Environmental Assessment of Refinery-Derived Hydrocarbon and Trace Metal Contamination in Coastal and Groundwater Systems: A Case Study from Zawia, Libya

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***Abstract*—Oil refining activities can represent a persistent source of hydrocarbon contamination in coastal and groundwater environments, particularly in regions where long-term monitoring data are limited. This study presents an integrated environmental assessment of refinery-derived hydrocarbon and trace metal contamination in offshore, shoreline, and groundwater systems surrounding the Zawia Refinery, western Libya. Twenty samples were collected from offshore waters, shoreline zones, and groundwater wells and analysed for total petroleum hydrocarbons (TPH), chemical oxygen demand (COD), dissolved oxygen (DO), total dissolved solids (TDS), pH, and selected trace metals. The results show strong spatial variability in contamination, with offshore stations AS7 and AS8 exhibiting the highest TPH concentrations (up to 43 mg/L). Groundwater wells AG2 and AG6 also showed elevated TPH, accompanied by pronounced oxygen depletion, indicating strongly reducing conditions in the most impacted wells. Correlation analysis identified a strong positive relationship between TPH and COD and a significant negative relationship between TPH and DO, consistent with oxygen consumption during microbial degradation of petroleum hydrocarbons. Nickel and vanadium enrichment in the most contaminated groundwater wells further supports refinery-related source signatures. Overall, the findings indicate both horizontal dispersion in marine waters and vertical migration into the shallow aquifer, emphasizing the need for integrated monitoring and targeted mitigation in refinery-impacted Mediterranean coastal settings.**

Keywords*—Oil pollution; Total petroleum hydrocarbons (TPH); Groundwater contamination; Trace metals; Coastal environment; Zawia Refinery.

I. INTRODUCTION

Oil refining and petrochemical activities are widely recognized as major sources of environmental contamination in coastal regions, releasing complex mixtures of petroleum hydrocarbons and associated trace metals into marine and subsurface systems. These contaminants may originate from routine operational discharges, accidental spills leaking pipelines, storage facilities, and inadequate waste disposal practices, and they can persist in aquatic environments for extended periods. In semi-enclosed basins such as the Mediterranean Sea, limited water exchange combined with high anthropogenic pressure can enhance contaminant accumulation and increase the vulnerability of coastal ecosystems to refinery-derived pollution [1]. Petroleum hydrocarbons in aquatic environments are commonly quantified as total petroleum hydrocarbons (TPH), which represent a broad range of aliphatic and aromatic compounds with diverse physicochemical properties and environmental behaviours. Elevated TPH concentrations have been reported in coastal waters adjacent to refineries and oil terminals, often accompanied by increased organic loading, oxygen depletion, and ecological stress [2], [3]. Microbial degradation of hydrocarbons consumes dissolved oxygen (DO) increases chemical oxygen demand (COD), which can generate localized hypoxic condition and disrupt biogeochemical cycling [4]. In addition to hydrocarbons, refinery operations can introduce trace metals into surrounding environments. Nickel (Ni) and vanadium (V) are of particular importance because they are naturally enriched in crude oil and are widely used as geochemical indicators of petroleum-related inputs [5]. Other metals-including lead (Pb), chromium (Cr), copper (Cu), cadmium (Cd), and mercury (Hg), may originate from both refinery processes and ancillary industrial sources and pose ecological and human health concerns due to their toxicity, persistence, and potential for bioaccumulation [6]. Numerous studies have

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shown that co-occurring hydrocarbons and trace metals can amplify environmental risk by altering redox conditions, affecting metal mobility, and promoting organic complexation processes [7]. Groundwater systems near oil refineries represent an additional and often underappreciated pathway for contaminant transport. hydrocarbon and dissolved metals can infiltrate aquifers through surface spills, contaminated soils, or leaking infrastructure, resulting in long-term groundwater pollution that is difficult to remediate [8]. In coastal settings, contaminated groundwater may discharge into nearshore marine environments through submarine groundwater discharge, facilitating land-to-sea transfer of refinery-derived pollutants and contributing to coastal water degradation [9]. Accordingly, integrated assessments that jointly evaluate marine, shoreline, and groundwater compartments are essential to characterize contaminant sources, transport mechanisms, and environmental implications.

Despite the importance of refinery-related pollution in the Mediterranean region, data from North African coastal zones remain scarce in the international literature. Libya hosts large oil refining complexes located directly on the Mediterranean coast, yet systematic peer-reviewed environmental assessments are limited. The Zawia Refinery-one of the largest refineries in Libya, is situated close to sensitive coastal environments and shallow groundwater systems used for local water supply. Previous investigation along the Libyan coast have reported elevated hydrocarbons and trace metals associated with industrial activities, underscoring the need for site-specific studies to support environmental management and pollution control [10].

The present study addresses this gap through an integrated environmental assessment of refinery-derived hydrocarbon and trace metal contamination in coastal and groundwater systems surrounding the Zawia Refinery, western Libya. The specific objectives are to:

1- Determine the spatial distribution of TPH and key physicochemical parameters in shoreline, offshore, and groundwater samples;
2- Evaluate the occurrence of trace metals associated with petroleum refining activities;
3- Examine relationships between hydrocarbons, oxygen loading, and organic depletion; and
4- Assess contaminant migration patterns relevant to coastal and groundwater protection. The results provide baseline data for refinery-impacted Mediterranean environments and support the development of environmental engineering strategies for monitoring, risk assessment, and mitigation in data-limited regions.

II. MATERIALS AND METHODS

A. Study Area and Sampling Design

The study area is located along the western Libyan Mediterranean coast near the city of Zawia, approximately 48 km west of Tripoli. The Zawia Oil Refinery is situated adjacent to the shoreline and represents one of the largest petroleum refining facilities in Libya. Refinery-adjacent coastal zones are vulnerable to petroleum hydrocarbon dispersion due to continuous operational inputs and hydrodynamic transport processes [11]. Sampling locations were selected to represent three interconnected environmental compartments: (i) offshore marine waters, (ii) shoreline waters, and (iii) groundwater wells located in the vicinity of the refinery. This spatial design enables evaluation of both horizontal dispersion in marine waters and vertical migration into groundwater systems, which is essential for understanding contaminant transport in refinery-influenced coastal settings [12]. The spatial distribution of sampling stations is show in Fig. 1, and the geographic coordinates of all locations are provided in Table 1.

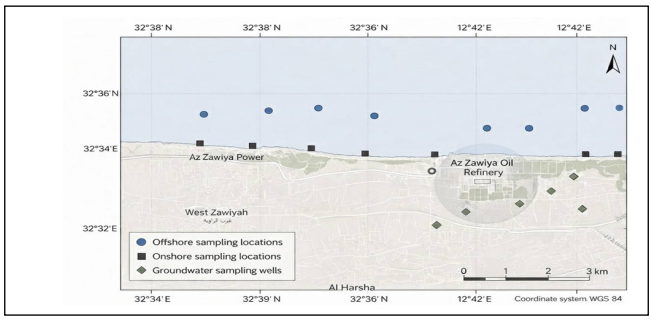

Figure 1. Spatial distribution of offshore, onshore, and groundwater sampling locations around the Zawia Oil Refinery, Libya.

TABLE 1. GEOGRAPHIC COORDINATES OF SAMPLING LOCATIONS AROUND THE ZAWIA REFINERY

Sample ID	Geographic Coordinates		
	Location type	*Latitude (N^0)*	*Longitude (E^0)*
A1	Shoreline	32.793556	12.723439
A2	Shoreline	32.792620	12.712513
A3	Shoreline	32.791674	12.657962
A4	Shoreline	32.794102	12.647428
A5	Shoreline	32.793783	12.636086
A6	Shoreline	32.793379	12.623368
AS1	Offshore	32.802540	12.722528
AS2	Offshore	32.801635	12.712328
AS3	Offshore	32.800460	12.660360
AS4	Offshore	32.803115	12.647128
AS5	Offshore	32.802795	12.635747
AS6	Offshore	32.796667	12.698611
AS7	Offshore	32.796667	12.695000
AS8	Offshore	32.795556	12.704000
AG1	Groundwater	32.785623	12.709516
AG2	Groundwater	32.784090	12.707973
AG3	Groundwater	32.777890	12.714067
AG4	Groundwater	32.783191	12.681036
AG5	Groundwater	32.765860	12.684594

Sample ID	Geographic Coordinates		
	Location type	*Latitude (N^0)*	*Longitude (E^0)*
AG6	Groundwater	32.788775	12.714900

Coordinates are reported in decimal degrees (WGS84).

Hydrogeological context. A preliminary hydrogeological assessment suggests a local southward groundwater flow near the refinery site, which is consistent with elevated petroleum hydrocarbon contamination observed in the southern monitoring area. However, this inferred flow direction may represent a localized condition rather than the regional groundwater pattern of the Jifarah Plain. Local stratigraphic variability and groundwater pumping may influence hydraulic gradients in the shallow aquifer. Therefore, additional hydraulic head measurements (multi-well water-level monitoring) and site-scale groundwater flow/transport modelling are recommended to confirm the long-term contaminant migration pathway.

B. Sample Collection and Preservation

A total of twenty samples were collected from areas surrounding the refinery, including six shoreline samples (A1–A6), eight offshore samples (AS1–AS8), and six groundwater samples (AG1–AG6). Offshore and shoreline samples were collected on 11 June 2025, and groundwater samples were collected on 23 June 2025. Offshore samples were collected approximately 1 km from the shoreline using sterile glass containers deployed from a sampling boat to minimize contamination and sample disturbance. Shoreline samples were collected manually from locations potentially influenced by refinery-related activities.

Groundwater samples were obtained from six wells located in nearby residential and agricultural areas. Prior to sampling, each well was purged by removing three well volumes to ensure that collected samples were representative of aquifer conditions, following standard groundwater sampling procedures [13]. All samples were preserved at 4 °C, transported to the laboratory within 18 hours, and handled in accordance with established sampling guidance [13], [14]. Samples for metal analysis were acidified with HNO_3 to pH < 2 to stabilize dissolved ions prior to analysis.

C. Physicochemical and Trace-Metal Analysis

All samples were analysed for total petroleum hydrocarbons (TPH), chemical oxygen demand (COD), dissolved oxygen (DO), total dissolved solids (TDS), and pH. TPH was quantified using a Horiba OCMA-310 oil content analyzer (infrared spectrophotometry) following S-316 solvent extraction. Each sample was extracted and analyzed in triplicate, and results are reported as mean value. a commonly applied screening method for petroleum hydrocarbon assessment in environmental matrices [15]. COD was measured using the closed reflux colorimetric method, while DO was determined using the Winkler titration method. Measurements of pH and TDS were conducted using calibrated digital meters.

Quality assurance/quality control (QA/QC) for TPH. Method blanks and spike recovery tests were performed. The method detection limit (LOD) and quantification limit (LOQ) for TPH were 1.0 mg/L and 3.0 mg/L, respectively; method blanks were < 1.0 mg/L, and spike recoveries ranged from 92% to 106%.

Trace metal concentrations (Fe, Ni, V, Pb, Cr, Cu, Cd, and Hg) were determined using flame atomic absorption spectrophotometry (Shimadzu AA-7000), while Hg was analyzed using cold vapor AAS. Each sample was measured in triplicate, and analytical precision was verified by maintaining RSD < 5%. Element-Cr 1.0/3.0, Hg 0.01/0.03, Cu 1.0/3.0, and Fe 10/30. Recoveries were approximately 94%-101% based on laboratory control checks [16].

D. Statistical Analysis

Descriptive statistics were used to summarize physicochemical characteristics of the collected samples. Pearson correlation analysis was applied to evaluate relationships among TPH, COD, DO, and selected trace metals [14]. Principal component analysis (PCA) was used to identify dominant contamination factors and support source attribution lined to refinery activities, as commonly applied in contamination studies [12]. Statistical significance was assessed at a 95% confidence level.

III. RESULTS AND DISCUSSION

A. Spatial Distribution of Petroleum Hydrocarbons

The physicochemical characteristics of shoreline, offshore, and groundwater samples are summarized in Table2. TPH concentrations exhibited pronounced spatial variability across the study area, reflecting the combined effects of refinery proximity, hydrodynamic transport, and subsurface migration processes. Offshore stations AS7 and AS8 recorded the highest TPH concentrations (43 and 37 mg/L, respectively), indicating substantial hydrocarbon accumulation in offshore waters. Such offshore enrichment is consistent with refinery-influenced coastal systems, where coastal circulation and density-driven transport can redistribute petroleum hydrocarbons away from shoreline sources [11], [17]. Shoreline samples showed moderate TPH concentrations, likely influenced by dilution, volatilization, and weathering processes typical of dynamic nearshore environments.

TABLE 2. PHYSICOCHEMICAL CHARACTERISTTICS OF SHORELINE, OFFSHORE, AND GROUNDWATER SAMPLES AROUND THE ZAWIA REFINERY

Sample	Physicochemical characteristics					
	Location	*pH*	*COD (mg/ L)*	*DO (mg/L)*	*TDS (mg/L)*	*TPH (mg/ L)*
A1	Shore	8.2	27.1	4.34	35932	9.0
AS1	Offshore	7.9	25.7	5.51	34511	4.0
A2	Shore	7.7	34.5	5.11	32084	11
AS2	Offshore	7.4	33.9	5.13	35643	5.0
A3	Shore	8.0	32.0	4.16	32095	13
AS3	Offshore	8.0	45.1	4.39	31547	17
A4	Shore	7.1	28.9	6.01	33412	7.0

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Sample	Physicochemical characteristics					
	Location	*pH*	*COD (mg/L)*	*DO (mg/L)*	*TDS (mg/L)*	*TPH (mg/L)*
AS4	Offshore	6.9	21.8	6.11	35080	4.0
A5	Shore	7.1	19.7	5.14	35087	2.0
AS5	Offshore	7.2	20.4	5.65	32655	3.0
A6	Shore	8.3	25.9	4.78	35439	2.0
AS6	Offshore	8.2	18.5	6.87	35241	0.0
AS7	Shore	8.4	65.5	3.91	33700	43
AS8	Offshore	7.8	70.1	3.80	32600	37
AG1	Groundwater	7.3	15.0	2.10	640.0	0.0
AG2	Groundwater	8.1	53.0	0.30	2350.0	38
AG3	Groundwater	7.3	37.0	1.30	1023.0	7.0
AG4	Groundwater	7.9	19.0	2.40	1430.0	1.0
AG5	Groundwater	7.4	16.0	2.20	700.0	0.5
AG6	Groundwater	7.8	55.0	0.40	2400.0	36.0

TPH- total petroleum hydrocarbons; COD- chemical oxygen demand; DO- dissolved oxygen; TDS- total dissolved solids; PH- acidity level.

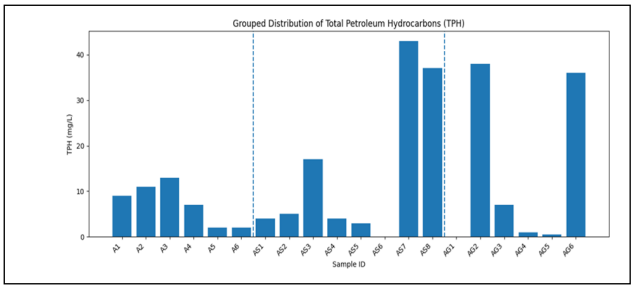

Fig.2. Grouped distribution of total petroleum hydrocarbon (TPH) concentrations in shoreline (A1-A6), offshore (AS1-AS8), and groundwater (AG1-AG6) samples collected around the Zawia Refinery. Dashed lines indicate between environmental compartments.

In groundwater, localized but severe contamination was observed at wells AG2 (38mg/L) and AG6 (36 mg/L) (Table 2). As shown in Fig. 2, these wells coincide with the highest groundwater TPH levels, supporting vertical migration of petroleum hydrocarbons through subsurface pathways. This interpretation is consistent with sediments into shallow aquifers [11]. In addition, the preliminary hydrogeological assessment indicates locally southward groundwater flow near the refinery, aligning with elevated contamination in the southern monitoring area; however, this may reflect localized gradients influenced by stratigraphy and pumping rather the regional Jifarah Plain flow pattern.

B. Relationship Between TPH, COD, and Dissolved Oxygen

Elevated TPH concentrations were consistently associated with increased COD and reduced DO across both marine and groundwater samples Table2. Correlation analysis showed a strong positive relationship between TPH and COD and a significant negative relationship between TPH and DO. This pattern reflects microbial degradation of petroleum hydrocarbons, which increases oxygen demand and causes oxygen depletion in contaminated environments [14]. Offshore stations AS7 and AS8 exhibited DO below 4 mg/L, coinciding with the highest COD values in marine waters. Groundwater wells AG2 and AG6 showed even more severe oxygen depletion, with DO below 0.5 mg/L, indicating near-anoxic conditions. Such conditions are characteristic of shallow or semi-confined aquifers impacted by organic pollution and can disrupt subsurface biogeochemical processes, potentially prolonging contaminant persistence and limiting natural attenuation [18].

C. Trace Metal Distribution and Petroleum-Related Signatures

Trace metal concentrations in surface water and groundwater samples are presented in Table3. Elevated concentrations of Ni and V were particularly evident in groundwater wells AG2 and AG6. These metals are widely recognized as diagnostic tracers of crude oil and refinery effluents due to their enrichment in petroleum fractions and their tendency to co-migrate with hydrocarbons in contaminated environments [14]. The concurrent elevation of TPH and Ni/V in AG2 and AG6 supports refinery-related source influence and subsurface co-migration.

TABLE 3. TRACE METAL CONCENTRATIONS IN SURFACE AND GROUNDWATER SAMPLES (µg/L).

Sample	*Fe*	*Ni*	*V*	*Pb*	*Cr*	*Cu*	*Cd*	*Hg*
A3	121.3	30.5	25.8	18.7	8.50	15.0	1.8	0.55
AG1	49.70	5.50	4.20	2.90	2.20	3.50	0.2	0.08
AG2	182.4	48.9	41.3	29.5	11.5	22.5	3.5	1.80
AG3	90.60	22.5	18.2	14.5	6.10	11.5	1.5	0.45
AG4	61.20	8.50	6.90	4.80	3.20	5.50	0.5	0.25
AG5	70.80	10.2	8.50	5.50	3.90	7.50	0.7	0.30
AG6	198.5	60.1	50.5	35.9	13.5	26.0	4.2	2.20

*Fe-iron; Ni-nickel; V-vanadium; Pb-lead; Cr-chromium; Cu-copper; Cd-cadmium; Hg- mercury.

Iron (Fe) exhibited the highest absolute concentrations across all compartments (Table 3), which may reflect natural mineral dissolution and enhanced mobilization under reducing conditions induced by hydrocarbon degradation. Moderate levels of Pb, Cr, and Cu suggesting additional contributions from refinery operation, corroded infrastructure, and historical industrial activities. The co-occurrence of hydrocarbons and trace metals indicates compounded environmental stress, as organic contamination can alter redox conditions, enhance metal mobility, and potentially increase bioavailability in both surface and groundwater systems [18]. Nickel (Ni) and vanadium (V) showed pronounced enrichment in groundwater samples AG2 and AG6 compared with other locations. These elements are commonly associated with crude oil and refinery-derived inputs and are frequently reported as geochemical indicators of petroleum contamination. Teir elevated concentrations in downgradient wells suggest subsurface migration of refinery-related pollutants and strong interaction between hydrocarbons and trace metals. Lead

(Pb), chromium (Cr, and copper (Cu) were detected at moderate concentrations, with higher values observed in the most contaminated groundwater wells. These metals may originate from a combination of refinery effluents, corroded infrastructure, and historical industrial activities. Cadmium (Cd) and mercury (Hg), although present at lower absolute concentrations, reached levels of concern in groundwater samples, particularly AG6, due to their high toxicity even at low concentrations.

Overall, the groundwater samples exhibited substantially higher trace metal concentrations than surface water, indicating that subsurface environments are more vulnerable to contaminant accumulation. The co-occurrence of petroleum hydrocarbons and trac metals suggests that hydrocarbon contamination has altered subsurface geochemical conditions, promoted metal mobilization and increased environmental and potential human health risks.

D. Comparison With International Drinking-Water Standards (WHO/EPA)

To enhance regulatory relevance, groundwater trace-metal concentrations (AG1-AG6) were compared with WHO drinking-water guideline values and US EPA drinking-water regulations (Table 4). Pb exceeded the WHO guideline value of 10 µg/L in AG2, AG3, and AG6 [19], while Cd exceeded the WHO guideline value of 3 µg/L in AG2 and AG6 [20] (Table 4). In addition, Hg in AG6 (2.20 µg/L) slightly exceeded the US EPA MCL for inorganic mercury (2 µg/L) [21], [24] (Table 4). Other measured metals (e.g., total chromium and copper) remained below WHO guideline limits [22], [23], indicating that exceedances are localized and concentrated in specific wells.

TABLE 4. COMPARISON OF GROUNDWATER TRACE METAL (AG1-AG6) WITH WHO/EPA DRINKING-WATER LIMITS (µg/L).

Well	*Pb (µg/L)*	*WHO GV (Pb=10)*	*Cd (µg/L)*	*WHO GV (Cd=3)*	*Hg (µg/L)*	*US EPA MCL (Hg=2)*	*Exceedance summary*
AG 1	**2.90**	**10**	**0.20**	**3**	**0.08**	**2**	**None**
AG 2	**29.5**	**10**	**3.5**	**3**	**1.80**	**2**	**Pb>WHO; Cd>WHO**
AG 3	**14.5**	**10**	**1.5**	**3**	**0.45**	**2**	**Pb>WHO**
AG 4	**4.80**	**10**	**0.5**	**3**	**0.25**	**2**	**None**
AG 5	**5.50**	**10**	**0.7**	**3**	**0.30**	**2**	**None**
AG 6	**35.9**	**10**	**4.2**	**3**	**2.20**	**2**	**Pb>WHO; Cd>WHO; Hg>EPA**

Notes: WHO guideline values for Pb and Cd are taken from WHO Chemical Fact Sheets [19], [20]. The US EPA MCL for inorganic mercury is taken from the National Primary Drinking Water Regulations [21] (see also mercury technical sheet [24]).

E. Screening-Level Contamination Index (CF and PLI)

To quantify environmental implications, contamination factors (CF) were calculated for groundwater metals relative to the cited WHO/EPA guideline values [19]-[24], and an integrated Pollution Load Index (PLI) was computed as the geometric mean of CFs across Fe, Ni, Pb, Cr, Cu, Cd, and Hg (Table 5) following the original formulation proposed by Tomlinson et al. [25] and as widely applied in recent pollution-index assessments [26]. Pb dominated the index at AG2, AG3, and AG6 (CF(Pb) > 1), while Cd exceeded unity at AG2 and AG6, and Hg exceeded unity at AG6. The highest integrated loads occurred at AG6 (PLI = 0.559) and AG2 (PLI =0.472), supporting prioritization of these wells for confirmatory monitoring and risk-management actions.

TABLE 5. SCREENING-LEVEL CONTAMINATION FACTORS (CF) AND POLLUTION LOAD INDEX (PLI)FOR GROUNDWATER WELLS (AG1-1G6).

Well	*CF (Fe)*	*CF (Ni)*	*CF (Pb)*	*CF (Cr)*	*CF (Cu)*	*CF (Cd)*	*CF (Hg)*	*PLI*
AG 1	0.166	0.079	0.290	0.044	0.003	0.067	0.040	**0.053**
AG 2	0.608	0.699	**2.950**	0.230	0.017	**1.167**	0.900	**0.472**
AG 3	0.302	0.321	**1.450**	0.122	0.009	0.500	0.225	**0.208**
AG 4	0.204	0.121	0.480	0.064	0.004	0.167	0.125	**0.094**
AG 5	0.236	0.146	0.550	0.078	0.006	0.233	0.150	**0.117**
AG 6	0.662	0.859	**3.590**	0.270	0.020	**1.400**	**1.100**	**0.559**

"CF computed relative to WHO/EPA guideline values [19]-[24]. PLI computed following Tomlinson et al. [25] and recent pollution-index review [26].

F. Multivariate Analysis and Source Attribution

Principal component analysis identified two dominant components governing contamination patterns across the study area. The first component was strongly associated with TPH, COD, Ni, and V, indicating a common source linked to refinery-derived petroleum inputs. THE second component was associated primarily with DO and pH, reflecting natural variability in background water-quality conditions. The clustering of highly contaminated offshore and groundwater samples within the same component space supports an integrated contamination mechanism involving both surface and subsurface transport pathways. This reinforces the interpretation that refinery-derived pollutants are not confined to a single environmental compartment but migrate through interconnected marine, coastal, and groundwater systems, potentially amplifying environmental risk.

IV. ENVIRONMENTAL IMPLICATIONS AND CONCLSION

The results demonstrate that refinery-related petroleum hydrocarbon contamination in the Zawia coastal zone is spatially heterogeneous and involves both horizontal dispersion in marine waters and vertical migration into groundwater. Offshore stations AS7 (43 mg/L) and AS8 (37 mg/L) exhibited the highest TPH concentrations, indicating substantial accumulation and transport of hydrocarbons within offshore waters (Table 2, Fig. 2). Groundwater wells AG2 (38 mg/L) and AG6 (36 mg/L) showed similarly high TPH levels, providing strong evidence of subsurface migration and shallow aquifer vulnerability in refinery-adjacent settings (Table 2). These findings confirm that monitoring restricted to surface waters alone can underestimate contamination pathways and may fail to

identify groundwater exposure risks. Hydrocarbon enrichment was accompanied by elevated COD and depressed DO, with near-anoxic conditions observed in the most contaminated wells (DO < 0.5 mg/L in AG2 and AG6). Such oxygen depletion reflects active biodegradation processes and can alter subsurface redox conditions, potentially increasing contaminant persistence and enhancing mobilization of redox-sensitive metals. Trace metals further reinforced the refinery-related signature: Ni and V were enriched in the most contaminated wells (AG2 and AG6), consistent with petroleum-associated tracers (Table 3). Comparison with international drinking-water standards indicates that Pb exceeded the WHO guideline value (10 µg/L) in AG2, AG3, and AG6, Cd exceeded the WHO guideline value (3 µg/L) in AG2 and AG6, and Hg in AG6 (2.2 µg/L) slightly exceeded the US EPA MCL (2 µg/L) (Table 4). These exceedances indicate potential concern for groundwater use and justify prioritizing AG6 (and secondarily AG2 and AG3) for confirmatory monitoring and risk management. Frome a management perspective, the study supports an integrated environmental strategy that simultaneously considers offshore waters, shoreline zones, and groundwater rather than treating them as independent compartments. Based on the results, the following actions are recommended: (i) implement routine multi-season monitoring to capture hydrodynamic and recharge-driven variability; (ii) prioritize AG6 and AG2 for follow-up sampling, including replicate confirmation and expanded analyte coverage (e.g., BTEX and PAHs as health-relevant petroleum compounds) [27]; (iii) conduct hydraulic head measurements and develop a site-scale groundwater flow/transport model to verify the inferred local flow direction and long-term migration pathways; and (iv) evaluate practical mitigation options (e.g., source control near the refinery, containment, and targeted remediation) guided by the spatial hotspot patterns identified in this assessment. Overall, the findings provide a baseline framework for environmental decision-making and demonstrate the need for integrated monitoring and management to reduce long-term ecological and groundwater risks in refinery-impacted coastal system.

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