

Wastewater pollution from the city of Taza and its impact on the Oued Larbaa (Morocco): Seasonal contrast, flow-path attenuation and a weighted pollution index

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ABSTRACT

Understanding how untreated wastewater degrades an intermittently flowing Mediterranean river requires repeated sampling across contrasting hydrological periods and cautious statistical interpretation. Ten stations in the Oued Larbaa catchment, which receives untreated wastewater from Taza City, were sampled during the high-water season in January 2025 ($n = 10$) and the low-water season in July 2025 ($n = 7$; the three most upstream stations were dry). At the seven stations sampled in both seasons, pollution-related parameters increased significantly during the low-water period: TSS, TKN, PO_4 , BOD_5 and COD all showed significant seasonal differences according to the paired, two-sided Wilcoxon signed-rank test ($p = 0.016$). Mean BOD_5 increased from 177.9 to 547.6 $\text{mg O}_2/\text{L}$, while COD increased from 299.1 to 1,153.7 $\text{mg O}_2/\text{L}$, corresponding to increases of 208% and 286%, respectively. Dissolved oxygen decreased significantly, whereas electrical conductivity showed no significant seasonal change (1493.1 versus 1828.1 $\mu\text{S}/\text{cm}$; $p = 0.109$). A principal component analysis of the nine field and laboratory determinands showed that the first principal component accounted for 79.2% of the total variance, while the first two components together explained 92.6%. The main axis represented an organic-pollution gradient separating naturally mineralised headwaters from sewage-dominated low-water samples. Ward hierarchical clustering recovered the same three descriptive groups. Contrary to a simple upstream-to-downstream deterioration model, TSS and COD decreased significantly with downstream distance from the principal discharge point during low water (Spearman's $\rho = -0.79$, $p = 0.036$ for both; $n = 7$). This pattern indicates downstream attenuation of concentrations, but remains exploratory. A weighted arithmetic pollution index based on Moroccan discharge-limit values classified every summer station and one winter station as poor, whereas all winter headwater stations were classified as excellent. Total Kjeldahl nitrogen and suspended solids contributed most to the index score despite not having the largest nominal weights. Because water discharge, pollutant loads and transformation processes were not measured, the observed concentration decrease cannot be attributed specifically to self-purification. Overall, the results indicate that the Oued Larbaa functions for much of the year as an open wastewater-receiving channel whose quality is strongly controlled by discharge timing, with only modest downstream attenuation of pollutant concentrations.

Keywords: environmental quality, Oued Larbaa, wastewater, suspended solids, chemical oxygen demand, weighted pollution index, flow-path attenuation, Wilcoxon signed-rank test.

INTRODUCTION

Rapid urban growth across semi-arid regions of North Africa is placing unprecedented strain on freshwater resources, and Morocco illustrates this tension particularly sharply: rising demand from a growing population and expanding economic activity meets a naturally irregular rainfall regime dominated by prolonged dry spells, leaving little margin to absorb additional pressure (Towards Sustainable Water Management in Morocco, 2025; UNESCO, 2023). Pollution of the country's already limited freshwater resources therefore ranks among the most pressing dimensions of its environmental degradation, as intensive exploitation of these reserves exposes the country to serious and lasting consequences (Miftah et al., 2025).

Taza illustrates this pattern directly: the city releases its wastewater untreated into the natural environment, at a volume estimated at 16,534 m³/day in 2020 and projected to reach 20,056 m³/day by 2030 (AWEDAT, 2010). This effluent enters the Oued Larbaa network through an open drain and its tributaries – the Oued Jaouna, Oued Dfali and Oued Taza – before the combined flow joins the Oued Inaouene (Ben Abbou et al., 2025).

The Oued Larbaa catchment plays a significant ecological and economic role, in particular by supplying water for market-garden irrigation over substantial areas (Abbou et al., 2014a), which makes tracking pollution indicators throughout the study period essential for anticipating and managing the risks this dependence entails.

The water quality documented in this catchment therefore results from the superposition of natural constraints – a semi-arid climate and marked hydrological variability – and human pressures, including urbanisation, intensive agriculture and untreated discharges of domestic, industrial and agricultural waste, which together drive up concentrations of organic matter (BOD₅, COD) and nutrients (NO₃⁻, NO₂⁻) (Bougarne et al., 2019; Mahmoud et al., 2023). This combination degrades groundwater and irrigation-water quality (Ben Abbou et al., 2024), threatens the stability of aquatic ecosystems, and carries tangible socio-economic costs for the region, reinforcing the case for integrated water-resource management strategies that reconcile environmental protection with the population's growing needs, and for local authorities to weigh the associated public-health risks explicitly in their

decisions (Layan et al., 2026b). These pressures are not confined to the Larbaa alone: basin-wide assessments of the wider Sebou watershed, into which the Larbaa ultimately drains via the Oued Inaouene, have repeatedly classed long stretches as poor to very poor and explicitly named the Inaouene network among the reaches no longer fit for irrigation (Chadli, 2023; Bouriqi et al., 2024).

Although the Oued Larbaa is primarily of regional applied interest, this study offers three contributions. First, it combines, within a single framework, a seasonal contrast between high- and low-water periods at the same stations, a longitudinal (flow-path) analysis of concentrations downstream of the main discharge point, and a weighted pollution index built on the Moroccan discharge limits. Second, it documents an intermittent, semi-arid Mediterranean catchment that receives untreated urban wastewater and that remains comparatively little documented. Third, the approach relies on a small set of routine parameters and is therefore transferable to other small Moroccan and Mediterranean watersheds facing similar pressures. Accordingly, the objectives were (i) to quantify the seasonal change in water quality at the stations sampled in both seasons, (ii) to describe the main patterns of covariation among the determinands by multivariate analysis, (iii) to examine how concentrations change with distance downstream of the main discharge point, and (iv) to summarise overall water quality with a weighted pollution index.

MATERIALS AND METHODS

Study area

Located in the eastern foothills of the Rif-Moyen Atlas transition zone, the Larbaa catchment forms part of the wider Mediterranean bioclimatic domain of northern Morocco (Layan et al., 2025a), with a semi-arid regime prevailing over most of its area and a more humid influence from the Middle Atlas felt toward its southern margin (Layan et al., 2025b); rainfall distribution closely tracks this elevation gradient, and vegetation cover across the catchment shows clear signs of degradation (Mofidi et al., 2025). Geologically, impermeable marl formations dominate the northern sector while more permeable formations extend across the south (Layan et al., 2026a), a contrast that leaves a strong imprint on the natural

mineralisation of the river. This lithological setting combines with a hydrological regime marked by prolonged summer low-water periods and abrupt winter flood events to determine much of the catchment's present-day water quality (Mofidi et al., 2025). A multi-decadal characterisation of rainfall in this same Upper Larbaa basin confirms that this is not merely a seasonal contrast but part of a sustained drying trend, with mean annual totals falling markedly since the late 1970s and the basin persisting in drought conditions for most of the subsequent decades (Bougdira et al., 2025), reinforcing that the low-water season sampled here corresponds to the river's now-ordinary state rather than an anomalous one.

Experimental protocol

Guided by preliminary field observations, ten sampling stations were established along the Oued Larbaa (Fig. 1), chosen to capture the impact of wastewater discharges from Taza and the villages the river crosses, together with the influence of agricultural activity along its course (Ben Abbou et al., 2026b); the hydrological significance of each tributary and the practical accessibility of each site were also taken into account in finalising the network.

The ten stations (O1–O10) were sampled on Thursday 16 January 2025 (high-water season, $n=10$ stations) and on Thursday 17 July 2025 (low-water season, $n = 7$ stations; the three most

upstream stations, O1–O3, were dry). In January, sampling started at 09:00 at the first station (O1); in July, it started at about 08:30 at O4. The interval between successive stations was about 40–50 min (Table 1). Water temperature was of the order of 12 °C in January and 29 °C in July. In January, flow was strong, with flood events and muddy water; in July, flow was low and consisted only of raw wastewater from the city of Taza, blackish to greyish in colour. River discharge could not be measured because no flowmeter was available. The complete dataset therefore comprised 17 station-season observations: 10 winter observations and 7 summer observations; O1–O3 were dry and not sampled in July.

On-site measurements, taken after instrument calibration, covered temperature, pH, conductivity and dissolved oxygen, while five further determinands indicative of pollution – BOD₅, COD, TSS, TKN and orthophosphate (PO₄) – were quantified in the laboratory following AFNOR-certified methods as compiled by Rodier (Rodier et al., 2010). BOD₅ was measured using an OxiTop respirometric system; COD was determined by oxidation with excess potassium dichromate at 148 °C in the presence of silver sulphate as catalyst and mercury sulphate; suspended solids were quantified by filtration on a 0.45 µm membrane; TKN was determined by the selenium mineralisation method (standard NF EN 25663, January 1994; classification index T90110); and orthophosphate was

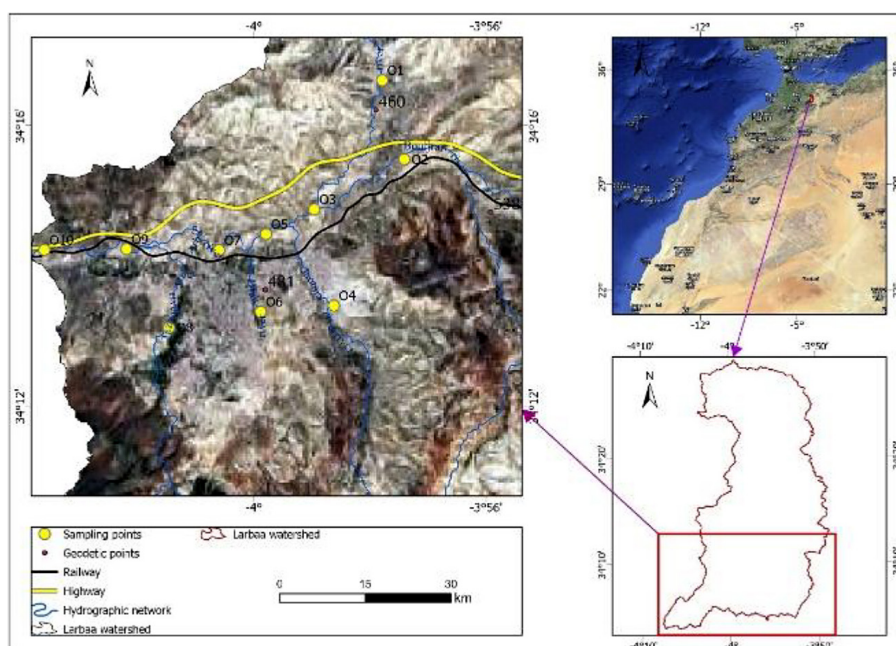


Fig. 1. Geographical location of the Larbaa watershed

Table 1. Location (WGS84 coordinates) and approximate sampling times of the ten stations of the Oued Larbaa network (sampling on 16 January and 17 July 2025)

Station	Latitude (N)	Longitude (W)	Approx. time, winter (Thursday 16 Jan. 2025)	Approx. time, summer (Thursday 17 Jul. 2025)
O1	34.353798	3.922228	~09:00	Dry, not sampled
O2	34.243816	3.981357	~09:40	Dry, not sampled
O3	34.3563	3.9233	~10:20	Dry, not sampled
O4	34.240372	3.991174	~11:00	~08:30
O5	34.2436	3.9930	~11:40	~09:10
O6	34.2330	3.999685	~12:20	~10:00
O7	34.2372	4.0025	~13:00	~11:20
O8	34.236023	4.024228	~13:40	~11:40
O9	34.2388	4.0269	~14:20	~12:10
O10	34.232902	4.061789	~15:00	~13:00

measured by the ammonium molybdate spectrophotometric method (Rodier et al., 2010).

Water samples were collected at mid-stream, at a depth of 20–30 cm, so as to obtain a homogeneous and representative sample, in polyethylene bottles: 500 mL bottles for nitrogen compounds, fixed with concentrated sulphuric acid, and 1 L bottles for the other, unfixed parameters. In accordance with the Moroccan standard NM 03.7.059, the bottles were labelled and transported in a cooler at low temperature (about 4 °C) to the laboratory, together with a sheet giving the origin, date and time of sampling. The delay between sampling and arrival at the laboratory was less than 24 h.

Each analytical series followed the laboratory's routine quality control: for COD, a four-point calibration curve (0, 15, 60 and 150 mg/L; correlation coefficient of at least 0.995) with a reagent blank, a reference material, a duplicate sample (acceptance < 20%) and a mid-range control standard (acceptance < 10%); for BOD₅, a blank, reference materials and a duplicate; for TSS, a blank, reference materials (25 and 100 mg/L) and a duplicate. Quality-control results for COD (low and high levels) and BOD₅ are given in Table 2: the blanks were 0 mg/L for COD and 3 mg/L for

BOD₅, and the relative differences between duplicates were 6.3% and 1.6% for COD (low and high level, respectively) and 0% for BOD₅, all within the 20% acceptance criterion. Each determination was performed as a single measurement; one duplicate was analysed per analytical batch ($n = 2$) as a batch-level quality-control replicate. No formal study-specific limits of detection or quantification were established; instrument-specific detection information, where available, is reported in the Supplementary Material.

Statistical analysis

Descriptive statistics (minimum, maximum, mean, standard deviation) were computed for each of the nine field and laboratory determinands (temperature, pH, electrical conductivity, dissolved oxygen, total suspended solids TSS, total Kjeldahl nitrogen TKN, orthophosphate PO₄, BOD₅ and COD) by season. Because the seven stations common to both campaigns (O4–O10) describe the same reaches revisited twice, the winter–summer contrast was tested with the paired, two-sided Wilcoxon signed-rank test (exact method, $n = 7$) rather than an unpaired test. When every difference at these seven stations

Table 2. Quality-control results (blank, reference material, sample and duplicate) for COD (low and high levels) and BOD₅, in mg O₂/L

Parameter	COD, low level	COD, high level	BOD ₅
Blank	0.00	0.00	3
Reference material	95.12	458.62	200
Sample	151.77	652.01	380
Duplicate of the same sample	161.68	662.30	380

shared the same sign, the exact p-value (0.016) was the smallest attainable at this sample size. Relationships between determinands were explored using Spearman rank correlation ($n = 17$ station $\times$ season combinations), and the joint structure of the dataset was summarised by principal component analysis (PCA) on standardised variables followed by Ward's hierarchical agglomerative clustering. Spatial structure was tested by correlating each determinand with downstream station rank and, for the low-water campaign only, with the great-circle distance travelled from the main discharge point (station O4, Oued Jaouna), using Spearman's rho; a log10-linear regression of concentration against this distance quantified the rate of in-channel attenuation. The weighted arithmetic pollution index (IP) was computed following the classical formulation of Brown et al. For every parameter with a defined discharge limit S_i (temperature, TSS, conductivity, TKN, BOD₅ and COD; Loi n°6199-2013), $q_i = 100 \times C_i/S_i$ was calculated; for pH, $q_i = 100 \times |pH - 7.5|/(9.5 - 7.5)$. Each parameter was weighted w_i proportional to $1/S_i$, normalised so that the sum of weights equalled 1, and $IP = \sum(w_i \times q_i)$. The index was classified as excellent ($IP < 50$), good (50–100), poor (100–200), very poor (200–300) or unsuitable (≥ 300). All index formulas are implemented as native, editable spreadsheet formulas in the accompanying database, and the raw data and calculation files are provided as Supplementary Material (Files S1–S3). Analyses used Python 3 (pandas, SciPy, scikit-learn and Matplotlib). Because the same stations were sampled in both seasons, the 17 station-season observations used for the correlation matrix, PCA and clustering are not fully independent; these methods were therefore used descriptively, not for formal inference, and associated p-values are indicative only. Given the small number of stations ($n = 7$ for the paired seasonal test and the distance-based analysis), all spatial results are considered exploratory.

RESULTS AND DISCUSSION

Parameters measured on site

Because it governs both the solubility of dissolved oxygen and the release of hydrogen sulphide in aquatic systems, water temperature can, on its own, reshape the distribution and diversity of aquatic communities (Bi et al., 2022). In this

catchment, temperature tracked the seasonal climatic cycle closely and varied little between stations, giving no indication of any artificial thermal input: values ranged from 12.33 °C in winter at the uppermost station (O1) to 28.27 °C in summer at O4, on the Oued Jaouna. Even at this upper end, conditions favour the proliferation of bacteria, parasites and mosquito larvae, yet because every value remained below the 30°C regulatory ceiling, temperature alone would classify these waters as good.

pH is shaped jointly by biological activity, chemical equilibria and, where present, industrial effluent (Idrissi et al., 2018); here it stayed within a narrow neutral-to-slightly-alkaline band across the whole catchment, from 7.68 in winter – likely depressed somewhat by the high organic-matter content typical of that season – to 8.22 in summer, without a single measurement approaching either bound of the applicable discharge standard, so that pH complies fully with the national surface-water classification (Ministère de l'Équipement et de l'Eau, 2008).

Electrical conductivity, which scales with the total dissolved-ion content of water (Chu et al., 2018), proved in this catchment to be governed chiefly by geology rather than by wastewater inputs (Figure 2).

Conductivity reached its catchment-wide maximum of 4820 $\mu\text{S}/\text{cm}$ at station O1 in winter, upstream of any wastewater input from Taza, before falling to a winter minimum of 708 $\mu\text{S}/\text{cm}$ at O8; both extremes fall within the range attributable to the catchment's marl geology rather than to pollution. During the summer campaign, by contrast, conductivity was confined to a much narrower band (1446–2090 $\mu\text{S}/\text{cm}$), because the naturally mineralised headwater stations run dry and only Taza's untreated effluent – itself only moderately conductive relative to the local geological background, and comparable to the 300–2000 $\mu\text{S}/\text{cm}$ range reported for the town's drinking-water supply – continues to flow. Every measured value remained below the 2700 $\mu\text{S}/\text{cm}$ discharge ceiling, so conductivity would classify these waters as good throughout.

Dissolved oxygen, among the determinands most sensitive to organic enrichment, dropped below the 1 mg/L threshold used by the national classification at every station from O4 to O10 during the summer campaign (Figure 3), placing these waters in the poor category on this criterion alone. This deficit tracks the intense biochemical

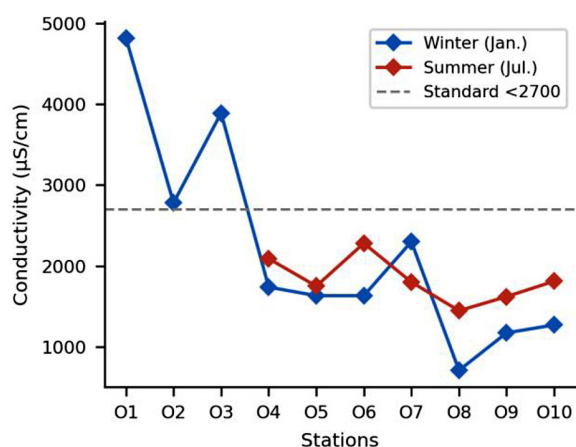


Fig. 2. Spatial and seasonal distribution of electrical conductivity ($\mu\text{S}/\text{cm}$) across the Oued Larbaa network in 2025

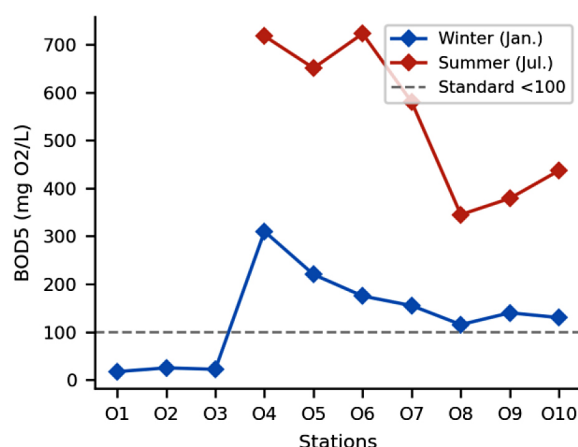


Fig. 3. Spatial and seasonal variation of five-day biochemical oxygen demand (BOD_5 , $\text{mg O}_2/\text{L}$) across the Oued Larbaa network, 2025

oxygen demand documented below: the same heterotrophic microbial communities responsible for degrading the organic load consume the available oxygen as they do so (Fiouz et al., 2024), and the effect is most severe at O6, immediately downstream of the Oued Dfali, which carries untreated effluent from Taza's CHP Ibno Baja provincial hospital. Winter oxygen levels recovered appreciably, consistent with the lower water temperatures of that season slowing microbial metabolism and reducing biological oxygen demand (Edberg et al., 2000).

Chemical oxygen demand quantifies the oxygen equivalent of the dichromate consumed in fully oxidising the organic pollutants present in a sample (Mekawi et al., 2023). During the summer campaign, COD exceeded the national surface-water threshold by close to threefold at all seven stations downstream of Taza (O4–O10), and most severely at O6, which receives hospital effluent via the Oued Dfali, as summarised in Figure 4.

These summer values place every downstream station well outside the range that would be expected from natural background processes alone, reinforcing the case, developed further in the statistical sections below, that Taza's discharge is the dominant driver of organic loading in this reach of the catchment.

Winter COD values fell markedly at every monitoring point as higher river flow diluted the effluent load; yet even under these higher-flow conditions, several tributaries continued to register elevated COD, most plausibly because raw sewage rich in slowly biodegradable, darkly coloured polyphenolic compounds keeps entering

the network regardless of season. On this basis, the Jaouna, Dfali, Taza and Larbaa wadis (particularly at O4, O5 and O6) remain classified as very poor for COD throughout the year (Mahmoud et al., 2023).

Because BOD_5 and COD values both exceeded the applicable discharge standards, distinguishing readily biodegradable from more recalcitrant organic matter requires comparing the two directly through their ratio (Figure 5): a COD/ BOD_5 ratio below three indicates that the organic load remains largely biodegradable (Grossule et al., 2022), as observed at most stations, whereas the ratio rose above this threshold at O4 and O8 during winter, coinciding with the olive-pressing season, when reduced flow concentrates the more refractory effluent characteristic of that activity, consistent with documented discharges from olive-oil mills operating without adequate treatment elsewhere in Taza province (Elachhab et al., 2026).

Total Kjeldahl nitrogen concentrations far exceeded the national surface-water threshold throughout the catchment, placing every station in the very poor category during summer and the stations from O4 to O10 in the poor category during winter (Ministère de l'Équipement et de l'Eau, 2008) (Figure 6).

Where suspended solids settle out of the water column, they can seal the soil surface and impede the gas exchange crops depend on. Concentrations reached 890 mg/L at O6 (Oued Dfali) and 963 mg/L at O4 (Oued Jaouna) during summer, placing both stations firmly in the very poor category (Figure 7).

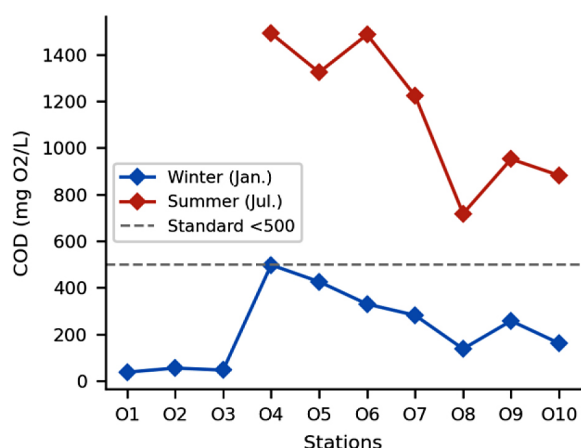


Fig. 4. Spatial and seasonal variation of chemical oxygen demand (COD, mg O₂/L) across the Oued Larbaa network, 2025

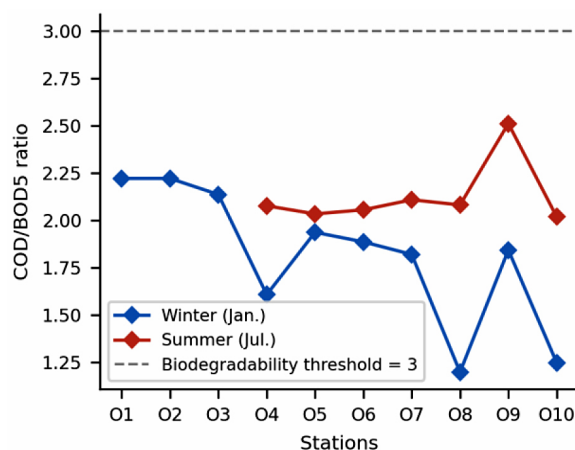


Fig. 5. Spatial and seasonal variation of the COD/BOD₅ ratio across the Oued Larbaa network, 2025

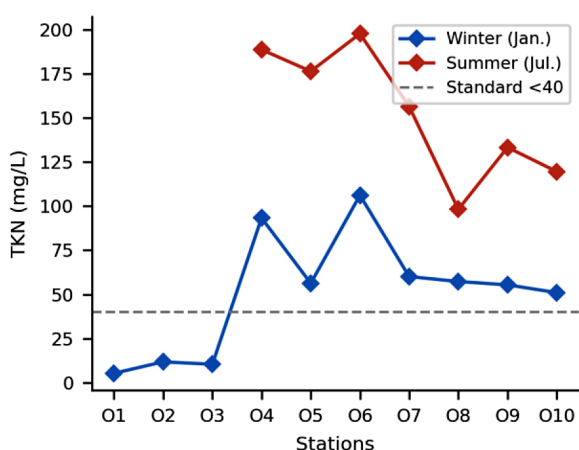


Fig. 6. Spatial and seasonal variation of total Kjeldahl nitrogen (TKN, mg/L) across the Oued Larbaa network, 2025

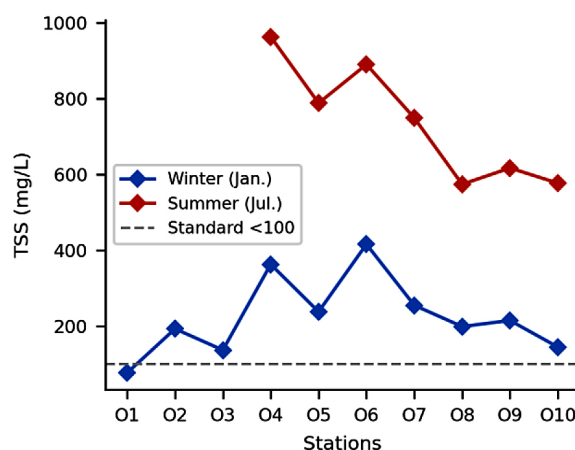


Fig. 7. Spatial and seasonal variation of total suspended solids (TSS, mg/L) across the Oued Larbaa network, 2025

Concentrations peaked along the reaches that cross central Taza, where urban runoff and untreated wastewater converge, before declining somewhat further downstream as the coarser fraction settled out; even so, the suspended-solids loads recorded here, while clearly indicative of pollution, do not appear high enough on their own to pose a soil-clogging risk in the irrigated areas served by these waters.

The TSS/BOD₅ ratio complements this picture by separating the particulate component of pollution, captured by suspended solids, from its dissolved component, captured by BOD₅.

Orthophosphate concentrations increased at all seven stations sampled in both seasons.

Their mean concentration increased from 6.9 mg/L in winter to 19.2 mg/L in summer, with the sharpest rises concentrated at stations nearest Taza (Figure 9). This pattern is consistent with combined urban wastewater and fertiliser-derived agricultural runoff as possible sources.

Winter concentrations of orthophosphate, like those of the other nutrient and organic determinands discussed above, were generally though not universally lower than in summer, even accounting for the diluting effect of rainfall and soil leaching – a pattern regular enough at the stations within Taza itself to motivate the formal seasonal comparison that follows.

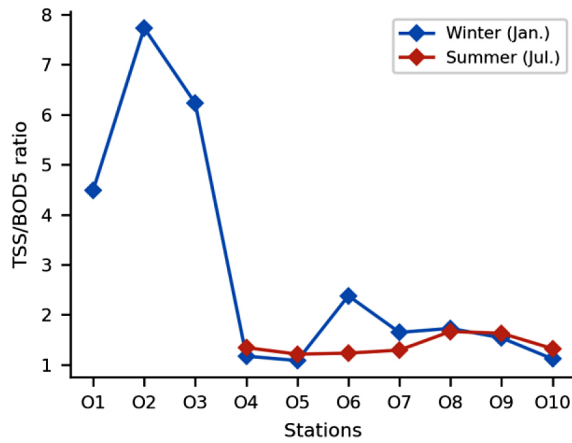


Fig. 8. Spatial and seasonal variation of the TSS/BOD₅ ratio across the Oued Larbaa network, 2025

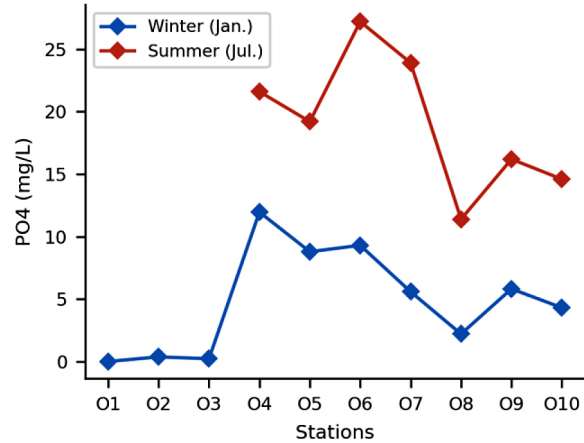


Fig. 9. Spatial and seasonal variation of orthophosphate concentrations across the Oued Larbaa network, 2025

Seasonal contrast between high- and low-water periods

At the seven stations sampled in both campaigns, every determinand degraded significantly in summer relative to winter (paired, two-sided Wilcoxon signed-rank test, exact method; Table 3; Fig. 10): TSS rose 182% (mean 261.6 to 736.9 mg/L), TKN 123% (68.5 to 152.9 mg/L), PO₄ 179% (6.9 to 19.2 mg/L), BOD₅ 208% (177.9 to 547.6 mg O₂/L) and COD 286% (299.1 to 1,153.7 mg O₂/L); dissolved oxygen fell 90% (3.1 to 0.3 mg/L) and pH dropped from a mean of 8.30 to 7.68 (all $p=0.016$, the minimal exact p-value attainable with seven paired differences of a single sign). Conductivity increased by 22% on average but not significantly ($p=0.109$), and varied non-monotonically among stations, consistent with a shift from a mixed marl-and-sewage signal in winter to an almost pure sewage signal in summer, rather than a uniform concentration effect.

Statistical relationships between parameters and station typology

The nine determinands are far from independent (Fig. 11). Organic and nutrient enrichment covaries almost perfectly: TSS, TKN, PO₄, BOD₅ and COD are pairwise correlated at Spearman rho ≥ 0.96 ($n = 17$), and each of them correlates with dissolved oxygen at rho between -0.96 and -0.98, suggesting that a single oxygen-demand process governs most of the observed variability. Temperature also loads onto this axis (rho = 0.80–0.86 with the organic determinands), consistent with the timing of the two campaigns, whereas conductivity behaves independently of every other variable ($|\text{rho}| \leq 0.32$), signalling that mineralisation and organic pollution have distinct origins in this catchment.

A principal component analysis of the standardised determinands condensed 92.6% of the total variance into two axes (Fig. 12). The first

Table 3. Paired seasonal comparison at the seven common stations (O4-O10). p-values from the exact, two-sided Wilcoxon signed-rank test (scipy.stats.wilcoxon)

Parameter	Winter mean	Summer mean	Change (%)	p-value
Temperature (°C)	15.6	28.3	+82	0.016
pH	8.30	7.68	-7.5	0.016
TSS (mg/L)	261.6	736.9	+182	0.016
Conductivity (µS/cm)	1493.1	1828.1	+22 (ns)	0.109
Dissolved O ₂ (mg/L)	3.13	0.31	-90	0.016
TKN (mg/L)	68.5	152.9	+123	0.016
PO ₄ (mg/L)	6.9	19.2	+179	0.016
BOD ₅ (mg O ₂ /L)	177.9	547.6	+208	0.016
COD (mg O ₂ /L)	299.1	1153.7	+286	0.016

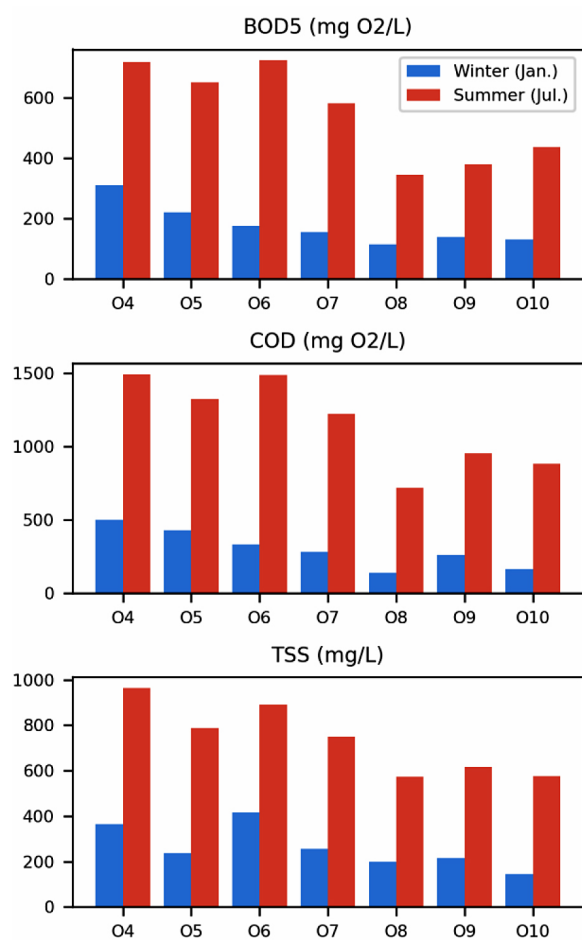


Fig. 10. Seasonal comparison (winter vs. summer) of BOD₅, COD and TSS at the seven common stations (O4–O10); TKN and PO₄ show the same pattern (Table 3)

axis accounted for 79.2% and was loaded positively by TSS, TKN, PO₄, BOD₅, COD and temperature and negatively by dissolved oxygen and pH; it therefore represented an organic-pollution axis. The second axis accounted for 13.3%, was dominated by conductivity and, to a lesser extent, pH, and was essentially unrelated to organic load. Projected onto these axes, the seventeen station-season combinations separated into three well-defined descriptive groups, recovered independently by Ward hierarchical clustering: the winter headwater stations (O1–O3), displaced along PC2 by their naturally high conductivity (2780–4820 $\mu\text{S}/\text{cm}$) but scoring low on the organic axis; the winter downstream stations (O4–O10), intermediate on PC1, where winter flow measurably diluted the Taza discharge; and every summer station, which occupied the extreme positive end of PC1. As the same stations contributed to both seasons, these groupings should be read as descriptive patterns rather than independent statistical evidence.

Attenuation rather than progressive deterioration downstream of the discharge

The prevailing assumption in similarly-designed studies is that water quality worsens monotonically from upstream to downstream as pollutant loads accumulate. Testing this assumption against the actual data shows the opposite

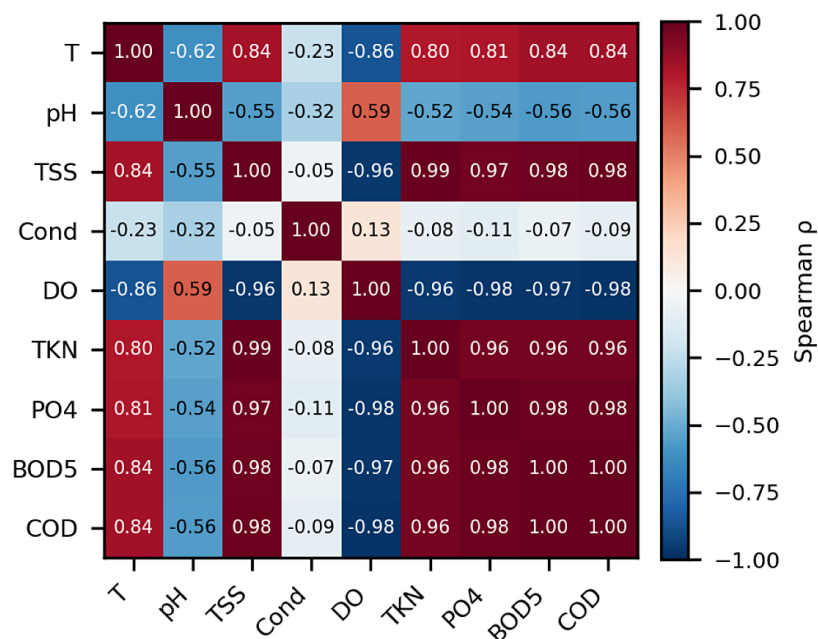


Fig. 11. The nine determinands table

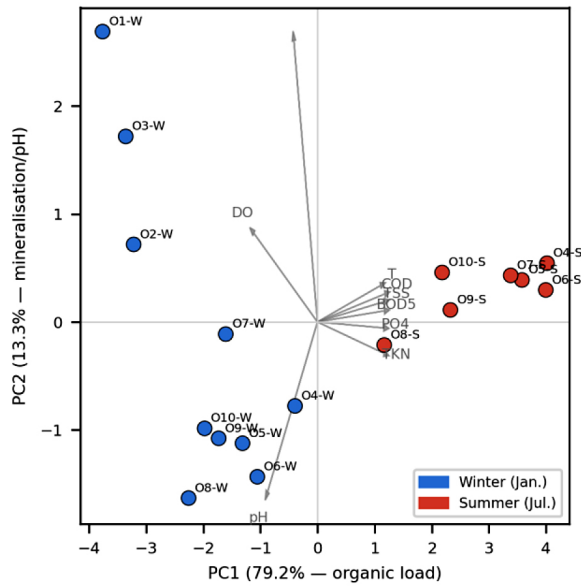


Fig. 12. Principal component biplot of the nine standardised determinands (W – winter/high water, S – summer/low water)

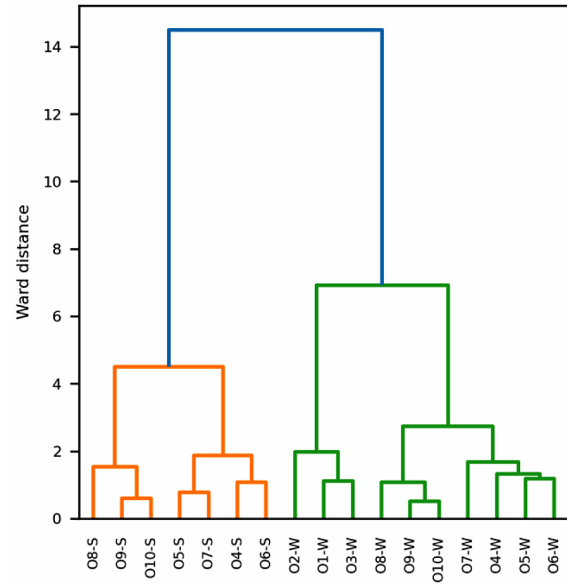


Fig. 13. Ward hierarchical clustering dendrogram of the seventeen station×season combinations

pattern during low water. Ranking the seven summer stations by great-circle distance downstream of O4 (Oued Jaouna, the main receptor of Taza's discharge), TSS and COD decrease significantly with distance (Spearman $\rho = -0.79$, $p = 0.036$ for both) and TKN decreases at the margin of significance ($\rho = -0.68$, $p = 0.094$), while BOD_5 shows the same tendency without reaching significance at this sample size ($\rho = -0.64$, $p = 0.12$) (Fig. 14). A log10-linear model estimates an attenuation rate of roughly 7–9% loss in concentration per kilometre of flow path for TSS, COD and TKN ($R^2 = 0.52\text{--}0.70$), even though the total distance covered by the seven stations is under 7 km. Station O10, the most distant, departs from this trend for BOD_5 and COD, plausibly because it also receives the combined tributary inputs of Oued Taza and Oued Dfali rather than Oued Jaouna alone. This downstream attenuation of concentrations is consistent with the biodegradable character of the organic load already indicated by the COD/ BOD_5 ratios reported above (Fig. 5), and suggests a measurable, if modest, decrease in concentrations along the flow path even under the effluent-dominated conditions of low water. However, this decrease may result from sedimentation of particulate matter, biological and chemical transformation, dilution by tributary or groundwater inputs, or a combination of these; separating these processes would require discharge measurements and pollutant load (flux)

calculations, which were not available in this study. We therefore refer to attenuation of concentrations rather than to self-purification. This is in line with nutrient-spiraling theory, in which the distance a dissolved solute travels before leaving the water column, rather than the catchment area drained, sets the scale of attenuation, with net uptake lengths of the order of a few kilometres reported immediately below wastewater outfalls elsewhere (Ensign & Doyle, 2006; Finkler et al., 2023) – comparable to the sub-7 km reach over which attenuation is observed here. The winter dataset, sampled across the full ten-station network, shows no equivalent downstream gradient for the organic determinands ($|\rho| \leq 0.51$, $p > 0.13$) but does show a strong downstream decline in conductivity ($\rho = -0.86$, $p = 0.001$), tracing the dilution of the naturally mineralised headwater signal as tributaries of different lithological origin join the main channel.

A weighted pollution index confirms the seasonal and spatial pattern

Combining the discharge-limit exceedances into a single weighted arithmetic pollution index (IP; see section 2.3) reproduces the same structure (Fig. 15; Supplementary Data). Every winter headwater station (O1–O3) is rated excellent ($\text{IP} = 28.0\text{--}42.4$), reflecting the absence of any organic signal upstream of Taza. Winter stations

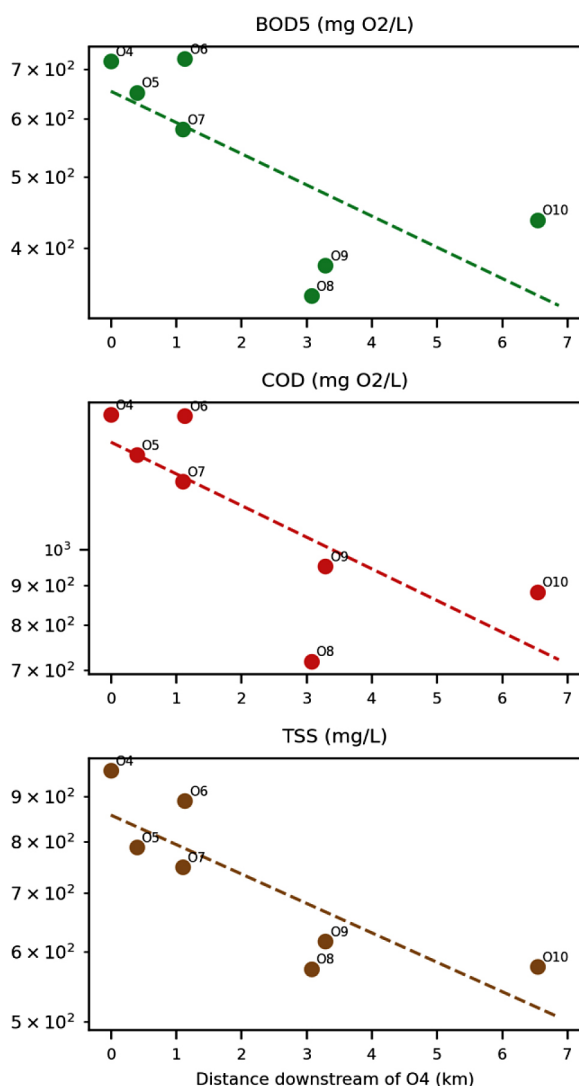


Fig. 14. Attenuation of BOD₅, COD and TSS with distance downstream of the main discharge point O4 during low water (summer, $n = 7$; dashed line: log10-linear fit)

downstream of the town (O4-O10) are rated good to poor ($IP = 59.7\text{--}107.0$), and every summer station, without exception, is rated poor ($IP = 110.9\text{--}184.0$), a class it shares only with the single most degraded winter station (O6, $IP = 107.0$), located directly downstream of the Oued Dfali hospital effluent. Total Kjeldahl nitrogen and suspended solids together account for over half of the mean index score despite carrying less than a fifth of the nominal weight, whereas pH, whose narrow regulatory tolerance gives it the single largest weight, contributes only a small share of the score because measured values rarely departed far from neutrality. This mirrors a structural property already reported for the classical weighted arithmetic index elsewhere: it is the degree of

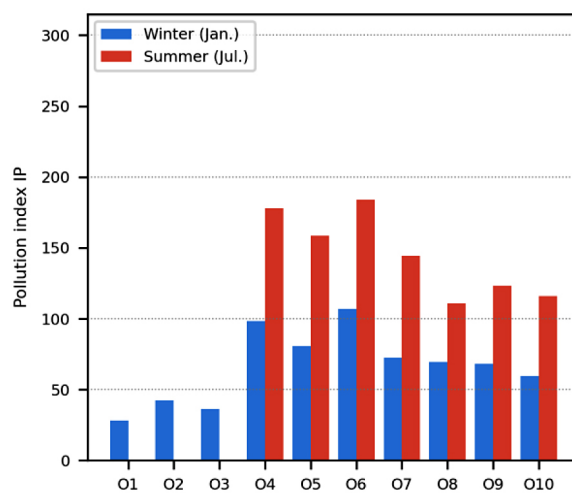


Fig. 15. Weighted arithmetic pollution index (IP) by station and season, with quality-class boundaries (Ramakrishnaiah et al., 2009)

exceedance, not the nominal weight assigned to a parameter, that ultimately governs its influence on the aggregate score. A formal decomposition of index uncertainty reaches the same conclusion, attributing over ten times more of the total variance in the index to the choice of sub-index (scoring) function than to indicator selection and weighting combined (Uddin et al., 2023), and an equivalent flow-path analysis of the neighbouring Inaouene network – into which the Larbaa itself drains – similarly finds that ammonium and phosphate, despite carrying the bulk of the nominal weight, contribute only a minor share of the score once exceedance is accounted for (Layan et al., in preparation).

Map of surface water quality in the Oued Larbaa

Overlaying the station-by-station classification of every determinand measured in this study, following the national surface-water quality grid (NMQES), yields the composite map presented in Figure 16.

This composite view corroborates the determinand-by-determinand analysis above: water quality is comparatively better upstream of Taza, where the catchment still functions as a naturally mineralised but otherwise little-impacted system, and deteriorates markedly downstream under the combined effect of diffuse and point-source anthropogenic pressure – most visibly below the Oued Jaouna, which receives urban and industrial wastewater, and below the Oued

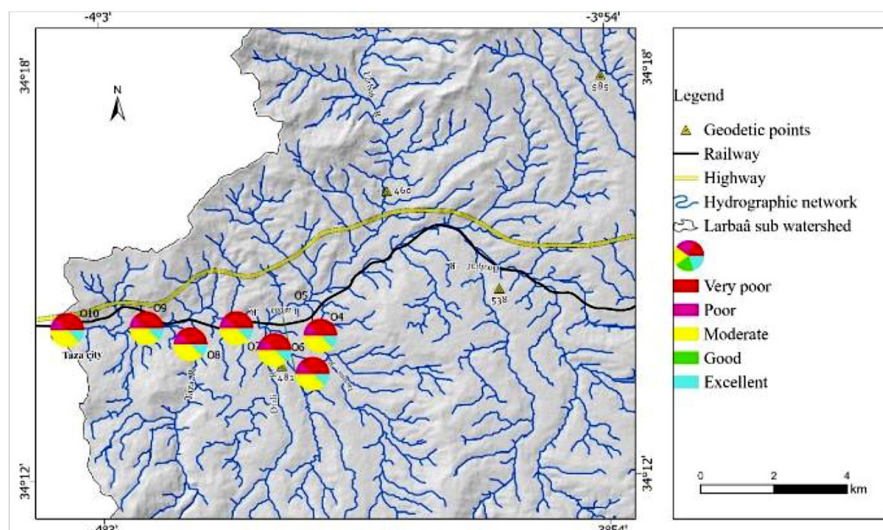


Fig. 16. Composite surface-water quality classification of the Oued Larbaa catchment, 2025 (NMQES grid)

Dfali, which additionally carries untreated hospital effluent. This pattern echoes findings from elsewhere in the Sebou basin, where comparably elevated BOD₅, suspended-solids and nutrient concentrations have likewise translated into poor to very poor water-quality classifications (Elmadani et al., 2019; Ben Abbou et al., 2026a). On the Larbaa itself, seasonal deterioration of a similar magnitude to the one documented here has already been reported for its parasitological and bacteriological quality (Mherzi et al., 2021), and a parallel comparison of a normal against a dry hydrological cycle on the Inaouene and its Larbaa and Lahdar tributaries found BOD₅, COD and total phosphorus rising by 37–42% and dissolved oxygen falling by 46% between seasons (Mahmoud et al., 2023), corroborating the direction, if not always the magnitude, of the winter-to-summer changes reported in Table 3. A flow-path-based re-analysis of the receiving Inaouene network has reported a qualitatively similar distance-related pattern, but that comparison does not establish the mechanisms responsible for the attenuation observed in the present study (Layan et al., in preparation).

Limitations of the study

Several limitations qualify the conclusions of this study. (i) Sample size: the seasonal comparison relies on seven stations common to both campaigns, and the distance-based analysis on seven summer stations spanning less than 7 km; spatial conclusions are therefore indicative and

exploratory and should not be generalised beyond the sampled reaches. Sampling consisted of a single campaign per season (16 January and 17 July 2025), so that intra-seasonal and inter-annual variability and the transitional seasons are not captured. (ii) Non-independence of observations: the correlation matrix, PCA and clustering rest on 17 station-season observations in which the same stations appear twice; repeated measurements were not modelled explicitly (for example with mixed-effects models, which would require a larger dataset), and these tools were therefore used descriptively. (iii) Absence of discharge and load data: only concentrations were analysed, and river discharge was not measured because no flowmeter was available. Consequently, the contributions of dilution, sedimentation and biological or chemical transformation to the downstream decrease in concentrations cannot be separated, and self-purification cannot be demonstrated. Future work should combine discharge gauging, pollutant load calculations and process-oriented measurements along the flow path.

CONCLUSIONS

The Oued Larbaa and its principal tributaries – the Bouljraf, Jaouna, Dfali and Taza wadis – operate under a markedly irregular flow regime, from near-total cessation of flow in summer to substantial winter discharge, and this regime is an important determinant of the water quality documented here: it dictates whether the river has any

capacity at all to dilute the untreated effluent that Taza discharges into it year-round.

The physicochemical survey revealed pronounced spatial and temporal variability, arising from the superposition of two largely independent processes: a natural mineralisation signal, expressed as the high conductivity of the headwater stations, and an anthropogenic organic-and-nutrient signal, expressed as elevated BOD₅, COD, TKN and orthophosphate concentrations wherever the river has received Taza's wastewater.

Formal statistical testing corroborates the main seasonal pattern. The pollution-related determinands increased significantly from winter to summer, while dissolved oxygen decreased; electrical conductivity did not change significantly (paired Wilcoxon signed-rank test, $p = 0.109$). The principal component analysis identified a dominant organic-pollution axis explaining 79.2% of the variance, and the weighted pollution index built from national discharge limits rated every summer station as poor while every winter headwater station remained excellent. Organic concentrations also decreased measurably with distance travelled once effluent had entered the channel (Spearman rho up to -0.79 for TSS and COD against distance from the main discharge point), indicating modest downstream attenuation. The underlying mechanisms (dilution, sedimentation and transformation) could not be separated without discharge and load data.

Taken together, these results confirm that the catchment is exposed to compound pressures rather than a single dominant source: naturally elevated mineral content upstream, and a mixture of untreated urban sewage, agricultural runoff and at least one identifiable point source of hospital effluent downstream, each leaving a distinguishable signature in the data.

The composite quality map derived from these measurements reinforces this picture, showing that classifications of moderate to very poor quality dominate the catchment for most of the year, and that the very poor category is essentially confined to, and downstream of, the urban reaches of Taza.

Data availability

The complete raw dataset (all stations and seasons, original laboratory and field values, sampling coordinates and dates), the QA/QC records, the spreadsheet containing all index formulas, and

the input files for the PCA, clustering and statistical tests are provided as Supplementary Material (Files S1–S3). The supplementary files should be checked to ensure that all manuscript values, units, station labels and dates match exactly.

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