GWSDAT-Based Spatiotemporal Analysis of MTBE and BTEX Plumes in Jordanian Aquifers

Ali El-Naqa*

*Professor of Hydrogeology, Department of Water Management and Environment, Prince El Hassan Bin Talal Faculty of Natural Resources and Environment, The Hashemite University, Zarqa 13115, P.O. Box 150459, Jordan. E-mail: elnaqa@hu.edu.jo.

Abstract

This study aims to characterize the occurrence and spatial-temporal behavior of methyl tert-butyl ether (MTBE) and the gasoline-related aromatic hydrocarbons benzene, toluene, ethylbenzene, and xylenes (BTEX) in groundwater of the Amman-Zarqa Basin, Jordan. Groundwater from 66 wells representing shallow and deeper aquifer settings was sampled and analyzed for MTBE and BTEX using gas chromatography-mass spectrometry, with USEPA Method 524.2 and DIN 38407-F9 used as the principal analytical references. Major-ion chemistry and field parameters were evaluated to define the hydrochemical framework, while the Groundwater Spatiotemporal Data Analysis Tool (GWSDAT) was applied to visualize concentration patterns and assess temporal tendencies with Mann-Kendall trend statistics. Detectable MTBE/BTEX concentrations were reported in 32 wells and were generally low (approximately 1.0-1.8 µg/L). Detections were concentrated in shallow groundwater in the Seil Zarqa-Awjan/Russeifa-Zarqa corridor, where fuel stations, petroleum handling infrastructure, and a shallow permeable aquifer increase vulnerability to releases. Groundwater chemistry was dominated by Ca-Mg-Cl and Na-Cl facies, with substantial variability in salinity and redox conditions. GWSDAT outputs delineated coherent areas of elevated modeled concentration and supported comparison of temporal behavior among monitoring locations. Because the analytical reporting limit was approximately 1 µg/L, model-smoothed concentrations below this limit are interpreted only as screening-level predictions and not as confirmed detections or definitive plume boundaries. The results support risk-based monitoring of shallow urban groundwater, improved integrity management of underground storage tanks, and continued long-term sampling to distinguish persistent contamination from short-term variability.

Article impact statement: Low-level MTBE and BTEX detections are concentrated in vulnerable shallow groundwater; GWSDAT provides a useful screening framework when model predictions are interpreted in relation to the analytical reporting limit.

Keywords: MTBE; BTEX; GWSDAT; groundwater contamination; Amman-Zarqa Basin; underground storage tanks; Jordan

1. Introduction

Groundwater is the principal strategic freshwater reserve in many arid and semi-arid regions, where limited surface-water availability increases the consequences of aquifer contamination. Urban expansion, industrial activity, transport corridors, fuel storage, and petroleum distribution systems introduce multiple pathways by which volatile organic compounds can reach groundwater. Among these contaminants, methyl tert-butyl ether (MTBE) and the mono-aromatic hydrocarbons benzene, toluene, ethylbenzene, and xylenes (BTEX) are of particular concern because they are associated with gasoline releases and differ markedly in mobility, sorption, biodegradation, and toxicological significance (ATSDR, 2023; Deeb et al., 2000; Almuhtaseb et al., 2024).

MTBE was widely used as a gasoline oxygenate and is highly soluble relative to the hydrocarbon constituents of gasoline. Its weak sorption to aquifer solids and comparatively slow degradation can allow it to migrate farther from a release zone than many BTEX constituents. BTEX compounds originate from the same fuel-release pathways, but their transport is generally more strongly affected by sorption and biodegradation. Benzene is the most health-significant member of the BTEX group because of its carcinogenicity, while prolonged exposure to the other BTEX compounds may also produce adverse effects. These differences mean that the joint interpretation of MTBE and BTEX can provide useful information on source proximity, transport, and attenuation, although source attribution cannot be established solely from concentration patterns.

Interpretation of groundwater contamination requires both spatial and temporal context. A map based on a single sampling round may obscure transient behavior, whereas a time series at one well does not describe the wider distribution of a contaminant. GWSDAT integrates well locations, groundwater elevations, chemistry, and monitoring dates within a statistical framework for visualization and spatiotemporal smoothing (Jones et al., 2014; McLean et al., 2019). Subsequent applications have shown that the tool can support trend evaluation, monitoring-network assessment, and interpretation of plume behavior when the underlying data density and analytical limitations are explicitly considered (Jones et al., 2022).

The Amman-Zarqa Basin (AZB) is one of Jordan's most important and heavily stressed groundwater basins. Rapid urbanization and industrial development in Amman, Russeifa, and Zarqa coexist with dense fuel-distribution

infrastructure and extensive abstraction from carbonate aquifers. A previous basin-scale investigation of 179 wells reported low-level MTBE and BTEX occurrence near potential petroleum-related sources, with MTBE up to 4.1 µg/L and individual BTEX compounds up to 6.6 µg/L (Al Kuisi et al., 2012). That work established the regional relevance of gasoline-derived contaminants, but did not provide the present GWSDAT-based integration of hydrochemical setting, spatial distributions, and temporal behavior.

The present study therefore evaluates MTBE and BTEX occurrence in 66 groundwater wells from the AZB and applies GWSDAT as a screening and interpretation tool. The objectives are to: (1) characterize the occurrence and spatial distribution of MTBE and BTEX; (2) relate detections to aquifer setting, groundwater depth, and plausible petroleum-related source environments; (3) evaluate the hydrochemical conditions that may influence contaminant behavior; (4) examine spatial and temporal patterns using GWSDAT and Mann-Kendall trend analysis; and (5) identify practical monitoring and groundwater-protection implications. Particular attention is given to the analytical reporting limit so that interpolated or smoothed model values are not interpreted as confirmed contamination where measured concentrations are below quantifiable levels.

1.1 MTBE and BTEX in Groundwater

MTBE and BTEX are common indicators of gasoline-related impacts on groundwater. Releases can originate from leaking underground storage tanks (USTs), fuel-transfer areas, pipelines, accidental spills, and other petroleum-handling facilities. Their contrasting physicochemical properties are important for interpretation: MTBE is comparatively mobile in groundwater, whereas BTEX compounds generally show stronger sorption and faster biodegradation under favorable conditions. Consequently, the occurrence of MTBE outside the highest BTEX concentration zone is plausible, but the relative distributions depend on site-specific hydrogeology, release history, redox conditions, and biodegradation capacity (Zogorski et al., 1997; Deeb et al., 2000).

The relatively high aqueous solubility and low sorption of MTBE explain why even modest fuel releases can create a detectable dissolved signal. By contrast, BTEX compounds partition more strongly into organic matter and may attenuate more rapidly, although benzene can remain persistent under some redox conditions. These properties make shallow, permeable aquifers beneath densely urbanized fuel-service corridors particularly vulnerable. Table 1 summarizes the contrast in theoretical aqueous solubility and gasoline-related dissolved concentrations.

Published property data indicate that pure-phase MTBE has a water solubility on the order of tens of grams per liter, substantially greater than that of individual BTEX compounds. In gasoline-water systems, however, dissolved concentrations are constrained by fuel composition and multiphase partitioning; therefore, field concentrations are normally far below pure-compound solubilities (Zogorski et al., 1997).

Table 1. Solubilities of BTEX and MTBE in water and predicted dissolved concentrations from gasoline (after Zogorski et al., 1997).

Compound	Theoretical Aqueous Solubility (mg/L)	Approximate percent by volume in gasoline	Predicted dissolved concentration from gasoline (mg/L)
Benzene	1730	1	17
Toluene	535	11	59
Ethylbenzene	161	2	3
Xylene	175	11	19
MTBE	43000 to 54300	11 to 15	5280 to 7200

Source: Authors, adapted from Zogorski et al. (1997).

BTEX compounds enter groundwater through the same general release mechanisms. Benzene is the principal health concern within the group, while toluene, ethylbenzene, and xylenes may also affect human health at sufficiently high exposures. At the low µg/L concentrations considered in this study, interpretation should focus not only on comparison with drinking-water criteria but also on persistence, repeated detection, spatial coherence, and proximity to vulnerable receptors.

The environmental significance of MTBE and BTEX is therefore a function of both concentration and hydrogeological context. Low concentrations do not imply an immediate exceedance of drinking-water standards, but repeated low-level detections can provide early evidence of fuel-system leakage or migration through shallow groundwater. Monitoring programs should consequently distinguish confirmed analytical detections from model predictions and should evaluate trends over multiple sampling events rather than infer future behavior from a single concentration map.

Table 2 summarizes selected physical and chemical properties that influence subsurface transport. In general, higher water solubility and weaker sorption favor aqueous transport, whereas volatility, biodegradation, and aquifer redox conditions influence persistence. These properties provide a conceptual basis for interpreting the different spatial expressions of MTBE and BTEX in the AZB.

Table 2. Selected physical and chemical properties of BTEX and MTBE relevant to subsurface transport.

Physical and chemical properties	Benzene	Toluene	Ethylbenzene	Xylene	MTBE
Molecular Weight (g/mol)	78.11	92.14	106.17	106.17	88.15
Vapor Density at 1 atm., 10 C° (g/L)	3.36	3.97	4.57	4.57	3.80
Specific Gravity at 25 °C	0.88[a]	0.889[a]	0.867[a]	0.8802[a]	0.744a
Boiling Point (°C)	80.1[a]	110.6[a]	136.25[a]	144.4[a]	53.6 to 55.2[a]
Water solubility (mg/L)	1730[a]	534.8[a]	161[a]	175[a]	43000 to 54300
Vapor Pressure (mm Hg) at 25 °C	76,95.19°	28.4[a] 3.79b	9.53[a] 1.23[b]	6.6[a] 0.889[b]	245 to 276[a]
Henry's law constant [-]	0.23[b]	0.272[b]	0.336[b]	0.212[b]	0.02399[a] 0.04496[a] 0.05722[a] 0.1226[a] 0.026[a]
Log Koc	1.18 to 1.99 1.50 to 2.16[a]	1.56 to 2.25[a]	2.94 1.98 to 3.04[a]	1.68 to 1.83[a]	1091,1035,1049[a]
Log Kow	2.36[b]	2.73[b]	3.24b	3.10b	
Diffusivity (m^2/s): liquid / gas	9.95×10^{-10} 9.36×10^{-6} [b]	8.87×10^{-10} 8.35×10^{-6} [b]	8.6×10^{-10} 7.59×10^{-6} [b]	8.6×10^{-10} 7.56×10^{-6} [b]	8.58×10^{-10} 8.45×10^{-6} [b]

Source: Authors, compiled from the physical-property sources cited in the table.
a Values reported by Zogorski et al. (1997).
b Additional property values reported in the original compiled data source; dimensionless quantities are indicated by [-].

The monitoring significance of these contaminants extends beyond drinking-water compliance because shallow groundwater can discharge to surface-water systems and can act as a pathway toward deeper production zones. In an urban basin, an early-warning approach that combines source control, repeated chemical analysis, and hydrogeological interpretation is therefore preferable to reliance on regulatory exceedance alone.
For this reason, the present study combines conventional groundwater sampling with hydrochemical interpretation and GWSDAT visualization. The statistical outputs are used to support, rather than replace, the measured analytical data; modeled concentrations below the laboratory reporting limit are treated as screening information only.

2. Study Area and Hydrogeological Setting

2.1 Regional Setting

The Amman-Zarqa Basin (AZB) is located in north-central Jordan and covers approximately 4,710 km², including about 468 km² in southern Syria. It contains the major urban-industrial centers of Amman, Russeifa, and Zarqa and supports a large share of Jordan's municipal, industrial, and agricultural activity. The concentration of population, fuel stations, petroleum storage and transport facilities, roads, and industrial sites creates multiple potential sources of petroleum-related contaminants, particularly where the water table is shallow (Margane et al., 2002; Ministry of Water and Irrigation [MWI], 2020).
Climate varies from Mediterranean conditions in the western highlands to semi-arid and arid conditions eastward. Mean annual rainfall decreases from more than 500 mm in the western recharge areas to less than 100 mm in the eastern basin. This gradient controls natural recharge and contributes to large spatial differences in water-table depth, flow direction, and groundwater residence time (Margane et al., 2002).
Land use includes dense urban development, industrial zones, transportation corridors, irrigated agriculture, and open rangeland. Shallow alluvial and weathered/fractured zones along the Zarqa drainage corridor are particularly susceptible to rapid infiltration from surface or near-surface releases. Figure 1 shows the location of the study area and principal urban centers.

Figure 1. Location of the Amman-Zarqa Basin study area and principal urban centers.

2.2 Geological Framework

The AZB contains Lower Cretaceous to Quaternary sedimentary rocks. The main hydrostratigraphic units belong to the Kurnub, Ajlun, and Belqa groups and include sandstone, limestone, dolomitic limestone, marl, chert, and phosphorite. Carbonate units form the principal productive aquifers, whereas marl-rich intervals locally act as aquitards. Quaternary alluvium occupies wadi floors and can form a shallow, highly permeable groundwater zone that is particularly relevant to contaminant transport (Powell, 1989; Abed, 2000).

Regional faults, folds, flexures, and fracture networks influence aquifer connectivity and groundwater-flow directions. These structures are important for contaminant interpretation because they can enhance localized vertical or lateral hydraulic communication between hydrostratigraphic units (Salameh & Bannayan, 1993).

2.2.1 Lithostratigraphy

The lower part of the succession includes the Kurnub Sandstone Group, which is exposed mainly in the western and northwestern basin and consists predominantly of sandstone with shale, silt, marl, and local dolomitic interbeds. It is overlain by the Ajlun Group, including the Naur (A1/2), Fuheis (A3), Hummar (A4), Shuayb (A5/6), and Wadi Es Sir (A7) formations. The overlying Belqa Group includes the Amman-Al Hisa (B2) carbonate-chert-phosphorite succession. The A7 and B2 units together form the regionally important B2/A7 aquifer system.

Lithological contrasts within this succession control both groundwater storage and contaminant migration. Massive and fractured carbonate intervals provide high-permeability flow paths, while marl-rich units restrict

vertical movement where they are laterally continuous. In wadi corridors, alluvial sand and gravel may hydraulically connect shallow groundwater with fractured bedrock, increasing vulnerability to surface-derived contamination.

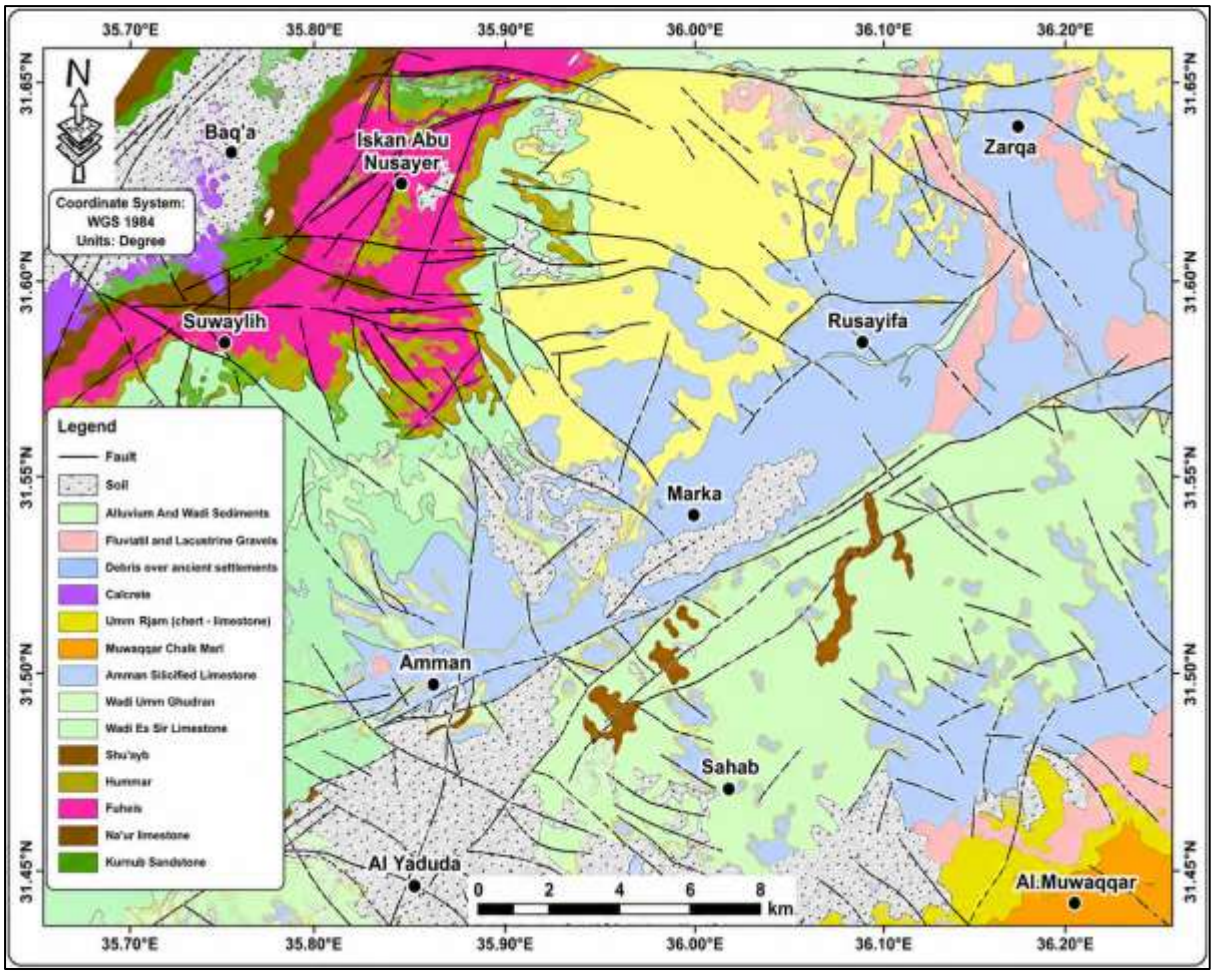

Figure 2. Geological map of the Amman-Zarqa area (source map: Natural Resources Authority, 2014).

2.3 Hydrogeology of the Amman-Zarqa Basin

The principal aquifer systems in the AZB are the upper Amman-Wadi Es Sir (B2/A7) aquifer, the middle Hummar (A4) and Naur (A1/2) aquifers, and the deeper Kurnub sandstone aquifer. Groundwater recharge occurs mainly in western highland outcrop areas and along locally favorable infiltration zones. Hydraulic gradients and abstraction have produced complex flow patterns, with local vertical leakage possible where confining units are thin, fractured, or structurally disrupted (MWI, 2020).

• Upper aquifer system: Amman-Wadi Es Sir (B2/A7), dominated by fractured limestone, dolomitic limestone, chert, and phosphorite.

• Middle aquifer system: Hummar (A4) and Naur (A1/2), productive locally and variably confined.

• Deep aquifer system: Kurnub sandstone, a regional aquifer that is generally confined beneath the Ajlun succession in the central basin.

Recharge is dominated by rainfall infiltration in aquifer outcrops and is strongly concentrated in the higher-rainfall western part of the basin.

2.3.1 Amman-Wadi Es Sir Aquifer (B2/A7)

The B2/A7 aquifer consists of the Amman-Al Hisa (B2) and Wadi Es Sir (A7) carbonate formations. It is the principal regional aquifer and is generally unconfined where it crops out. Along the Zarqa River and associated wadis, sand and gravel alluvium may locally form a shallow aquifer hydraulically connected to the carbonate system. The underlying A5/6 marl-rich succession generally limits downward flow, although leakage can occur where the aquitard is fractured or discontinuous (Howard Humphreys, 1983; MWI, 2020).

Recharge is concentrated in the western highlands and forms a regional recharge mound west of Amman. Reported transmissivity varies widely (approximately 9-900 m^2/d), reflecting karstification, fracturing, and lithological heterogeneity. The large range in hydraulic properties is important for contaminant migration because preferential flow can produce locally rapid transport that is not represented by basin-average conditions (MWI, 2020).

2.3.2 Hummar Aquifer (A4)

The Hummar (A4) is a productive carbonate aquifer in parts of the Amman-Zarqa and Sukhna areas. It is locally confined and may exhibit artesian conditions in synclinal settings. Reported transmissivity ranges from

approximately 230 to 2,800 m²/d, indicating that fracture and karst development can produce high local yields (MWI, 2020).

Groundwater flow is influenced by a divide extending northward from the Amman-Wadi Es Sir area. West of the divide, flow is generally toward Wadi Es Sir, whereas east of the divide the regional component is toward Amman and then east to northeast. Structural flexures and pumping modify these generalized patterns.

Direct recharge is limited by the relatively small outcrop area. Where A4 is confined beneath marl-rich units, contamination originating at the land surface is expected to be less direct than in the shallow B2/A7 or alluvial system; nevertheless, leakage through fractures, faults, or wells remains a possible pathway and should be evaluated with monitoring data.

2.3.3 Naur Aquifer (A1/2)

The Naur (A1/2) contains carbonate intervals interbedded with marl and is hydraulically separated from the Kurnub by lower-permeability strata. Recharge occurs mainly where the unit crops out west and southwest of Amman. Reported transmissivity is generally lower than in the Hummar aquifer, although local fracture zones can enhance productivity (MWI, 2020).

2.3.4 Kurnub Aquifer (K)

The Kurnub is a regional sandstone aquifer recharged mainly in western and northwestern outcrops and, locally, by leakage from overlying carbonate aquifers. It is generally confined beneath the Naur succession in the central AZB. Because it is deeper than the shallow contamination zones emphasized in this study, detections in Kurnub wells would require careful evaluation of well construction, vertical hydraulic gradients, and possible cross-formational leakage.

Reported Kurnub transmissivity varies from approximately 3 to 1,700 m²/d, again reflecting marked spatial heterogeneity. Table 3 summarizes the hydraulic parameters used as regional context in this study (MWI, 2020).

Table 3. Representative hydraulic parameters of aquifers in the Amman-Zarqa Basin (MWI, 2020).

Aquifer	Average Thickness (m)	Transmissivity (m²/d)	Storage Coefficient (S)	Recharge (MCM/y)
Basalt	220.0	2.0-113,000.0	0.001	28.0
Amman Wadi Es Sir (B2/A7)	220.0	9.0-900.0	0.01-0.30	40.0-45.0
Hummar (A4)	50.0	230-2,800.0	0.01-0.10	5.0
Nau'r (A1-2)	220.0	4.0- 10.0	0.004	4.5
Kurnub (K)	280.0	3.0- 1,700.0	0.001-0.10	4.5

Source: Authors, based on MWI hydrogeological data files (2020).

3. Materials and Methods

3.1 Sampling Design and Field Measurements

Groundwater samples were collected from 66 wells selected to represent different aquifer units, groundwater depths, positions along regional flow paths, and proximity to potential petroleum-release sources such as fuel stations and USTs. Both shallow and deeper wells were included to examine the vertical distribution of detections. Prior to sampling, wells were pumped for approximately 15 min to reduce the influence of stagnant casing water. Temperature, pH, electrical conductivity (EC), dissolved oxygen, and redox-related field observations were measured at the wellhead, and alkalinity was determined by titration. Well locations are shown in Figure 3.

3.2 Sample Preservation, Laboratory Analysis, and Quality Control

For major-ion and trace-element analysis, water was collected in clean polyethylene bottles, transported under cooled conditions, and filtered using membrane filtration. Samples intended for dissolved trace-element analysis were acidified with analytical-grade HNO3 to minimize precipitation and adsorption losses and were stored at 4 °C until analysis. A primary and spare bottle were collected at each sampling location. Major cations and anions, phosphorus, and selected trace elements were analyzed using the laboratory procedures applied to the monitoring program.

For MTBE and BTEX, samples were collected in 100 mL containers with no headspace, preserved with concentrated hydrochloric acid as specified by the analytical protocol, cooled to 4 °C, and analyzed within one week. Volatile organic compounds were determined by gas chromatography-mass spectrometry (GC-MS) with headspace/solid-phase microextraction procedures. USEPA Method 524.2 (Revision 4.1) and DIN 38407-F9 were used as analytical references and cross-checks. Analyses were performed in triplicate. The laboratory reporting/detection limit was approximately 1 µg/L, with a reported relative standard deviation of about 10%.

3.3 Hydrochemical and Spatiotemporal Data Analysis

Major-ion data were evaluated using descriptive statistics and Piper trilinear diagrams (Piper, 1944) to identify dominant hydrochemical facies and provide the hydrogeological context for contaminant transport. Relationships among major ions were considered qualitatively in relation to carbonate dissolution, irrigation return flow, urban inputs, and salinity evolution.

GWSDAT version 3.2 was used to integrate monitoring dates, well coordinates, groundwater elevations, and MTBE/BTEX concentrations. The software provides concentration-versus-time plots, Mann-Kendall trend testing, groundwater-flow visualization, and spatial/spatiotemporal smoothing of solute concentrations (Jones et al., 2014; Jones et al., 2022). For the Mann-Kendall test, $p < 0.05$ was treated as evidence of a statistically significant monotonic trend at the 95% confidence level; $p \geq 0.05$ was treated as insufficient evidence of a significant monotonic trend. The test identifies trend direction but does not establish the cause of the trend.

A critical interpretation rule was applied to the GWSDAT output: predicted or smoothed concentrations below the approximately 1 µg/L analytical reporting limit were not treated as confirmed detections. Such values were retained only to visualize relative spatial-temporal structure. Consequently, plume outlines and low-concentration model surfaces in Figures 7-10 are screening-level representations whose reliability depends on well spacing, sampling density, non-detect handling, and the temporal coverage of the monitoring data (McLean et al., 2019).

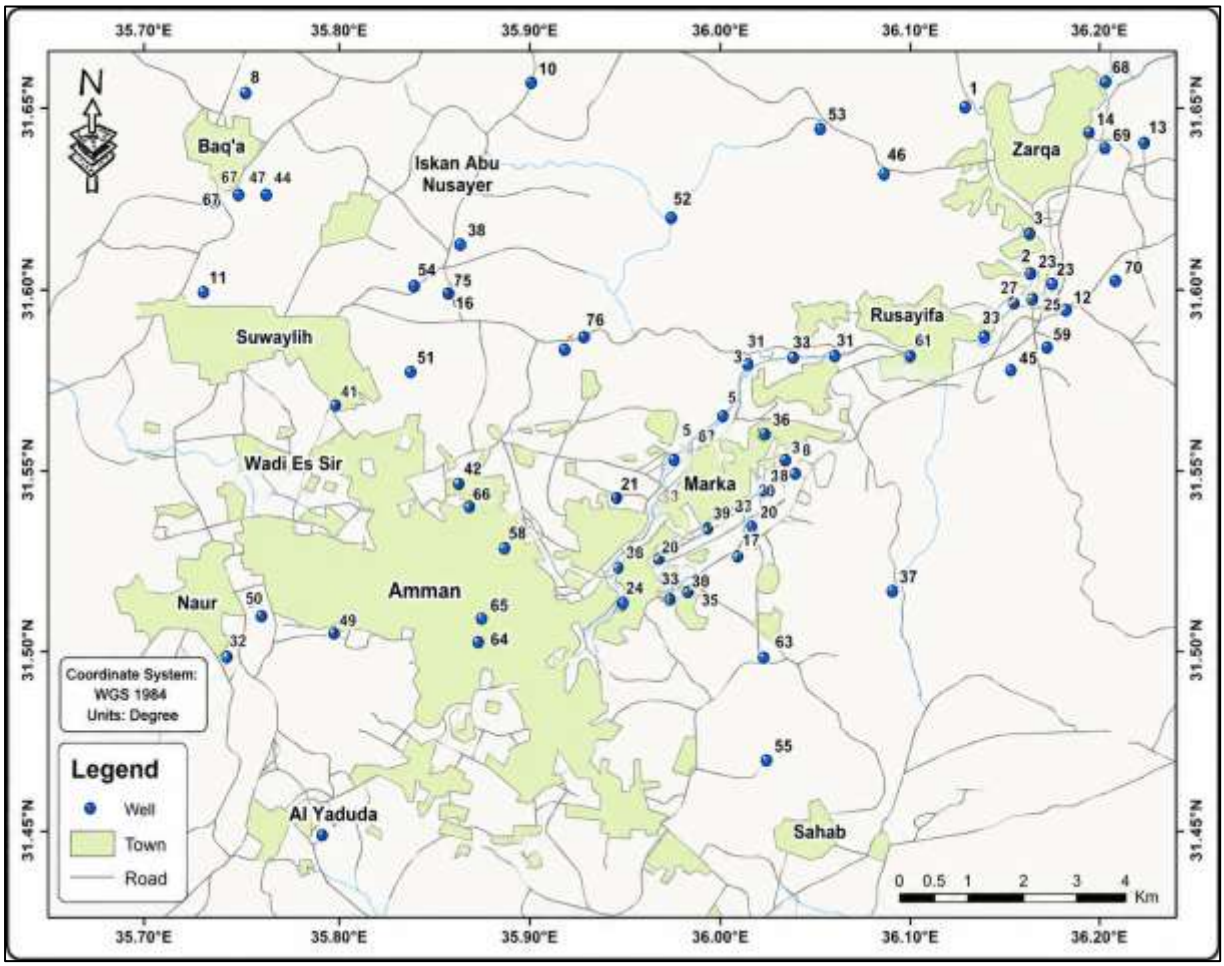

Figure 3. Locations of groundwater wells analyzed in the Amman-Zarqa Basin.

4. Results and Discussion

4.1 Hydrochemical Framework

Groundwater chemistry was heterogeneous across the 66-well network, consistent with the contrasting aquifer units, recharge conditions, abstraction histories, and urban/agricultural influences within the AZB. Measured pH ranged from 6.79 to 8.18 (mean 7.55), indicating neutral to moderately alkaline water. EC ranged from 428 to 6,268 µS/cm (mean 1,388 µS/cm), demonstrating a broad salinity range. Temperature varied from 20.85 to 37.0 °C and redox potential from -12 to +990 mV, indicating that the sampled wells span markedly different hydrochemical and oxidation-reduction settings.

Cation chemistry showed two principal patterns: 55% of samples followed Na > Ca > Mg > K, while 45% followed Ca > Na > Mg > K. Sodium ranged from 16.43 to 1,152.21 mg/L and was strongly correlated with chloride (reported $r = 0.94$). The Na/Cl ratio (0.23-1.38) and the wide salinity range are consistent with a combination of water-rock interaction, evaporation/concentration effects, irrigation return flow, and urban inputs. The Piper diagram (Figure 4) indicates that Ca-Mg-Cl and Na-Cl facies dominate, with subordinate Ca-Mg-HCO3 and Na-HCO3 compositions. These facies provide an important context because ionic strength, redox state, and groundwater residence time can influence biodegradation and the persistence of fuel-related contaminants.

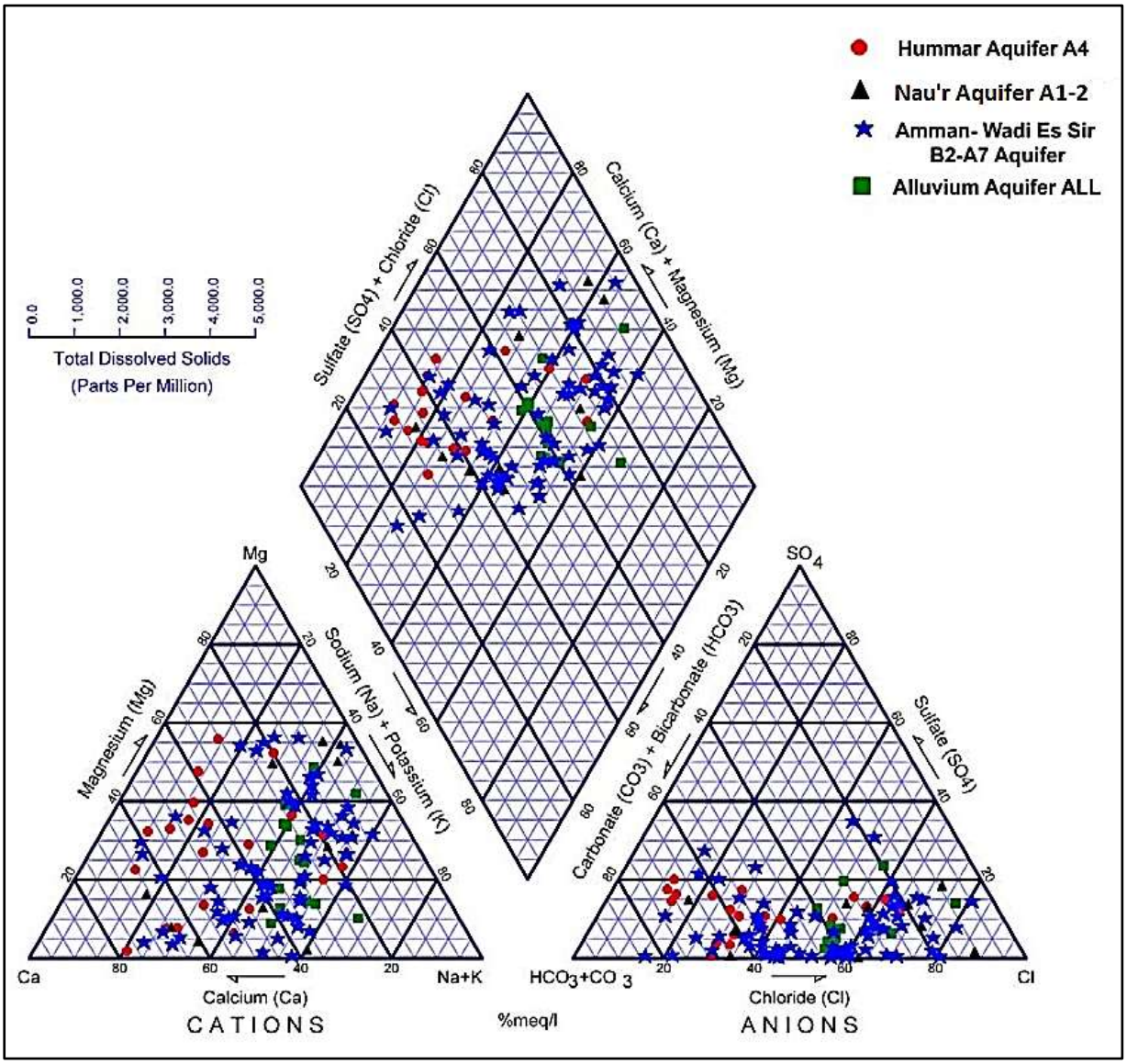

Figure 4. Piper diagram showing the principal hydrochemical facies of groundwater samples.

Bicarbonate ranged from 145.55 to 1,165.85 mg/L and chloride from 1.45 to 308.45 mg/L (Table 4), while sulfate and nitrate also showed large spatial variation. The coexistence of fresh recharge signatures with Na-Cl/Ca-Mg-Cl waters supports the interpretation of multiple hydrochemical controls rather than a single basin-wide process. Because MTBE and BTEX detections are concentrated in shallow groundwater, their occurrence is more plausibly related to local source vulnerability and short transport pathways than to the basin-scale salinity pattern alone. Hydrochemistry is therefore used here as supporting context rather than as a direct source tracer for petroleum contamination.

Table 4. Descriptive statistics for groundwater field parameters, major ions, and selected trace elements.

Parameter	Mean	Min	Max	SD	JS 286:2015 value
EC (µS/cm)	1388.00	428.00	6268.00	1045.00	1500
pH	7.55	6.79	8.18	0.50	6.5 – 8.5
Eh mV	450.00	-12.00	990.00	238.00	
Temp °C	28.20	20.85	37.00	2.92	25
Ca^{2+} (mg/L)	139.62	15.28	312.55	55.04	200
Mg^{2+} (mg/L)	83.95	1.46	593.08	92.01	
Na^{+} (mg/L)	209.69	16.43	1152.21	180.72	200
K^{+}(mg/L)	11.15	1.28	62.65	8.42	
Total hardness (TH) (mg/L)	622.88	265.12	2099.68	315.60	500
HCO_3 (mg/L)	455.38	145.55	1165.85	152.42	
$SO4^{2-}$ (mg/L)	442.31	26.21	2876.26	427.68	500

Cl^- (mg/L)	66.35	1.45	308.45	62.82	500
NO_3^- (mg/L)	58.16	1.10	247.58	48.32	70
PO_4^{3-} (mg/L)	0.04	0.00	0.16	0.02	
Fe (mg/L)	0.39	0.00	6.38	0.46	1
Mn^{2+} (mg/L)	0.025	0.00	0.66	0.07	0.1
Cu^{2+} (mg/L)	0.26	0.00	8.82	1.55	1
Cr^{2+} (mg/L)	0.14	0.00	10.65	0.94	0.05
Cd (mg/L)	0.03	0.00	0.06	0.01	0.003
Pb (mg/L)	0.03	0.00	1.08	0.02	0.01
As (µg/l)	8.02	1.05	18.15	2.71	10
Se (µg/l)	28.25	0.06	331.00	59.50	40

Source: Authors. Jordanian drinking-water comparison values are from JSMO JS 286:2015.

4.2 Occurrence and Spatial Setting of MTBE and BTEX

Low-level MTBE and BTEX detections were spatially concentrated in shallow groundwater between Russeifa and Zarqa and in the Seil Zarqa-Awjan corridor (Figure 5). Across the monitoring network, 32 of 66 wells contained detectable concentrations of one or more target compounds. MTBE was generally reported at approximately 1.0-1.8 µg/L, and BTEX constituents were reported in the same low-µg/L range. The narrow concentration interval close to the analytical reporting limit requires cautious interpretation of small differences among wells.

Several detected wells are located near fuel stations, petroleum handling infrastructure, or the Jordan Petroleum Refinery corridor. For example, one Zarqa sample downstream of the refinery area contained approximately 1.1-1.6 µg/L of target compounds, and other detections occurred in wells between Russeifa and Zarqa where groundwater depth is approximately 6-35 m. The shallow alluvial aquifer in this corridor has relatively high porosity and permeability, providing a plausible pathway for infiltration from surface or near-surface releases. A shallow Amman well was also located downgradient of an older fuel station. These spatial associations are consistent with petroleum-related sources, but proximity alone does not prove a specific leaking tank or facility; confirmation would require source-specific investigations, repeated monitoring, and, where possible, forensic hydrocarbon or isotopic evidence.

The predominance of detections in shallow groundwater is hydrogeologically coherent. A short unsaturated-zone travel distance, permeable alluvium, and fractured carbonate pathways increase the probability that dissolved gasoline constituents will reach monitoring wells before extensive attenuation occurs. Conversely, the absence of comparable detections in deeper units suggests that the available data do not support widespread vertical migration through the basin. This distinction is important for management because it prioritizes shallow urban monitoring and source-control measures while retaining targeted surveillance of deeper production aquifers.

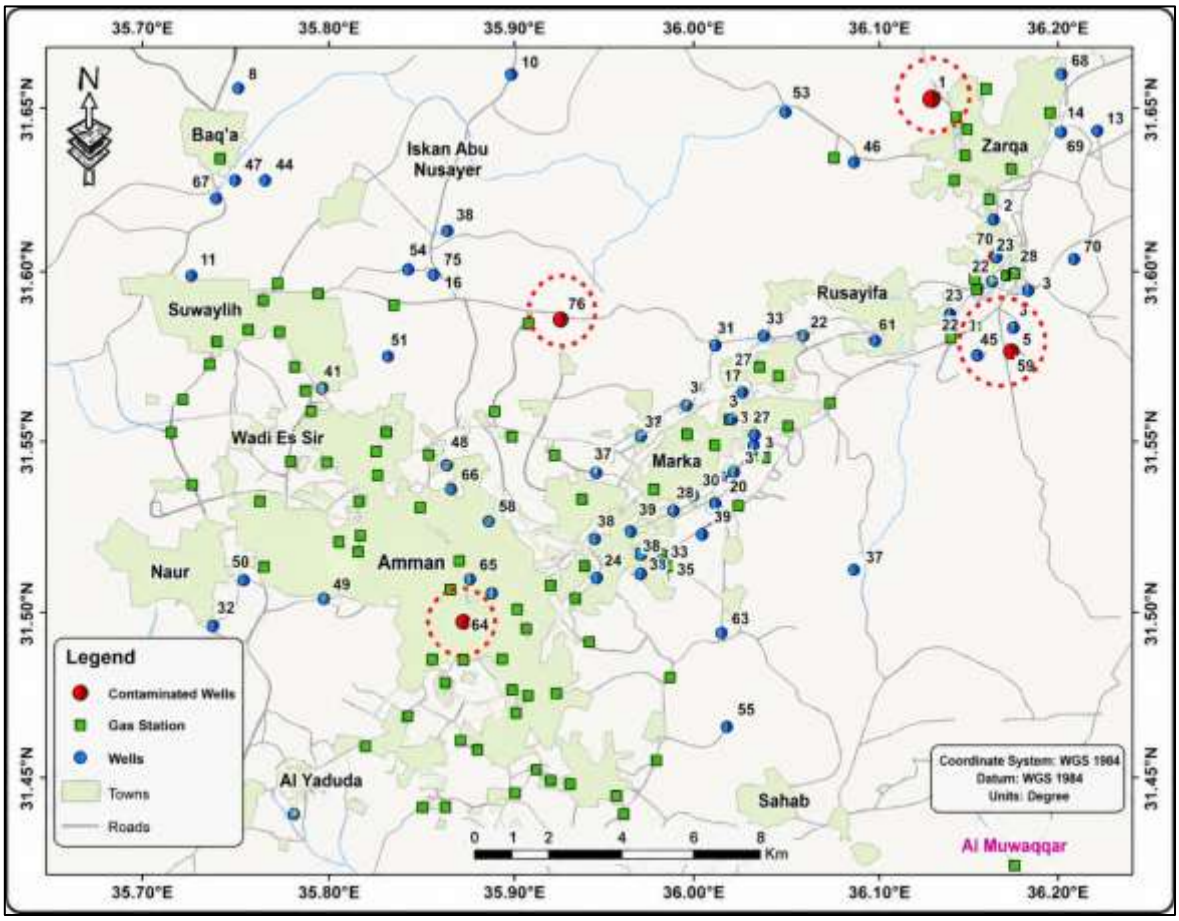

Figure 5. Wells with reported MTBE and/or BTEX detections. Detections are concentrated in shallow groundwater within the Russeifa-Zarqa/Seil Zarqa corridor.

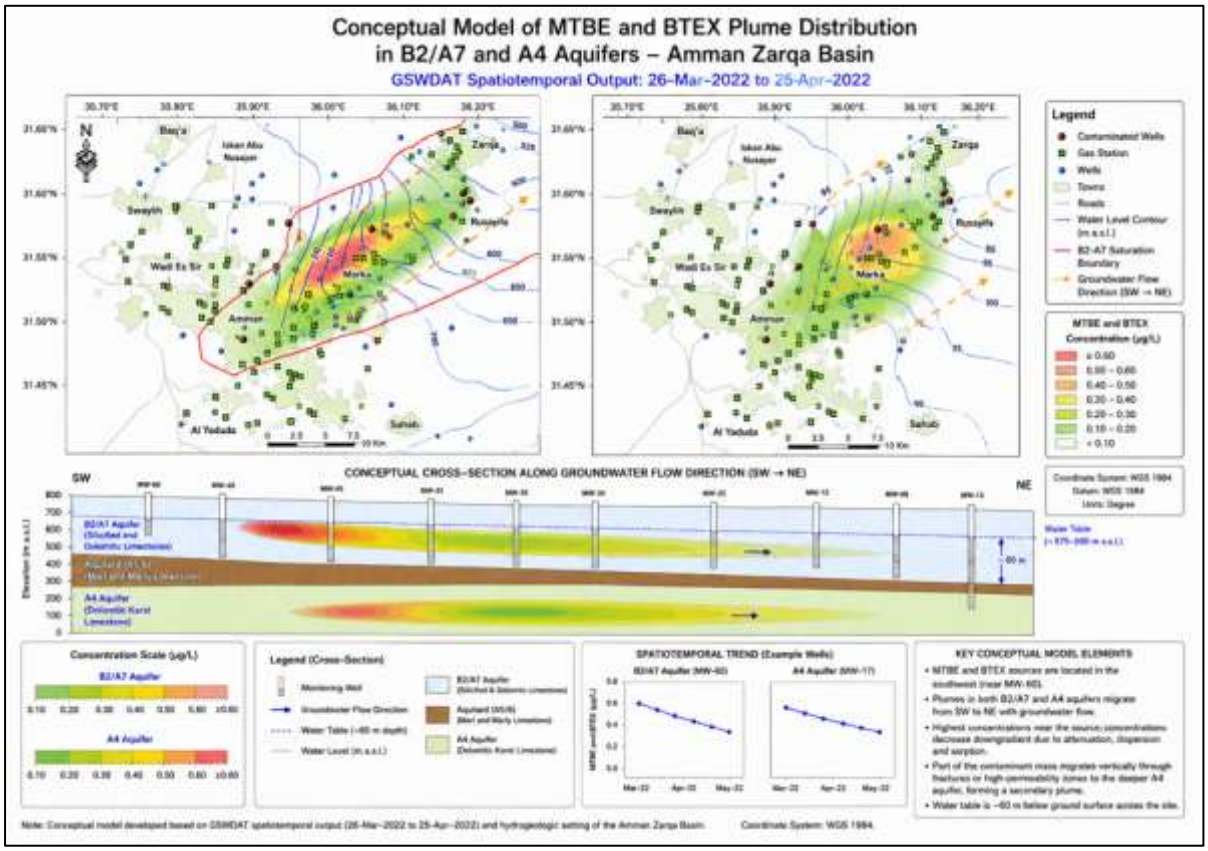

Figure 6. Conceptual interpretation of MTBE and BTEX transport in the B2/A7-A4 aquifer system. Arrows and modeled plume forms are conceptual/screening representations rather than verified release boundaries.

4.3 GWSDAT-Based Spatiotemporal Analysis

The GWSDAT evaluation was undertaken to determine whether the low-level detections form spatially and temporally coherent patterns. The measured dataset indicates that 32 of the 66 wells contained detectable MTBE and/or BTEX, with the strongest clustering in shallow wells near Seil Zarqa and Awjan. Because many reported concentrations are only slightly above the approximately 1 μg/L reporting limit, trend classification and spatial smoothing are more informative when used to identify persistent relative patterns than when used to infer precise concentration gradients.

At individual wells, GWSDAT applies concentration-time visualization and Mann-Kendall statistics to screen for monotonic trends. A statistically significant result ($p < 0.05$) indicates evidence of an increasing or decreasing monotonic trend, whereas $p \geq 0.05$ indicates that the available observations do not establish a significant trend. Importantly, statistical significance does not identify the cause of a change; pumping, recharge, source variability, sampling frequency, and analytical uncertainty may all influence temporal patterns. Trend results were therefore interpreted together with hydrogeological setting and measured concentrations rather than as stand-alone evidence of plume growth or attenuation.

The spatial component of GWSDAT jointly uses neighboring wells and adjacent monitoring times to generate smooth concentration surfaces. This is advantageous in an irregular monitoring network because information is shared across space and time (Jones et al., 2014; McLean et al., 2019). However, smoothing can generate modeled values below the analytical reporting limit and can visually imply continuity between sparse detections. In Figures 7-10, these low modeled values are therefore interpreted as relative probability/gradient structure rather than as measured contamination. The most defensible evidence is the combination of observed detections, repeat behavior at individual wells, and spatial consistency with groundwater flow and source environments.

GWSDAT plots were prepared for the B2/A7, A4, A1/2, Kurnub, and combined aquifer datasets. The B2/A7 and A4 panels shown in Figures 7-10 illustrate that modeled concentration maxima tend to occur within or downgradient of the urbanized Russeifa-Zarqa sector. This pattern is broadly consistent with the mapped detection locations and the expected regional groundwater-flow component. Nevertheless, the available data do not justify treating every interpolated contour as a physical plume boundary, particularly where contours are supported by few wells or modeled concentrations fall below 1 μg/L.

Comparison of the 2021 and 2022 visualization panels suggests persistence of the same broad area of concern rather than a basin-wide expansion of contamination. Local differences between panels may reflect temporal variability, changes in the wells sampled, or statistical smoothing as well as true concentration change. The narrow measured concentration range and limited number of monitoring rounds prevent a reliable estimate of plume mass, migration velocity, or contaminant half-life from this dataset alone. Accordingly, the figures are best used to identify monitoring priorities and hypotheses for subsequent sampling.

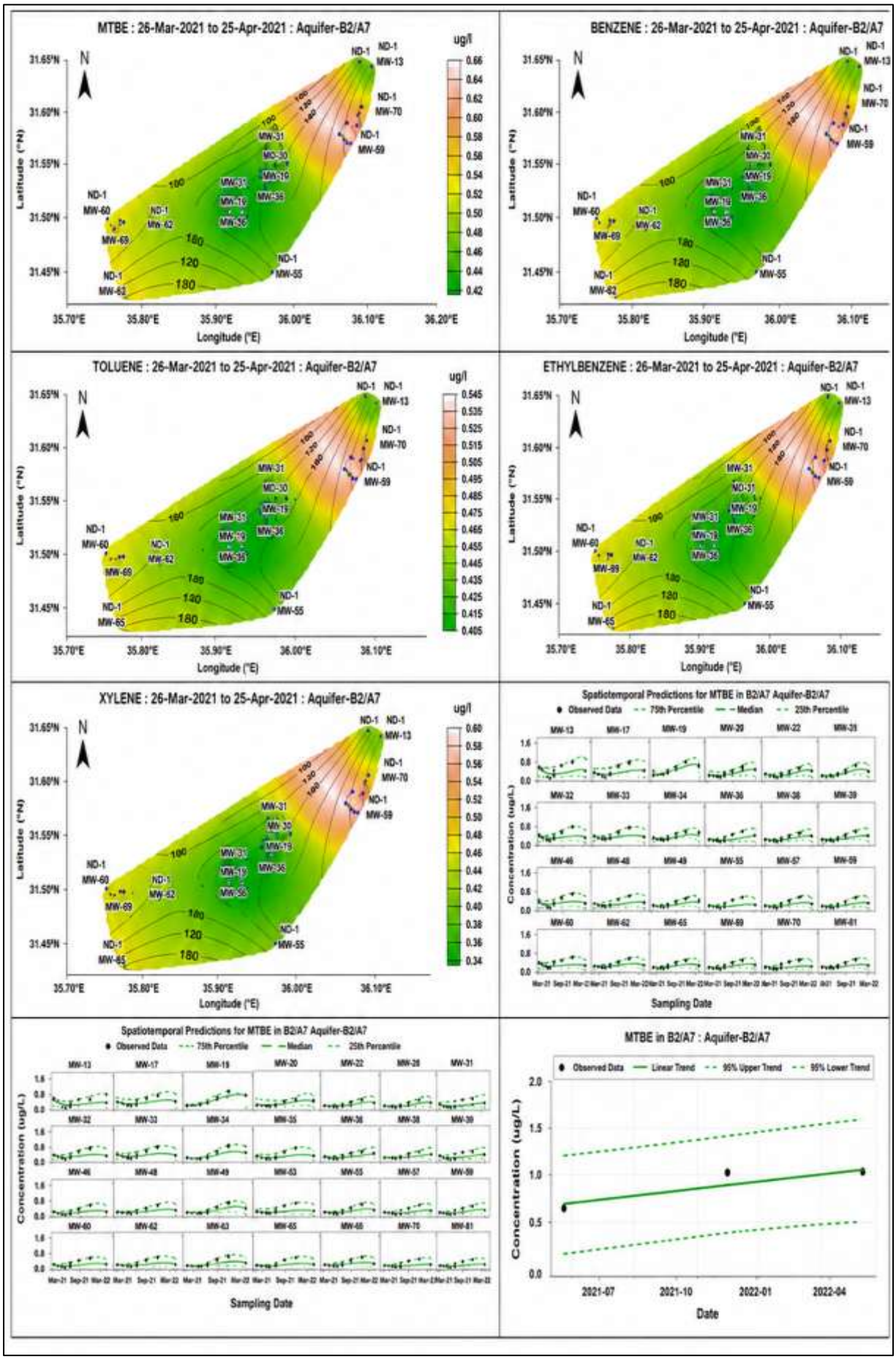

Figure 7. GWSDAT spatial and time-series visualization of MTBE and BTEX in the B2/A7 aquifer, 2021. Modeled concentrations below the analytical reporting limit are screening-level predictions, not confirmed detections.

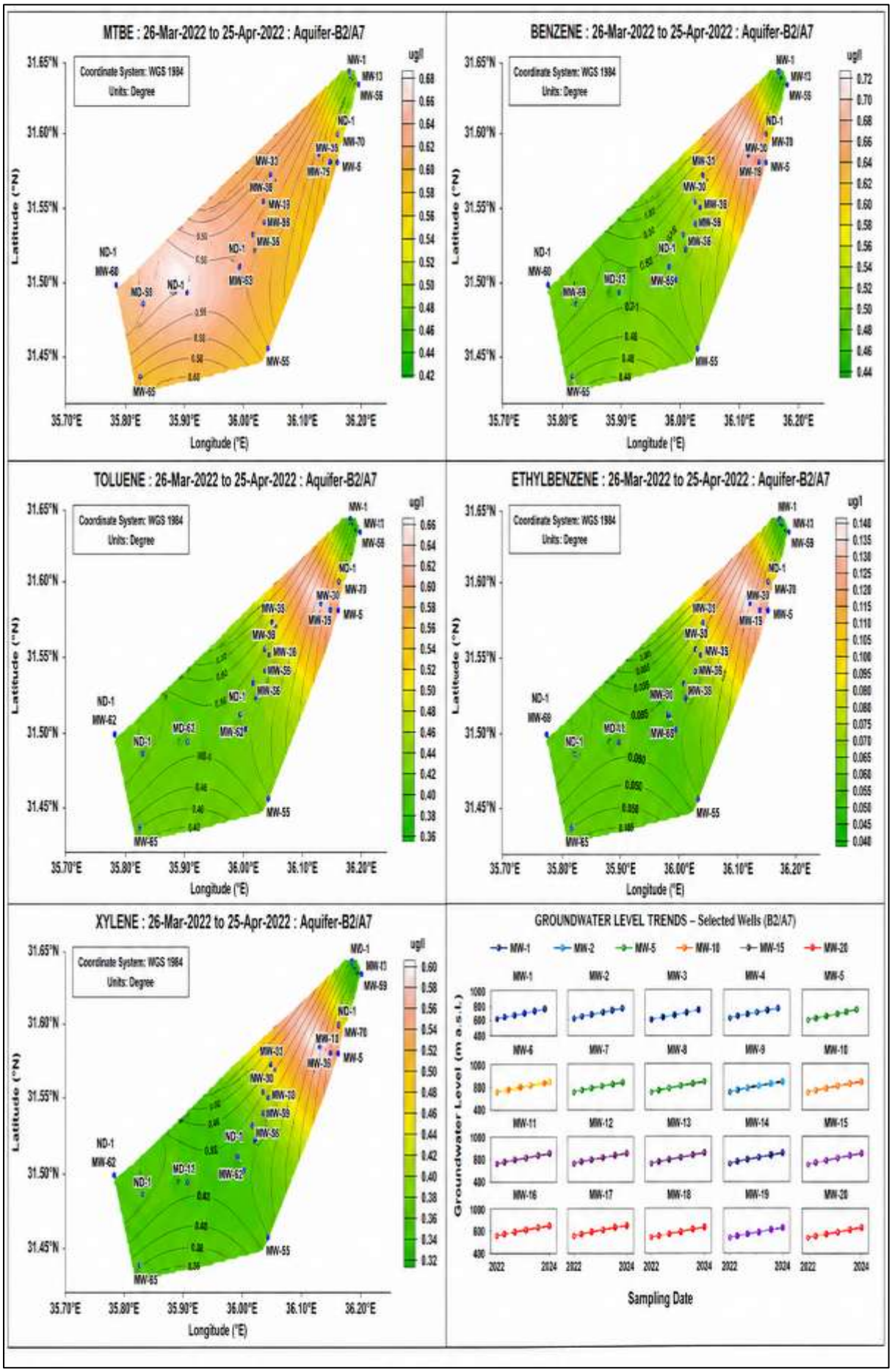

Figure 8. GWSDAT spatial and time-series visualization of MTBE and BTEX in the B2/A7 aquifer, 2022. Interpretation is constrained by well density, sampling frequency, and the approximately 1 µg/L reporting limit.

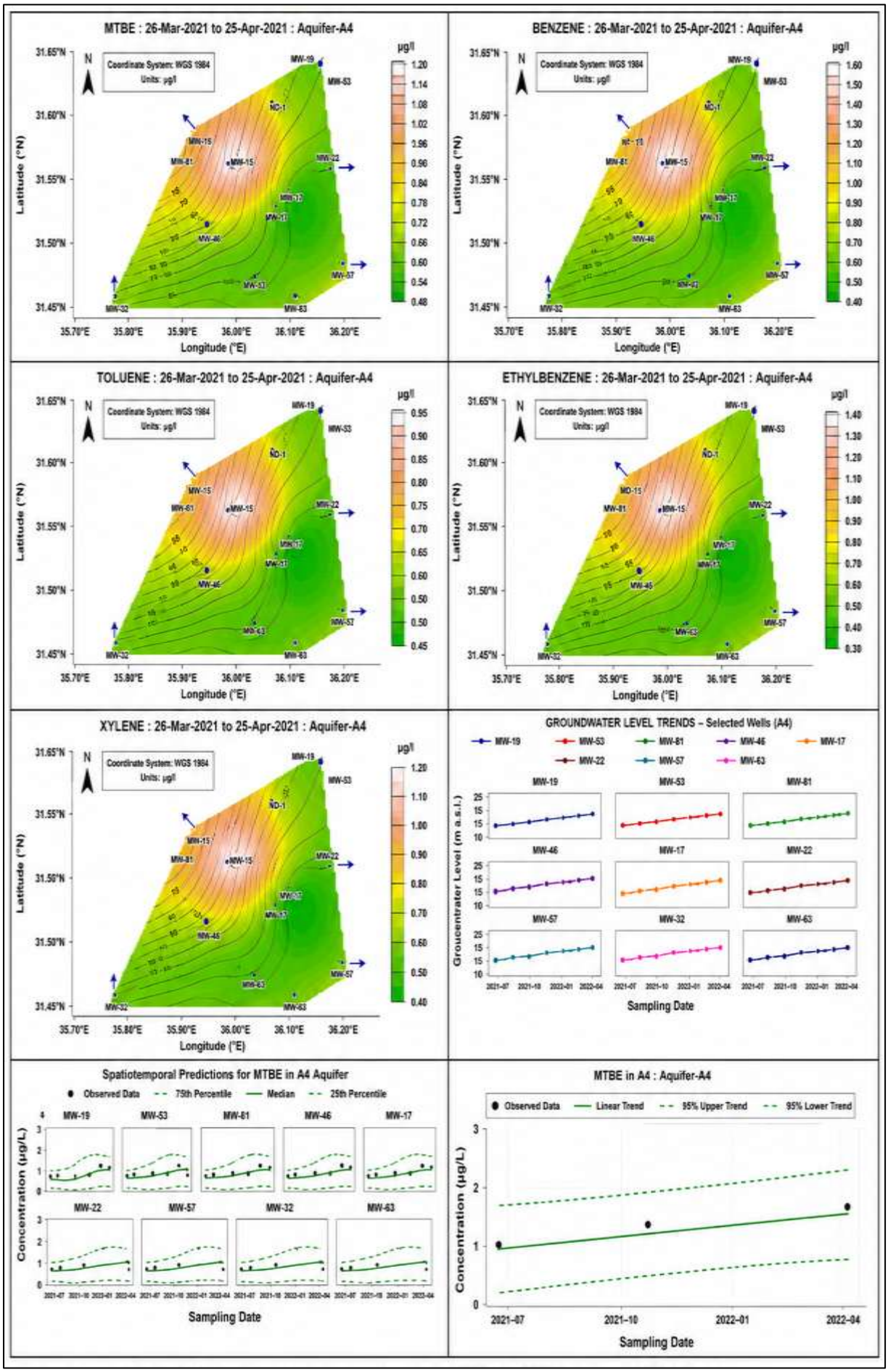

Figure 9. GWSDAT spatial and time-series visualization of MTBE and BTEX in the A4 aquifer, 2021. Smoothed surfaces are interpreted together with measured well concentrations.

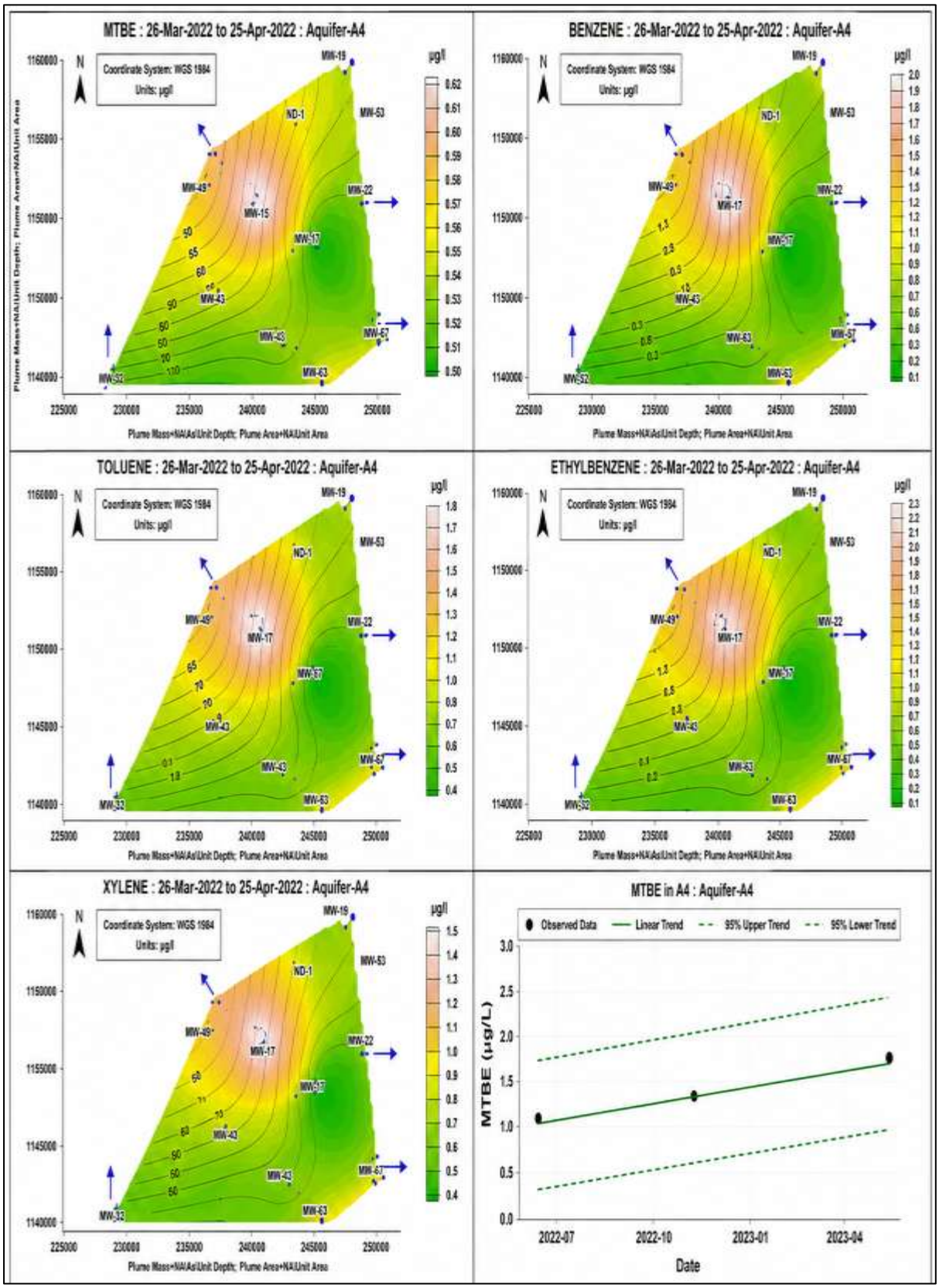

Figure 10. GWSDAT spatial and time-series visualization of MTBE and BTEX in the A4 aquifer, 2022. Low modeled values do not establish a confirmed plume outside measured detections.

The time-series panels illustrate how individual well histories complement spatial maps. Some wells show short sequences of detections close to the reporting limit, for which an apparent increasing or decreasing line can be highly sensitive to a small number of observations. For this reason, no deterministic increase in MTBE or BTEX concentrations is projected from the present dataset. A longer monitoring record with consistent seasonal sampling is required before robust rates of change, attenuation constants, or migration velocities can be estimated.

4.4 Comparison with Previous Studies and Hydrogeological Interpretation

The present results can be compared directly with the earlier AZB investigation by Al Kuisi et al. (2012), which analyzed 179 wells and reported MTBE from non-detect to 4.1 µg/L and BTEX from non-detect to a maximum of 6.6 µg/L for ethylbenzene. The current detected range of approximately 1.0-1.8 µg/L is lower and narrower, but the two studies agree in identifying petroleum-related contaminants at low µg/L concentrations in an urban basin where shallow groundwater occurs near fuel-handling activities. This agreement strengthens the interpretation that gasoline-related releases are a recurring groundwater-protection issue in the AZB, while the lower concentrations in the present dataset do not by themselves demonstrate either improvement or deterioration because the well networks, sampling periods, and analytical designs differ.

The spatial pattern is also consistent with the expected behavior of fuel constituents. MTBE can remain comparatively mobile because of its high solubility and weak sorption, whereas BTEX compounds commonly experience greater retardation and biodegradation (Deeb et al., 2000; Zogorski et al., 1997). In the AZB, shallow alluvial material and fractured carbonate pathways may shorten travel times from surface sources, while redox conditions ranging from reducing to strongly oxidizing can produce spatially variable biodegradation potential. These factors provide a plausible hydrogeological explanation for localized detections without requiring a continuous basin-scale plume.

The use of GWSDAT adds an interpretive dimension to conventional occurrence mapping by combining neighboring wells and adjacent monitoring times. This approach is consistent with the original GWSDAT framework (Jones et al., 2014) and subsequent case studies demonstrating its value for groundwater monitoring decisions (Jones et al., 2022). At the same time, McLean et al. (2019) emphasized the statistical nature of spatiotemporal prediction. In the present dataset, that distinction is especially important because many modeled values are below the laboratory reporting limit. The study therefore treats GWSDAT as a screening and decision-support tool, not as a substitute for analytical confirmation.

From a management perspective, the strongest evidence is the repeated association of detections with shallow urban groundwater and potential petroleum-source environments. This supports targeted inspection and integrity testing of UST systems, prioritized sampling of downgradient shallow wells, and the use of sentinel wells between high-risk facilities and public-supply abstractions. Where a well shows repeated or increasing detections, source investigation should precede any assumption that regional groundwater transport is responsible.

4.5 Health, Regulatory Context, and Practical Implications

Measured MTBE and BTEX concentrations in this study are low relative to the drinking-water criteria summarized in Table 5. The U.S. EPA has no federal maximum contaminant level (MCL) for MTBE; its 1997 drinking-water advisory recommends approximately 20-40 µg/L or lower primarily to avoid taste and odor while providing a substantial margin of safety. WHO does not establish a health-based guideline value for MTBE because an odor-based concentration would be lower than a calculated health-based value. For BTEX, health-based drinking-water criteria are compound-specific; benzene has the most stringent values because it is carcinogenic. Therefore, the statement that the study concentrations are below standards should not be interpreted as evidence that ongoing low-level leakage is acceptable. Persistent detections can still indicate a preventable source and justify surveillance, particularly where groundwater is used for drinking.

The practical implication is a risk-based response rather than broad remediation based only on the present low concentrations. Priority actions are: repeated sampling of detected shallow wells; inspection and leak testing of USTs and fuel-transfer systems; confirmation sampling before inferring a plume boundary; inclusion of groundwater elevations during each monitoring round; and escalation to site-specific source characterization where concentrations persist, increase, or approach drinking-water criteria. Deeper production aquifers should be monitored strategically where structural pathways, well-construction defects, or vertical gradients could connect them to shallow impacted groundwater.

Table 5. Jordanian and international drinking-water values relevant to MTBE and BTEX.

Chemical substance	JSMO JS 286:2015 (µg/L)	WHO guideline (µg/L)	U.S. EPA MCL/advisory (µg/L)
MTBE	10	No health-based guideline	20-40 advisory*
Benzene	10	10	5
Ethylbenzene	500	300	700
Xylenes (total)	700	500	10,000
Toluene	300	700	1,000

*Source: Authors, compiled from JSMO JS 286:2015, WHO drinking-water guidance, and U.S. EPA drinking-water regulations/advisory. *The U.S. EPA MTBE value is a non-regulatory advisory, not an MCL.*

5. Conclusions

This study identified localized, low-level MTBE and BTEX occurrence in the Amman-Zarqa Basin and used GWSDAT to integrate contaminant measurements with spatial and temporal monitoring information. Of 66 wells, 32 contained detectable MTBE and/or BTEX, generally at approximately 1.0-1.8 µg/L. Detections were concentrated in shallow groundwater in the Seil Zarqa-Awjan/Russeifa-Zarqa corridor, where a shallow permeable aquifer and dense petroleum-related infrastructure create a plausible vulnerability setting. The hydrochemical dataset shows a heterogeneous aquifer system dominated by Ca-Mg-Cl and Na-Cl facies, with wide ranges in salinity and redox conditions.

GWSDAT was useful for organizing well histories, visualizing relative concentration patterns, and screening monotonic trends. The analysis supports persistence of localized areas of concern rather than a demonstrated basin-wide plume. A key interpretive constraint is that the analytical reporting limit is approximately 1 µg/L; therefore, smoothed or interpolated concentrations below this value are model predictions and must not be presented as confirmed detections. The present dataset is not sufficient to quantify plume mass, migration velocity, or contaminant half-life, and it does not establish a unique source for individual detections.

The study has several limitations: the measured concentrations are close to the reporting limit; the temporal record is relatively short and not uniform for all wells; source histories and UST integrity data were not available for quantitative attribution; well construction and vertical hydraulic gradients are incompletely constrained; and the irregular monitoring network introduces uncertainty into spatial smoothing. Future work should use consistent seasonal sampling, lower analytical reporting limits where feasible, repeated groundwater-level measurements, source-area investigations, and expanded monitoring between suspected sources and critical receptors. Where sufficient temporal data become available, trend and mass-discharge analyses can be used to test whether contaminant conditions are stable, increasing, or attenuating.

The principal practical implication is that regulatory compliance alone should not be the endpoint of management. Repeated low-level detections in vulnerable shallow groundwater warrant preventive action, including UST integrity testing, improved spill control, targeted sentinel-well monitoring, and rapid investigation of persistent or increasing concentrations. These measures are particularly important in Jordan because groundwater is a strategic water-supply resource and contamination prevention is substantially more feasible than restoration of a widely impacted aquifer.

6. References

1. Abed, A. M. (2000). Geology of Jordan. Amman, Jordan.
2. Agency for Toxic Substances and Disease Registry. (2023). Toxicological profile for methyl tert-butyl ether (MTBE). U.S. Department of Health and Human Services.
3. Al Kuisi, M., Saffarini, G., Yaseen, N., & Alawi, M. (2012). Potential occurrence of MTBE and BTEX in groundwater resources of Amman-Zarqa Basin, Jordan. CLEAN - Soil, Air, Water, 40(8), 808-816. https://doi.org/10.1002/clen.201100473
4. Almuhtaseb, R. M., et al. (2024). A concise review on BTEX remediation from aqueous solutions by adsorption. Emergent Materials, 7, 695-719. https://doi.org/10.1007/s42247-024-00640-1
5. Deeb, R. A., Scow, K. M., & Alvarez-Cohen, L. (2000). Aerobic MTBE biodegradation: An examination of past studies, current challenges and future research directions. Biodegradation, 11(2-3), 171-186. https://doi.org/10.1023/A:1011113320414
6. Howard Humphreys & Sons. (1983). Hydrogeological investigations and water-resources studies for the Amman-Zarqa Basin. Amman, Jordan.
7. Jordan Standards and Metrology Organization. (2015). Jordanian Standard JS 286:2015 - Water - Drinking water (6th ed.). Amman, Jordan.
8. Jones, W. R., Spence, M. J., Bowman, A. W., & Evers, L. (2014). A software tool for the spatiotemporal analysis and reporting of groundwater monitoring data. Environmental Modelling & Software, 55, 242-249. https://doi.org/10.1016/j.envsoft.2014.01.020
9. Jones, W. R., Spence, M. J., & Bonte, M. (2015). Analyzing groundwater quality data and contamination plumes with GWSDAT. Groundwater, 53(4), 513-514. https://doi.org/10.1111/gwat.12340
10. Jones, W. R., Rock, L., Wesch, A., Marzusch, E., & Low, M. (2022). Groundwater Spatiotemporal Data Analysis Tool: Case studies, new features and future developments. Groundwater Monitoring & Remediation, 42(3), 14-22. https://doi.org/10.1111/gwmr.12522
11. Margane, A., Hobler, M., Almomani, M., & Subah, A. (2002). Contributions to the hydrogeology of northern and central Jordan. Geologisches Jahrbuch, Reihe C, 68.
12. McLean, M. I., Evers, L., Bowman, A. W., Bonte, M., & Jones, W. R. (2019). Statistical modelling of groundwater contamination monitoring data: A comparison of spatial and spatiotemporal methods. Science of the Total Environment, 652, 1339-1346. https://doi.org/10.1016/j.scitotenv.2018.10.231
13. Ministry of Water and Irrigation. (2020). Hydrogeological data files for the Amman-Zarqa Basin [Unpublished dataset]. Amman, Jordan.
14. Natural Resources Authority. (2014). Geological map of the Amman-Zarqa area [Map]. Amman, Jordan.
15. Piper, A. M. (1944). A graphic procedure in the geochemical interpretation of water-analyses. Transactions, American Geophysical Union, 25(6), 914-928. https://doi.org/10.1029/TR025i006p00914

16. Powell, J. H. (1989). Stratigraphy and sedimentation of the Phanerozoic rocks in central and south Jordan: Part B, Kurnub, Ajlun and Belqa Groups. Natural Resources Authority Bulletin 11B. Amman, Jordan.
17. Salameh, E., & Bannayan, H. (1993). Water resources of Jordan: Present status and future potentials. Friedrich-Ebert-Stiftung.
18. U.S. Environmental Protection Agency. (1995). Method 524.2: Measurement of purgeable organic compounds in water by capillary column gas chromatography/mass spectrometry (Revision 4.1). National Exposure Research Laboratory.
19. U.S. Environmental Protection Agency. (1997). Drinking water advisory: Consumer acceptability advice and health effects analysis on methyl tertiary-butyl ether (MTBE) (EPA-822-F-97-008). Office of Water.
20. U.S. Environmental Protection Agency. (2026). National primary drinking water regulations. https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations
21. World Health Organization. (2026). Guidelines for drinking-water quality: Fourth edition incorporating the first, second and third addenda. World Health Organization.
22. Zogorski, J. S., Morduchowitz, A., Baehr, A. L., Bauman, B. J., Conrad, D. L., Drew, R. T., Korte, N. I., Lapham, W. W., Pankow, J. F., & Washington, E. R. (1997). Fuel oxygenates and water quality. In Interagency assessment of oxygenated fuels (Chapter 2). National Science and Technology Council.