1: Location of the Zwara Desalination Plant on the Libyan Coastline

3. Data collection

3.1 Seawater Samples Data Collection

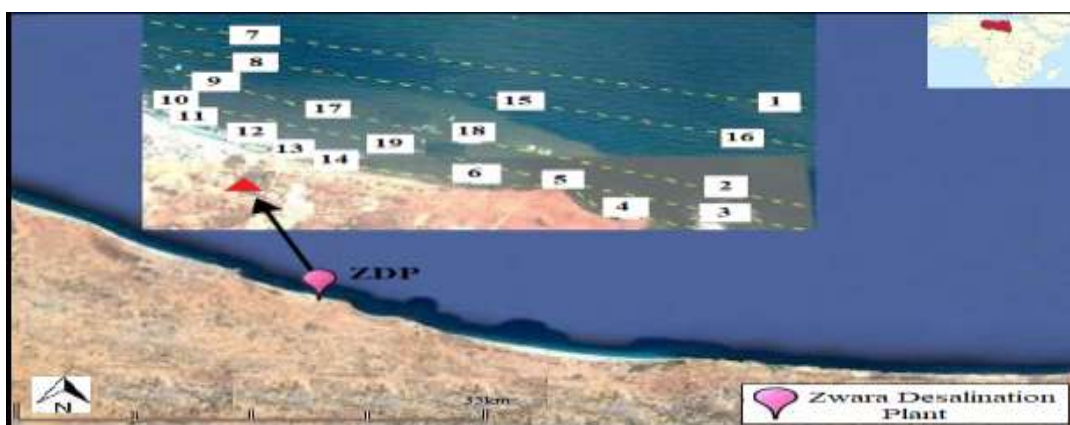


Figure 2: Sampling location at Zwara Desalination Plant on the Libyan Coastline: (Google Earth).

A total of nineteen sampling stations were established around the Zwara Desalination Plant (ZDP), oriented along the direction of brine discharge (Figure 2). At each station, seawater samples were collected at varying depths using a 7-litre Nansen bottle. Sampling locations were recorded using a GPS Map 420s device to ensure spatial accuracy and consistency in assessing physicochemical parameters.

Seawater samples were transferred into 300 mL and 500 mL bottles, which were pre-rinsed with seawater obtained from the sampling device. The bottles were then filled via a hose to minimize atmospheric exposure and immediately labeled according to station number. For dissolved oxygen analysis, 1 mL of WK1 manganese reagent and 1 mL of WK2 alkaline iodide reagent were added to each sample using a pre-calibrated pipette. Samples were

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carefully handled and stored in a plastic container, ensuring minimal contact with air to preserve dissolved oxygen concentrations.

Insite measurements of key physicochemical parameters including salinity (psu), conductivity ($\mu\text{S}/\text{cm}$), dissolved oxygen (mg/L), pH, total dissolved solids (mg/L), and bottom water temperature ($^{\circ}\text{C}$), were conducted immediately at each station using a YSI 556 MPS handheld multiparameter instrument (YSI Ltd., Hampshire, UK).

Further laboratory analyses were performed at the ZDP facility to determine total alkalinity, bicarbonate, total hardness, calcium and magnesium hardness, chloride, nitrate, sulphate, phosphorus, sodium, potassium, calcium, magnesium, and iron concentrations (Tables 1 and 2). In addition, brine samples discharged from the plant were analyzed (Table 3) following standard Hach methods for wastewater and seawater to evaluate their physicochemical characteristics.

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Table 1: The measurements of physiochemical parameters of Zwar a desalination plant around the outfall.

Physicochemical Parameters				Hach Method HQ 404	HQ40D meter test pro.	HQ40D meter test	Hach Method 8203	Hach Method 8203	Hach Method 8213	Hach Method 8203	Hach Method 8203	Hach Method 8207	Lange LCK 339	Lange LCK 335	Lange LCK 349	Flame photometer		Flame photometer	ASTM D1126-1	ASTM D1126-1	Hach Method 8008	YSI 556 multiprobe
Station	Latitude: N	Longitude: E	Depth (m)	Temperature (C°)	pH	Salinity (PSU)	Total Alkalinity as CaCO ₃ (mg/l)	Bicarbonate HCO ₃ ⁻ (mg/l)	Total Hardness as CaCO ₃ (mg/l)	Calcium Hardness as CaCO ₃ (mg/l)	Magnesium Hardness as CaCO ₃ (mg/l)	Chloride Cl ⁻ (mg/l)	Nitrate NO ₃ ⁻ (mg/l)	Sulphate SO ₄ ⁻⁻ (mg/l)	Phosphorus total PO ₄ ⁻⁻⁻	Sodium Na ⁺ (mg/l)		Potassium k ⁺ (mg/l)	Calcium (mg/l)	Magnesium (mg/l)	Iron (mg/l)	O ₂ (mg/l)
St.1	32.89220	12.18243	9.9	24	8.35	43	120.108	120.108	10,600	900	9,70	23,581	0.10	2,805	0.10	17,440		490.00	360.360	2,355	0.07	7.86
St.2	32.89522	12.20458	8.4	24	8.37	37	80.072	80.072	6,846	200	6,64	20,702	0.00	1,500	0.01	14,800		420.00	80.080	1,614	0.00	8.39
St.3	32.88724	12.20132	8.3	27	8.36	35	88.079	88.079	7,090	290	6,80	19,374	0.10	1,500	0.01	15,210		430.00	116.116	1,651	0.02	5.67
St.4	32.88551	12.20055	1.9	27	8.40	35	96.086	96.086	7,500	300	7,20	19,374	0.10	1,500	0.01	15,390		430.00	120.120	1,748	0.02	5.37
St.5	32.88530	12.19569	2.8	27	8.46	36	96.086	96.086	10,300	300	7,70	19,651	0.10	2,000	0.01	15,420		430.00	120.120	1,870	0.02	5.70
St.6	32.88856	12.19222	4.8	25	7.85	45	110.04	110.04	9,636	700	8,93	24,633	0.00	2,537	0.03	17,100		470.00	280.280	2,170	0.06	7.84
St.7	32.88901	12.18780	9.8	24	8.04	45	116.00	116.00	10,031	831	9,20	24,702	0.10	2,671	0.04	17,170		480.00	287.080	2,234	0.07	7.69
St.8	32.90253	12.17574	2.5	24	8.03	37	88.079	88.079	6,000	200	5,80	20,204	0.00	1,000	0.00	11,050		407.70	80.080	1,408	0.00	8.30
St.9	32.90036	12.17486	4.2	27	7.95	36	104.09	104.09	9,120	565	8,55	19,927	0.10	2,000	0.02	16,430		450.00	203.600	2,077	0.04	7.96
St.10	32.89855	12.17301	3.6	29	8.22	38	107.07	107.07	9,398	698	8,70	20,758	0.10	2,000	0.03	16,850		459.14	245.340	2,112	0.05	6.16
St.11	32.89655	12.17138	0.5	27	8.02	40	108.55	108.55	9,500	700	8,80	21,865	0.10	2,500	0.03	16,890		469.43	280.280	2,137	0.06	7.14
St.12	32.89520	12.17127	0.6	28	7.76	40	107.81	107.81	9,446	700	8,74	21,865	0.10	2,000	0.03	16,850		464.28	280.000	2,123	0.05	6.17
St.13	32.89292	12.17496	0.4	23	8.08	37	104.09	104.09	9,332	632	7,70	20,204	0.10	2,000	0.03	16,675		460.00	224.470	2,112	0.04	7.49
St.14	32.89136	12.17702	0.4	25	8.37	47	128.11	128.11	15,571	1,361	14,21	25,629	1.15	4,148	0.18	18,550		570.00	454.040	3,450	0.07	5.13
St.15	32.89076	12.17917	0.6	29	8.12	45	120.10	120.10	14,900	1,100	13,80	25,075	0.10	3,074	0.11	17,900		490.00	440.440	3,351	0.07	5.18
St.16	32.89606	12.18998	6.8	25	8.24	38	104.09	104.09	8,400	300	8,10	20,758	0.10	2,000	0.02	15,810		450.00	120.120	1,967	0.03	6.89
St.17	32.89242	12.20206	8.5	26	8.18	37	104.10	104.10	8,200	300	7,90	20,647	0.10	2,000	0.01	15,738		448.85	120.120	1,918	0.02	7.96
St.18	32.89553	12.17924	5.5	27	8.21	38	104.11	104.11	8,573	400	8,17	20,758	0.10	2,000	0.02	16,400		450.00	160.160	1,984	0.04	7.46
St.19	32.89270	12.18717	4.8	25	8.19	38	104.11	104.11	8,400	300	8,10	21,256	0.10	2,000	0.02	16,206		450.00	120.120	1,967	0.04	6.98

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Table 2: Measurement of Physicochemical Parameters for Zwara Desalination Plants from Evaporator.

Test parameter	Test Method	Result
pH	HQ40D meter test pro.	8.5
Salinity (psu)	HQ40D meter test pro.	52,000-56,000
Total Alkalinity as CaCO ₃ (mg/l)	Hach Method 8203	132
Carbonate CO ₃ ²⁻ (mg/l)	Hach Method 8203	0
Bicarbonate HCO ₃ ⁻ (mg/l)	Hach Method 8203	132
Total Hardness as CaCO ₃ (mg/l)	Hach Method 8213	10,509.50
Calcium Hardness as CaCO ₃ (mg/l)	Hach Method 8203	1641.5
Magnesium Hardness as CaCO ₃ (mg/l)	Hach Method 8203	8,867.10
Chloride Cl ⁻ (mg/l)	Hach Method 8207	28,784
Nitrate NO ₃ ⁻ (mg/l)	Lange LCK 339	1.25
Sulphate SO ₄ ²⁻ (mg/l)	Lange LCK 335	8,530
Phosphorus total PO ₄ ³⁻	Lange LCK 349	0.174
Sodium Na ⁺ (mg/l)	Flame photometer	12,870
Potassium K ⁺ (mg/l)	Flame photometer	561.1
Calcium (mg/l)	ASTM D1126-1	657.3
Magnesium (mg/l)	ASTM D1126-1	2,153.15
Iron (mg/l)	Hach Method 8008	0.08
Temperature (C°)	Hach Method HQ 40d	41-43
O ₂ (mg/l)	Hach Method HQ 40d	43

3.2 Seabed Sediment Samples Data Collection

A total of nineteen seabed sediment samples were collected from the study area using a Van Veen grab sampler and a PVC coring tube (40 cm length, 10 cm diameter) fitted with stoppers at both ends. Sampling was conducted at depths ranging from 0.4 to 9.9 m, with station locations recorded using a Garmin GPS Map 420s.

Each sediment sample was placed in a labeled plastic bag corresponding to its respective station to ensure accurate identification. All samples were subsequently stored at temperatures below 18°C in the laboratory prior to analysis.

Laboratory investigations included the determination of sediment organic content (Table 3) and grain size distribution (Table 4). Grain size analysis was performed following the method of Folk (1974), enabling classification of sediment type and calculation of statistical parameters, including kurtosis (KG), skewness (SKI), and standard deviation (δI).

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Table 3: Organic content level (%) of the sediments for Zwara Desalination Plant.

Organic content level (%)				
GPS.P	Station	Latitude	Longitude	Organic content level (%)
01	St. 1	32.89220	12.18243	4.5
02	St. 2	32.89522	12.20458	7.90
03	St. 3	32.88724	12.20132	5.60
04	St. 4	32.88551	12.20055	5.60
05	St. 5	32.88530	12.19569	5.10
06	St. 6	32.88856	12.19222	5.10
07	St. 7	32.88901	12.18780	4.80
08	St. 8	32.90253	12.17574	7.30
09	St. 9	32.90036	12.17486	5.90
10	St.10	32.89855	12.17301	6.50
11	St.11	32.89655	12.17138	4.90
12	St.12	32.89520	12.17127	4.90
13	St.13	32.89292	12.17496	3.40
14	St.14	32.89136	12.17702	2.80
15	St.15	32.89076	12.17917	4.10
16	St.16	32.89606	12.18998	5.80
17	St.17	32.89242	12.20206	6.60
18	St.18	32.89553	12.17924	4.40
19	St.19	32.89270	12.18717	5.10

3.3 Biological Samples Data Collection

Video footage was collected by a scuba diver along predefined transect lines at the study site (Figure 2), close to the seafloor, using a Fuji FinePix F500 EXR camera equipped with an underwater housing (Fuji WP-FXF500). Recording was conducted at varying depths ranging from 0.4 to 9.9 m, with locations verified using a Garmin GPS Map 420s.

From the recorded footage, a total of 68 still images were randomly selected and analyzed using ImageJ software (Rasband, W.S., U.S. National Institutes of Health, Bethesda, MD, [ImageJ official site](#)). A random systematic sampling approach was applied to quantify species coverage. Each image represented an area of 20×20 cm, over which a grid of 100 random points (representing 100% coverage) was superimposed. The species located beneath each point were identified and counted to estimate percentage cover for each species present

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Table 4: Classification used for defining sediment type and degree of sediment kurtosis (KG), Skewness (SKI) and Standard Deviation (δI) for ZDP.

Sediment Analysis					Sediment classification					Graphic Kurtosis (KG)					Inclusive Graphic Skewness (SKI)					Inclusive Graphic Standard Deviation (δI)							
Station	Mean grain size (Mz)	Graphic Kurtosis (KG)	Inclusive Graphic Skewness (SKI)	inclusive Graphic Standard Deviation (δI)	Coarse sand (0.5-1 mm) or (0.0-1Ø)	Medium sand (0.25-0.5 mm) or (1-2 Ø)	Fine sand (0.125-0.25 mm) or (2-3Ø)	Very fine sand (0.062-0.125 mm) or (3-4Ø)	Mud (less than 0.062 mm) or (more than 4Ø)	(0.41-0.67 Ø) Very platykurtic	(0.67-0.90 Ø) platykurtic	(0.90-1.11Ø) mesokurtic	(1.10-1.50 Ø) leptokurtic	1.50-3.00 Ø) very leptokurtic	(3.00 Ø) extremely leptokurtic	(+1 to + 0.30) strongly positive skewed – Very negative phi valued, coarse	(+ 0.3 to + 0.10) positive skewed-Negative phi values	(+ 0.10 to - 0.1) Near Symmetrical-Symmetrical	(- 0.10 to - 0.30) Negative skewed-positive phi values	(- 0.30 to - 1.00) strongly negative skewed-very positive phi values, fine	(0.00-0.35 Ø) very well sorted	(0.35-0.50 Ø) well sorted	(0.50-0.71 Ø) moderately well sorted	(0.71-1.00 Ø) moderately sorted	(1.00-2.00 Ø) poorly sorted	(2.00-4.00 Ø) very poorly sorted	(4.00 Ø) extremely poorly sorted
St.1	1.43	1.15	0.3	0.97		☑							☑				☑										
St.2	2.46	0.69	-0.2	0.70			☑				☑								☑					☑			
St.3	3.03	0.88	-0.3	0.98				☑			☑								☑					☑			
St.4	3.13	1.07	0.0	0.42				☑				☑						☑					☑				
St.5	3.60	1.02	0.3	0.50				☑				☑					☑						☑				
St.6	2.93	0.76	0.1	0.42			☑				☑							☑					☑				
St.7	2.53	0.74	-0.4	0.96			☑				☑									☑				☑			
St.8	1.06	0.43	-0.1	0.49		☑				☑									☑			☑					
St.9	1.03	0.60	0.0	0.49		☑				☑								☑				☑					
St.10	2.26	1.39	-0.3	0.51			☑						☑							☑				☑			
St.11	2.26	1.39	-0.2	0.51			☑						☑							☑				☑			
St.12	2.03	0.94	-0.2	0.65			☑					☑							☑					☑			
St.13	2.26	1.99	-0.3	0.91			☑							☑						☑				☑			
St.14	1.50	0.99	0.2	1.40		☑						☑				☑									☑		
St.15	2.40	1.54	-0.1	0.52			☑							☑					☑					☑			
St.16	1.40	1.13	0.1	1.07		☑							☑			☑				☑						☑	
St.17	1.19	0.75	-0.3	0.88		☑					☑									☑					☑		
St.18	1.50	0.79	0.4	1.19		☑					☑						☑								☑		
St.19	1.23	1.79	0.2	0.96		☑								☑		☑								☑			

4 Statistical Analysis

Statistical analyses were conducted using PRIMER® v6 software (Plymouth Routines In Multivariate Ecological Research) (Clarke and Gorley, 2006). Community composition data across sampling stations at the ZDP site were summarized using mean values $\pm$ standard error. Differences in community structure among stations were assessed using multivariate techniques based on the Bray–Curtis's similarity index and Analysis of Similarities (ANOSIM) (Clarke, 1993).

ANOSIM is a non-parametric permutation procedure applied to similarity matrices to test for differences between groups. The test generates a Global R statistic ranging from 0 to 1, where values approaching 1 indicate strong dissimilarity between groups, and values near 0 indicate no significant difference (Chapman and Underwood, 1999; Malcolm and Lancaster, 2013). Statistical significance was determined at $p < 0.05$.

To further examine the contribution of individual species to similarities and dissimilarities between stations, the Similarity Percentage (SIMPER) analysis was applied (Clarke, 1993). This method identifies the species primarily responsible for differences between groups based on average Bray–Curtis's dissimilarity.

Non-metric multidimensional scaling (nMDS) was used to visualize patterns in species composition among sampling stations. This ordination technique represents similarity relationships in a low-dimensional space, where the proximity between points reflects the degree of similarity between samples. The accuracy of the representation is indicated by the stress value, with lower values corresponding to better representation of the data (Hargrave, 2005).

Physicochemical parameters and seabed sediment characteristics (including organic content and grain size) were normalized prior to analysis and examined using Principal Component Analysis (PCA). PCA is a parametric ordination technique that reduces data dimensionality and identifies key factors influencing variability by generating linear combinations of variables. It is particularly suitable for summarizing relationships among environmental variables while minimizing information loss. Interpretation of PCA results was based on factor loadings, where values of ± 0.30 were considered minimal, ± 0.40 important, and ± 0.50 or higher practically significant (Hair et al., 1995; Pallant, 2010; Williams et al., 2010).

As PCA assumptions of normality and linearity were not fully met, non-parametric Spearman's rank correlation analysis was subsequently performed using IBM SPSS Statistics (IBM Corp., 2011). This analysis was used to assess relationships between physicochemical parameters, sediment characteristics, and benthic community structure. Spearman's correlation coefficients range from -1 to $+1$, indicating perfect negative or positive monotonic relationships, respectively (Field, 2013; Tabachnick and Fidell, 2013). The level of statistical significance for all analyses was set at 5%.

5 Results

5.1 Differences Between Stations in Community Composition

Eight species were identified at the ZDP site, including the seagrasses *Posidonia oceanica* and *Cymodocea nodosa*, as well as various macroalgae such as the brown algae *Taonia atomaria*, *Padina pavonica*, and *Sargassum vulgare*, and the red alga *Laurencia pinnatifida*. In addition, unidentified algal species were recorded. Fish species observed included *Spicara flexuosa*, *Diplodus annularis*, and *Diplodus vulgaris*. Non-living substrates, including sand and rocky seabed, were also present (Figure 3).

Statistical analysis revealed a significant variation in community composition among the ten sampling stations (ANOSIM Global R = 0.6332, $p < 0.001$; Figure 4), indicating substantial spatial differences in species distribution across the study area.

THE IMPACTS OF BRINE INFLUX FROM ZWARA DESALINATION PLANT ON THE MARINE ENVIRONMENT

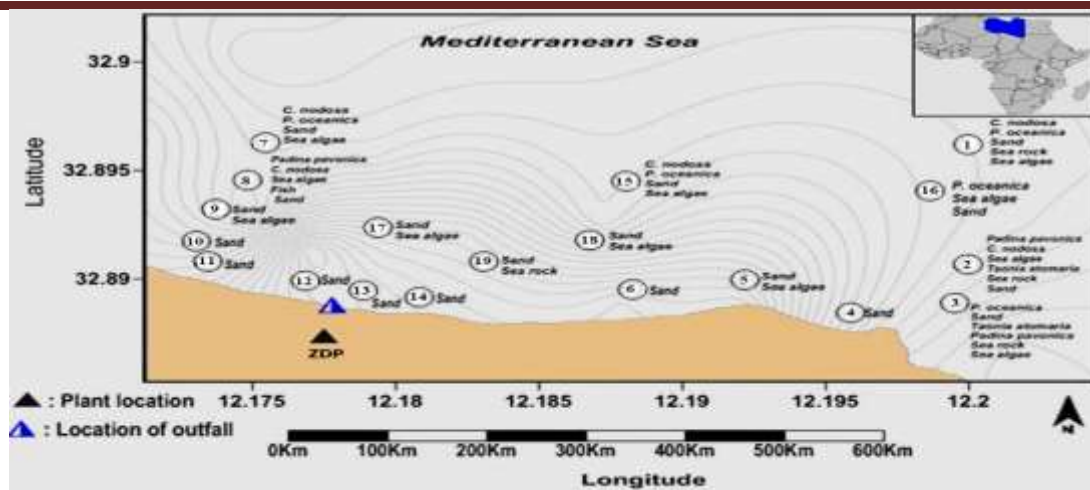


Figure 3: Community Composition at each Station for ZDP (With permission from ASCE: <https://ascelibrary.org/doi/pdf/10.1061/9780784413548.224>)

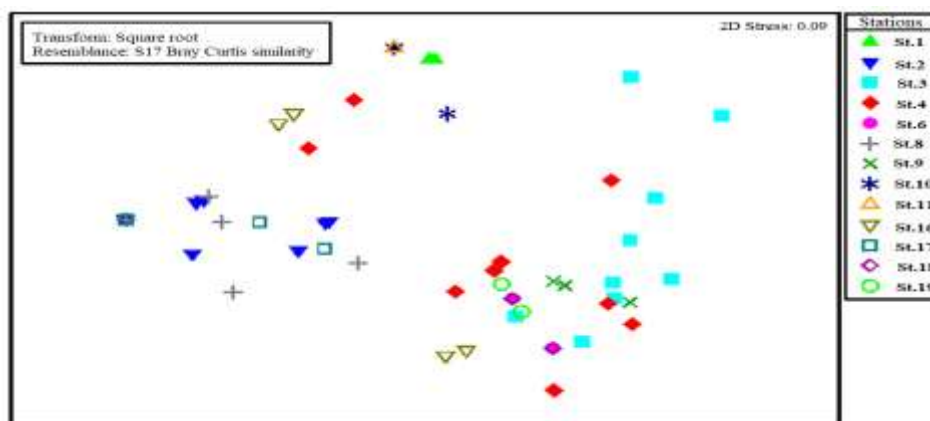


Figure 4: Two-dimensional ordination plots from multidimensional scaling analysis of Bray-Curtis similarity index (2D stress: 0.09; 5 replicates per station).

Significant differences in community composition were observed among several sampling stations. In particular, stations St.1, St.2, St.3, St.8, and St.17 exhibited strong dissimilarities (St.1: Global $R = 1$, $p < 0.001$, average dissimilarity = 92.02%; St.2: Global $R = 0.912$, $p < 0.001$, average dissimilarity = 97.31%; St.8: Global $R = 1$, $p < 0.001$, average dissimilarity = 94.75%; St.17: Global $R = 1$, $p < 0.001$, average dissimilarity = 97.10%). These differences were primarily driven by variations in species composition and percentage cover.

Posidonia oceanica was the dominant contributor to dissimilarity, accounting for 44.61% between St.1 and St.2, 42.74% between St.1 and St.8, and 97.10% between St.1 and St.17. Its average percentage cover was substantially higher at St.2 ($82.11\% \pm 42.96\%$), St.8 ($81\% \pm 41.72\%$), and St.17 ($93.70\% \pm 48.07\%$), while it was absent at St.1. In contrast, unidentified sea algae contributed 27.12% to the dissimilarity between St.1 and St.3, with higher coverage at St.3 ($52.78\% \pm 33.30\%$) compared to its absence at St.1. Similarly, *Padina pavonica* contributed 9.93% to this dissimilarity, with greater abundance at St.3 ($19.28\% \pm 15.56\%$).

Further significant differences were identified between St.2, St.3, and St.4 (St.3: Global $R = 0.911$, $p < 0.001$, average dissimilarity = 94.34%; St.4: Global $R = 0.709$, $p < 0.001$, average dissimilarity = 86.88%). *P. oceanica* again played a major role, contributing over 43% to dissimilarities, with markedly higher coverage at St.2 compared to St.3 and St.4. Unidentified sea algae also contributed substantially (approximately 26%), with higher coverage at St.3 and St.4 than at St.2. Additional contributors included *Padina pavonica*, *Sargassum vulgare*, and *Laurencia pinnatifida*, each showing higher abundance at stations where *P. oceanica* was less dominant.

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Comparisons between St.3, St.8, and St.17 also revealed significant differences (St.8: Global $R = 0.943$, $p < 0.001$; St.17: Global $R = 0.961$, $p < 0.001$). These differences were largely attributed to the presence of *P. oceanica* at St.8 and St.17, where it exhibited high percentage cover, in contrast to its absence at St.3. Conversely, unidentified sea algae and *Padina pavonica* were more abundant at St.3, contributing notably to dissimilarity patterns. *Cymodocea nodosa* also contributed to variation, though to a lesser extent.

Similarly, significant differences were observed between St.4, St.8, and St.17 (Global R values ranging from 0.733 to 0.821, $p < 0.001$). These differences were primarily influenced by the dominance of *P. oceanica* at St.8 and St.17 compared to its low abundance at St.4. Unidentified sea algae showed the opposite trend, with higher coverage at St.4. Additionally, *Laurencia pinnatifida* contributed to the observed dissimilarities, being more abundant at St.4 and absent at the other stations.

Overall, spatial variation in community composition across the study area was strongly influenced by the distribution and relative abundance of key species, particularly *Posidonia oceanica* and macroalgal assemblages.

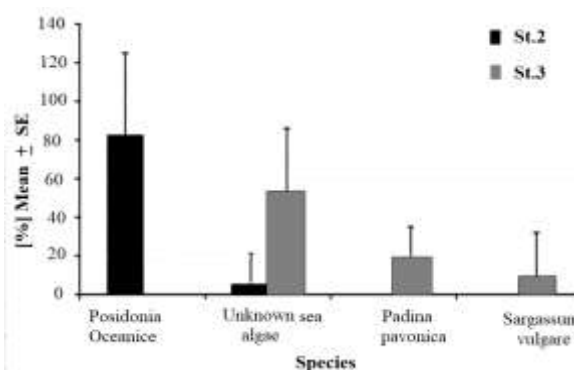


Figure 5: Species coverage [%] Mean ± SE between station 2 and 3.

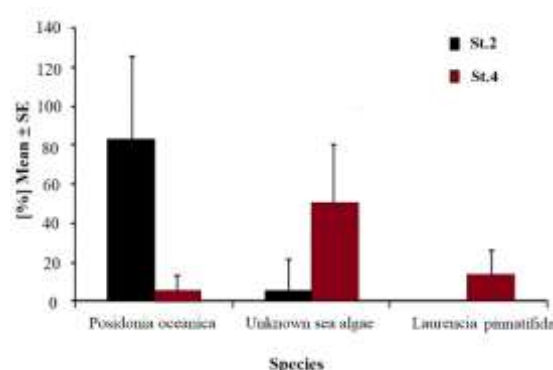


Figure 6: Species coverage [%] Mean ± SE between station 2 and 4.

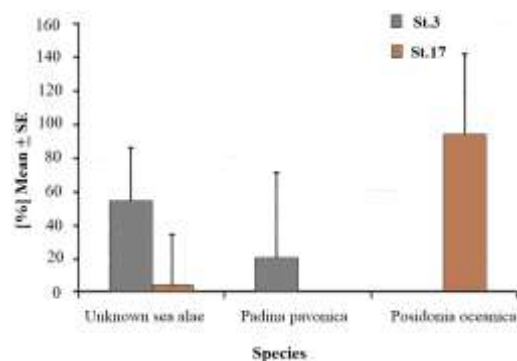


Figure 7: Species coverage [%] Mean ± SE between st.3 and 17.

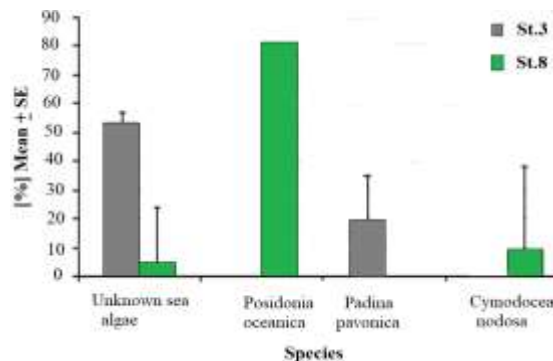


Figure 8: Species coverage [%] Mean ± SE between station 3 and 8.

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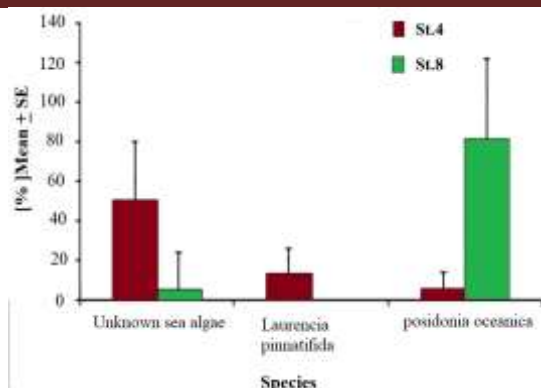


Figure 9: Species coverage [%] Mean $\pm$ SE between station 4 and 8.

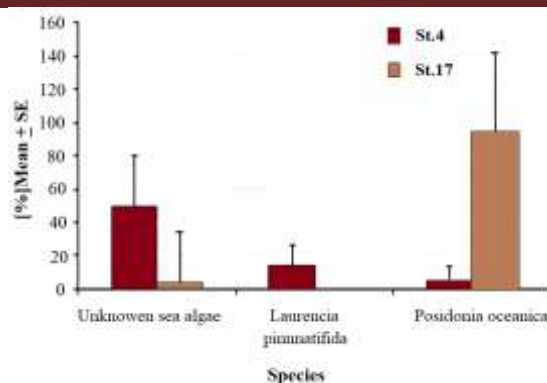


Figure 10: Species coverage [%] Mean $\pm$ SE between station 4 and 17.

5.2 Environmental Parameters at ZDP

At the ZDP site, Principal Component Analysis (PCA) of physicochemical parameters identified five principal components (Figure 13). The first principal component (PC1) explained 67.6% of the total variance, while the cumulative variance explained increased to 81.4%, 88.2%, 92.4%, and 94.9% with the inclusion of PC2, PC3, PC4, and PC5, respectively.

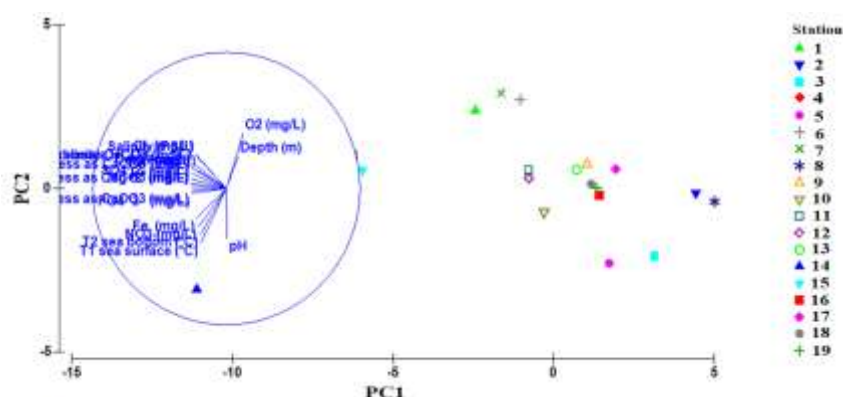


Figure 13: Principal components analysis (PCA) ordination of physicochemical parameters for ZDP. (With permission from ASCE: <https://ascelibrary.org/doi/pdf/10.1061/9780784413548.224>).

PC1 was primarily associated with total hardness as CaCO_3 , Ca^{2+} hardness, Mg^{2+} hardness, sulphate (SO_4^{2-}), phosphate (PO_4^{3-}), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). PC2 was mainly influenced by surface and bottom water temperatures, pH, nitrate (NO_3^-), and dissolved oxygen (O_2). PC3 was strongly associated with depth and pH, while PC4 reflected variations in pH, nitrate, sodium (Na^+), iron (Fe), and dissolved oxygen. PC5 was primarily related to salinity, chloride (Cl^-), and sodium concentrations. A significant positive correlation was identified between PC1 scores and the percentage cover of *Posidonia oceanica* (Spearman's $r_s = 0.673$; $p = 0.002$).

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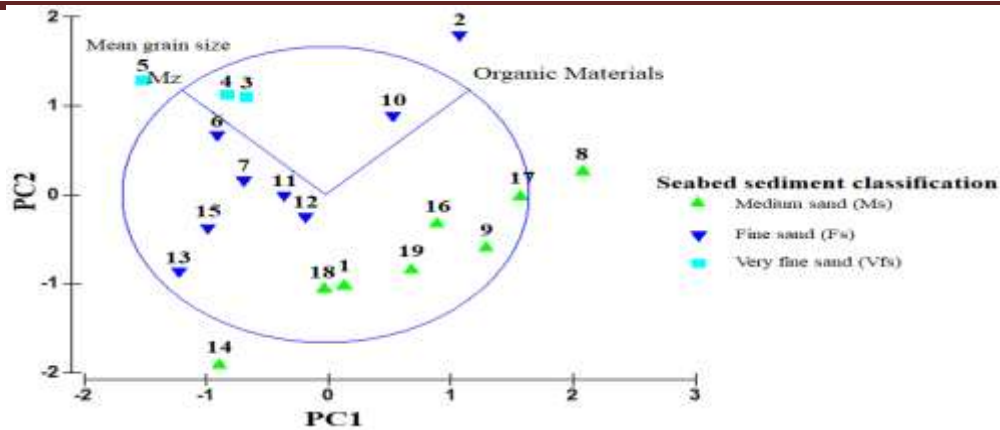


Figure14: Principal components analysis (PCA) ordination of sediment data for ZDP.

PCA of seabed sediment characteristics, including organic content and mean grain size, resulted in two principal components (Figure 14). PC1 accounted for 53.7% of the total variance, while PC2 increased the cumulative variance explained to 100%. PC1 was defined by a positive relationship with organic content and a negative relationship with mean grain size, whereas PC2 showed the inverse pattern. Organic content across all stations remained below 10%. A significant positive correlation was observed between organic content and *P. oceanica* cover ($r_s = 0.573$; $p = 0.001$), while the relationship between grain size and seagrass cover was positive but not statistically significant ($r_s = 0.359$; $p = 0.132$).

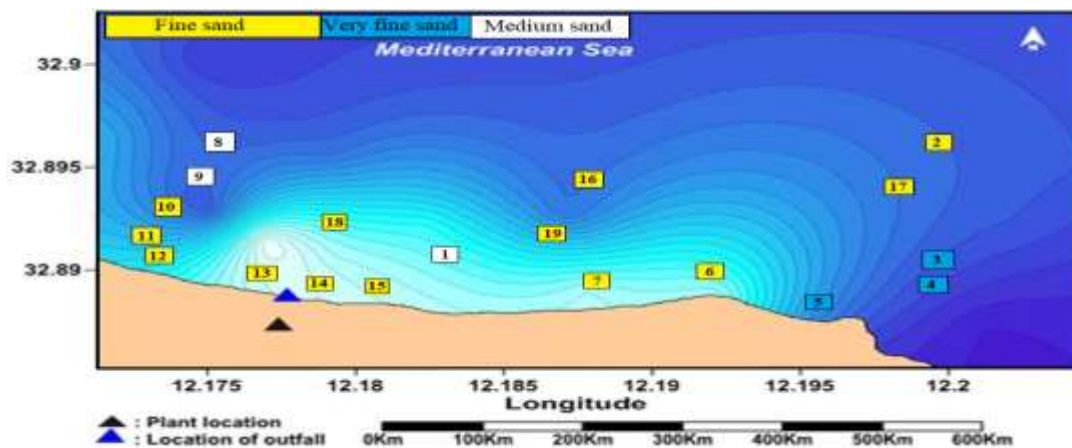


Figure 15: Sediments classification at ZDP

Grain size analysis indicated that sediments ranged from medium to very fine sand (1.03 ϕ to 3.6 ϕ). Kurtosis values varied from very platykurtic to very leptokurtic (0.66 ϕ to 2.46 ϕ), while skewness ranged from strongly negative to strongly positive (−0.4 ϕ to 0.4 ϕ). Sorting, as indicated by standard deviation (δI), ranged from well sorted to poorly sorted (0.4 ϕ to 1.4 ϕ). Fine sand was the dominant sediment type across the study area.

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Physicochemical analysis of seawater revealed considerable spatial variability. Total hardness ranged from 6,000 to 15,571 mg/L, with the lowest values recorded at Station 8 and the highest at Station 14. Similar variability was observed for Ca^{2+} and Mg^{2+} hardness, as well as calcium and magnesium ion concentrations, all of which were highest near Station 14. Sulphate concentrations ranged from 1,000 to 4,148 mg/L, while potassium levels showed relatively minor variation (408–570 mg/L). Sodium and chloride concentrations exhibited substantial variability, with peak values also recorded at Station 14.

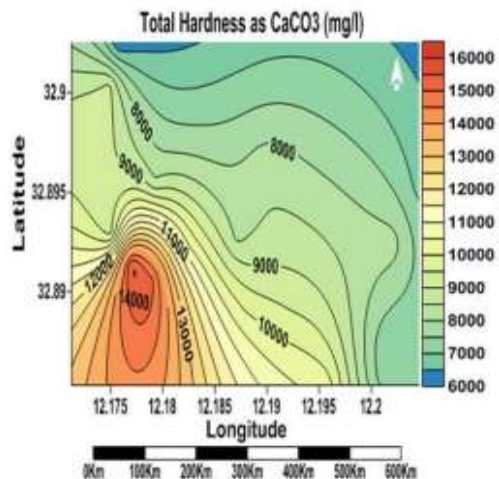


Figure 16: Total Hardness (mg l^{-1}) at ZDP
(With permission from ASCE <https://ascelibrary.org/doi/pdf/10.1061/9780784413548.224>)

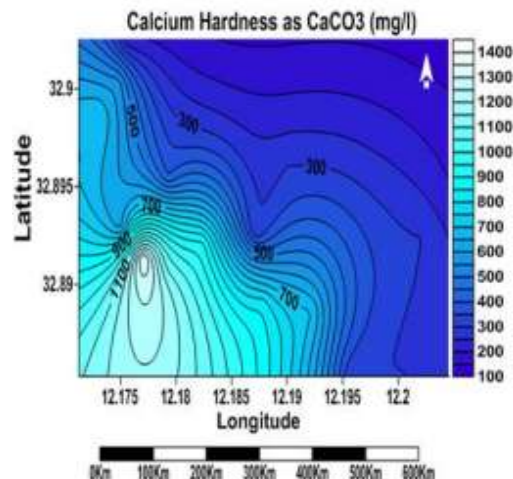


Figure 17: Ca^{+2} Hardness (mg l^{-1}) at ZDP

Nutrient concentrations, including phosphate and nitrate, showed relatively low and narrow ranges across stations, while iron concentrations remained minimal. Salinity levels varied between 35 and 47 psu, with the highest values recorded near the discharge point. Temperature measurements indicated elevated surface and bottom water temperatures near the outfall, while pH values ranged from 7.76 to 8.46. Dissolved oxygen levels varied between 5.13 and 8.39 mg/L, with lower values observed closer to the discharge location.

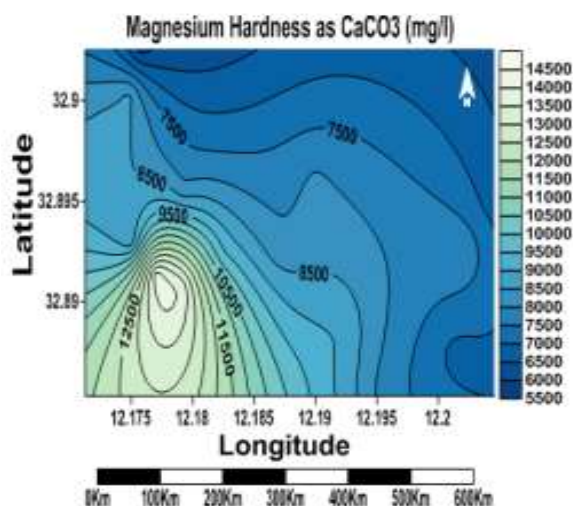


Figure 18: Mg^{+2} Hardness (mg l^{-1}) at ZDP
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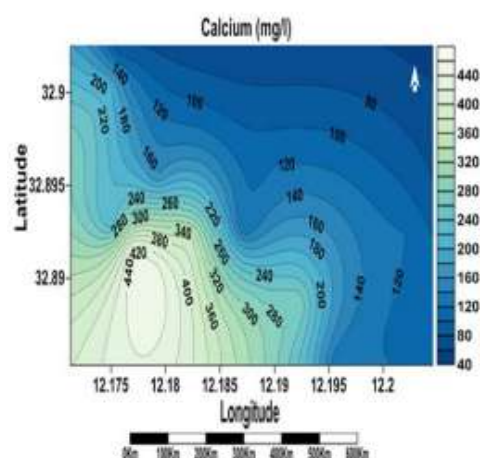


Figure 19: Ca^{+2} (mg l^{-1}) at ZDP

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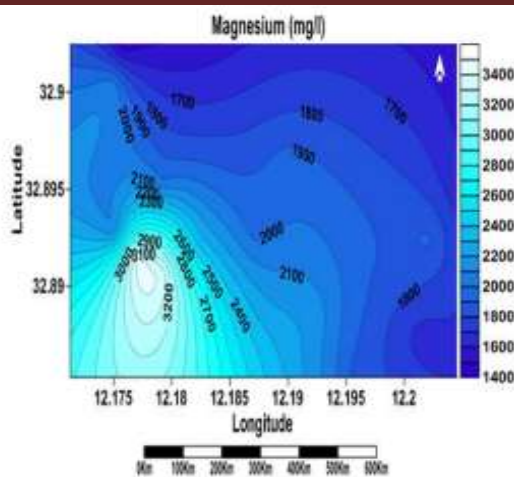


Figure 20: Mg^{+2} (mg l^{-1}) at ZDP

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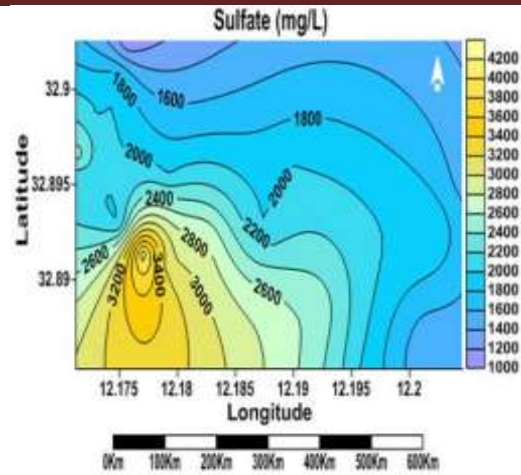


Figure 21: SO_4^{-2} (mg l^{-1}) at ZDP

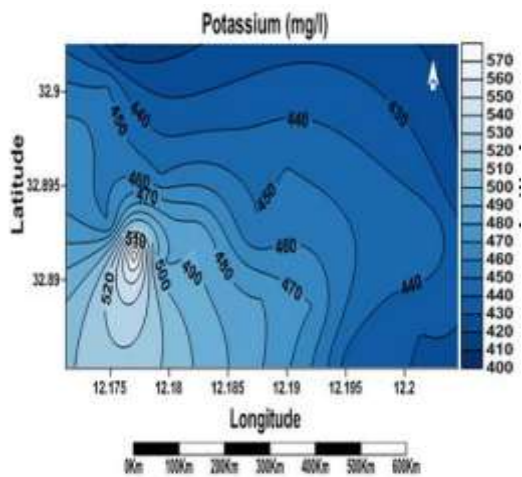


Figure 22: K^{+} (mg l^{-1}) at ZDP

(With permission from ASCE: <https://ascelibrary.org/doi/pdf/10.1061/9780784413548.224>)

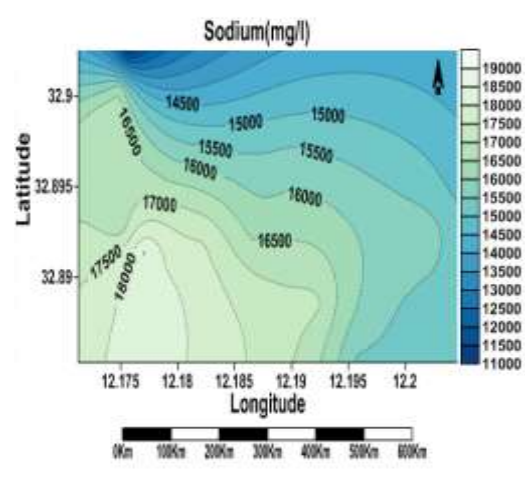


Figure 23: Na^{+} (mg l^{-1}) at ZDP

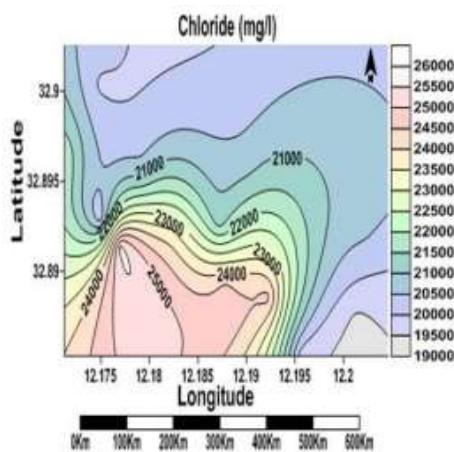


Figure 24: Cl^{-} (mg l^{-1}) at ZDP

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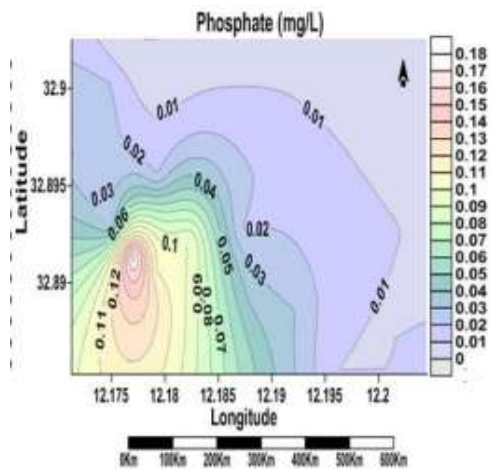


Figure 25: PO_4^{-3} (mg l^{-1}) at ZDP

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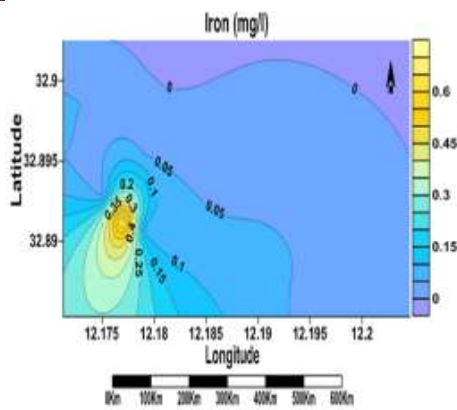


Figure 26: Fe (mg/l⁻¹) at ZDP

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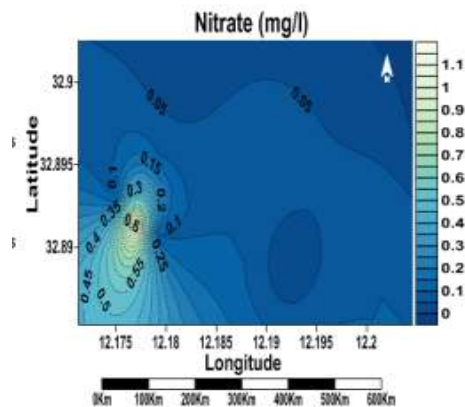


Figure 27: NO₃⁻ (mg/l) at ZDP

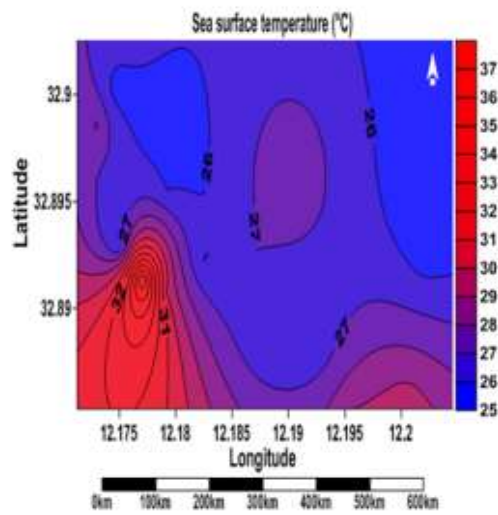


Figure 28: Surface temperature (C°) at ZDP

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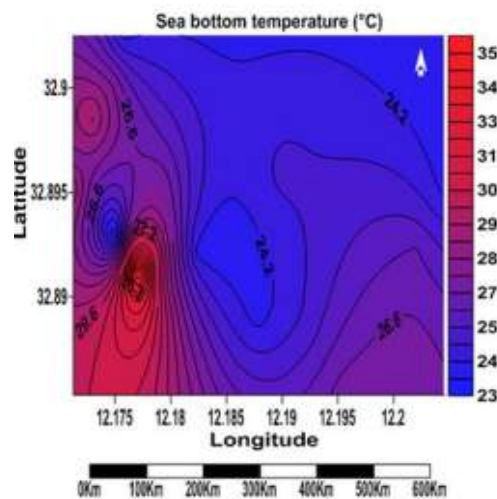


Figure 29: Bottom temperature (C°) at ZDP

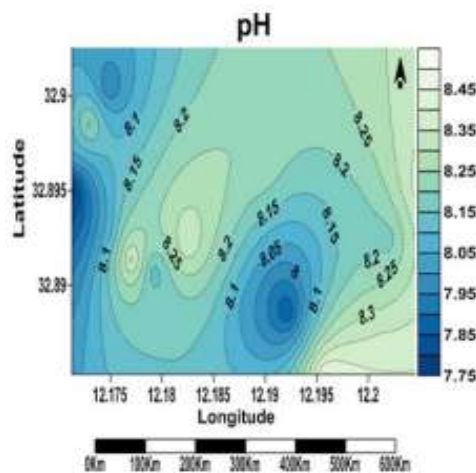


Figure 30: pH at ZDP

(With permission from ASCE: <https://ascelibrary.org/doi/pdf/10.1061/9780784413548.224>)

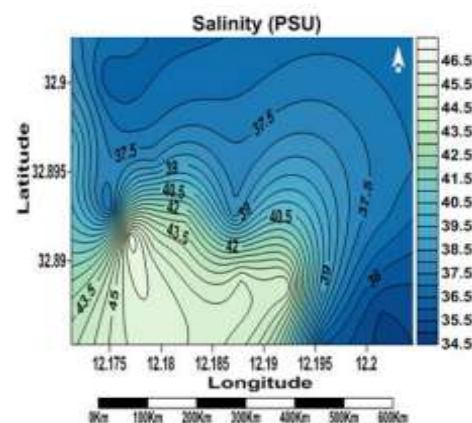


Figure 31: Salinity (psu) at ZDP

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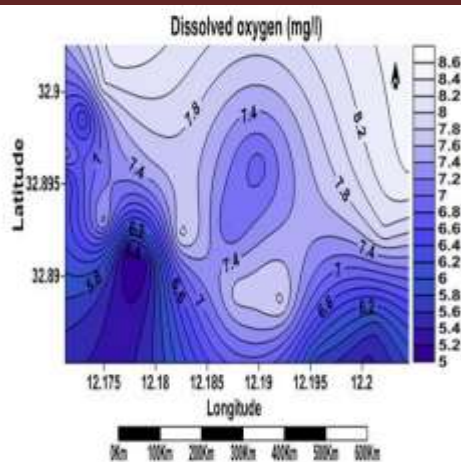


Figure 32: Dissolved oxygen (DO) (mg l^{-1}) at ZDP
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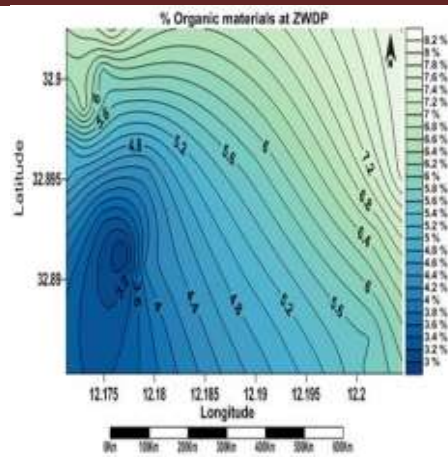


Figure 33: Organic materials (%) at ZDP

Sediment organic matter content ranged from 2.8% to 7.9%, remaining below 10% across all stations but showing spatial variability. Field observations further indicated visible stress on seagrass leaves near the discharge point compared to healthier specimens located farther from the outfall (Figure 34).

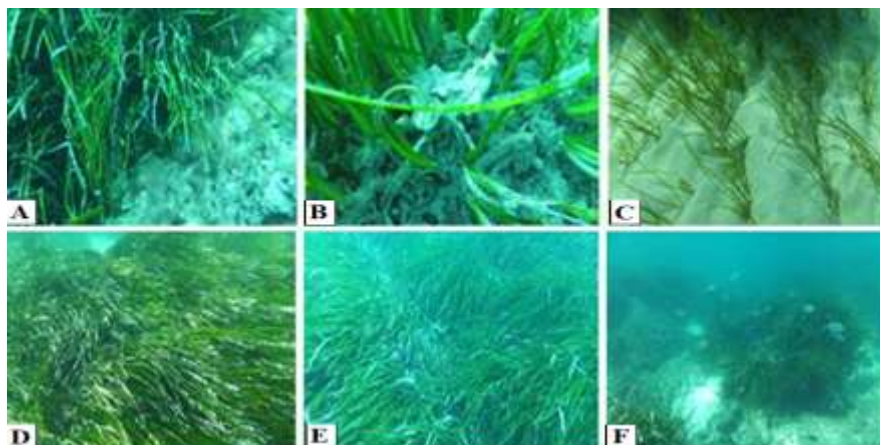


Figure 34: Seagrass is near and further away from the outfall for ZDP.

Additionally, emissions associated with the energy requirements of the desalination process, particularly from the use of light and heavy fuel oils, were observed to contribute to elevated levels of air pollutants and greenhouse gases in the surrounding environment (Figure 35).



Figure 35: Air pollution at Zwara Desalination Plant.

6 Discussion

The present study aimed to evaluate the physicochemical impacts of brine discharge from thermal desalination processes on the marine environment. At the ZDP site, eight species were identified, representing the biological community structure (Figure 3), including the seagrasses *Posidonia oceanica* and *Cymodocea nodosa*, as well as macroalgae such as *Taonia atomaria*, *Padina pavonica*, *Sargassum vulgare*, and *Laurencia pinnatifida*, in addition to unidentified algae and fish species such as *Spicara flexuosa*.

A clear spatial variation in community composition was observed across the study area. Stations located further from the discharge point (e.g., St.2, 3, 4, 6, 8, 9, 16, 17, 18, and 19) exhibited higher abundance and diversity of seagrasses and macroalgae. In contrast, stations closer to the outfall (e.g., St.1, 5, 7, 10–15) were largely dominated by non-living substrates such as sand and rocks, with limited biological presence. Fish species were scarce and recorded only at a single station, indicating potential environmental stress in areas affected by brine discharge.

Key physicochemical parameters influencing these patterns included total hardness, calcium and magnesium concentrations, sulphate, phosphate, potassium, sodium, chloride, nitrate, iron, temperature, pH, dissolved oxygen, salinity, and depth. Elevated levels of total hardness and associated ions near the discharge point are likely linked to the use of antiscalants and operational processes within the desalination plant (Soror, 2009; Wildebranda et al., 2007). These substances, discharged with brine, may adversely affect marine organisms.

Higher sulphate concentrations observed at the site may result from the use of sodium sulphite in boiler systems. The subsequent formation of sulphide in sediments can be toxic to seagrasses, inhibiting respiration and potentially altering ecosystem structure (Borum et al., 2004; Howarth and Teal, 1979). Similarly, elevated concentrations of sodium and chloride ions, likely associated with chlorination processes using sodium hypochlorite, may contribute to chemical stress in marine environments (Verdier, 2011; Hashim and Hajjaj, 2005).

Although seagrasses are generally tolerant to saline conditions, excessive concentrations of Na^+ and Cl^- can disrupt osmotic balance, leading to physiological stress, reduced growth, and increased mortality (Khalafallah et al., 2013; Touchette, 2007). This study identified strong correlations among Na^+ , Cl^- , and K^+ concentrations, suggesting potential ionic interactions affecting plant metabolism.

Nutrient enrichment, particularly phosphate and nitrate, was also observed and may be associated with chemical additives and operational processes. Elevated nutrient levels can promote eutrophication, resulting in excessive algal growth and subsequent ecological imbalance (Davis, 2015).

Thermal effects represent another critical factor. Elevated seawater temperatures near the discharge point reduce oxygen solubility and alter metabolic processes, leading to decreased dissolved oxygen levels. The recorded dissolved oxygen concentrations at ZDP were significantly lower than regional baseline values (Jack et al., 2009),

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potentially posing risks to marine life. Additionally, de-aeration processes and the use of oxygen scavengers may further contribute to reduced oxygen availability (Abuzinada et al., 2008).

Salinity levels near the outfall exceeded typical background values for the Libyan coast, reflecting the influence of concentrated brine discharge. Increased salinity, combined with elevated temperature, can impose physiological stress on marine organisms and limit species distribution (North et al., 1995; Joyce et al., 2005). Lower biodiversity observed at shallow stations near the discharge point supports this conclusion.

Sediment analysis indicated dominance of fine to very fine sand, suggesting transport by strong hydrodynamic processes. Organic matter content remained below 10% but showed spatial variability, likely influenced by organic compounds present in desalination additives (Lattemann, 2005). A significant positive relationship between sediment organic content and seagrass presence highlights the importance of sediment quality in supporting benthic vegetation (Morrison and Greening, 2015).

Seagrasses such as *P. oceanica* and *C. nodosa* play a crucial ecological role and are widely recognized as bioindicators of marine environmental quality in the Mediterranean region (Benkhayal et al., 2013). Their sensitivity to salinity, temperature, and chemical stress makes them particularly vulnerable to desalination impacts. Indeed, *P. oceanica* is known to be highly sensitive to hypersaline conditions associated with brine discharge (Laspidou et al., 2010).

Overall, the findings of this study demonstrate a clear relationship between physicochemical changes induced by brine discharge and alterations in marine community composition. Significant positive correlations between environmental parameters and biological data, as well as between sediment organic content and seagrass distribution, confirm the influence of desalination activities on the marine ecosystem. These results are consistent with previous studies, highlighting the need for improved management strategies to mitigate the environmental impacts of brine disposal from thermal desalination plants.

7 Conclusions

In summary, this study evaluated the impacts of brine discharge from thermal desalination processes on the Libyan marine environment, with reference to the Zwara Desalination Plant (ZDP). The findings indicate that brine effluent introduces elevated salinity, temperature, and chemical residues into the receiving seawater, resulting in measurable alterations to its physicochemical properties.

Increased concentrations of key ions and compounds associated with brine discharge reflect significant changes in seawater composition, which may adversely affect marine ecosystems. The discharge of high-temperature, high-salinity effluent can disrupt physiological processes in marine organisms, including osmotic balance and enzymatic activity, thereby influencing their survival, distribution, and overall ecological stability.

Furthermore, the reliance on fossil fuels for thermal desalination contributes to CO₂ emissions, which may exacerbate ocean acidification. The combined effects of low pH, high alkalinity, and elevated hardness—particularly from calcium and magnesium ions, highlight the potential for long-term changes in seawater chemistry.

Overall, the results demonstrate that brine discharge from desalination plants poses a tangible risk to marine environments. These findings underscore the need for effective management strategies and mitigation measures to minimize environmental impacts and support the sustainable operation of desalination facilities.

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