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Geological and hydrological approach to surface Water Pollution in Inaouene Catchment Area

BEN LAGHLAGH Oumaima[1], NAOURA Jamal[1], HAZYOUN Zineb[2]

[1] *Laboratory of Natural Georesources and Environment, Faculty of Science and Technology,Sidi Mohamed Ben Abdellah University, Fes 35000, Morocco*

[2] *Laboratory of Biotechnology, Conservation and Valorisation of Bioresources, Faculty of sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fes 35000, Morocco*

[1]oumaima.benlaghlagh@usmba.ac.ma

[1]Jamal.naoura@usmba.ac.ma

[2]zinebhazyoun@gmail.com

***Abstract*— The upper Inaouene waterched of approximately 1616 km² is a principal source of drinking and irrigation water for the Taza region and is subjected to extreme hydrological conditions (floods and low-flows). This study focuses on the effect of such extrêmes on the contamination of surface waters and surface sediments by trace metals, with respect to geological and morphometric controls. The methodology implemented here combines morphometric studies, geologic interpretations, the spatial analysis using GIS, and the measurements of trace metal content at monitoring stations scarttered on the oued network. This framework provides a means of evaluating the associations between geological materials, hydrololgical regims, and levels of metal contamination. The findings suggest that the heterogeneity of the geology toghether with morphometry of the watershed exert strong controls on the spatial variations of trace-metal contamination of the oueds. Floods favor erosion, sediment exchange and downstream transfer of metal-rich particles. Low-flows facilitate the build-up and accumulation of trace metals in isolated zones. The composition of the underlying geology exerts a contol on the level of metal contamination. By combining the above methodology with the small number of sampling stations, this research offers quantitative insights into the short-term impact of hydrological extrêmes on trace metals in oueds. It helps to deepen the understanding of the processes for sustainable water management in semi-arid regions.**

***Keywords*— water pollution – hydrological regims – vulnerability - Inaouen- lithology- trace metal - GIS.**

I. INTRODUCTION

Surface water is a crucial resource for domestic, agricultural and industrial uses. However, its quality in increasingly threatened by various forms of pollution, particularly those intensified by extreme hydrological events and the broader impacts of climate change. Among these events, floods and low-flow periods play a pivotal role in modulating pollutant transport in aquatic systems. Floods, through intense surface runoff and soil leaching, can introduce a large quantity of pollutants into watercourses in a short time. Conversely, low-flow conditions reduce the dilution capacity of rivers, leading to higher pollutant concentrations and altered geochemical balances. While anthropogenic pressures are often emphasized, the geological substrate remains a critical yet often understimated factor in pollutant, catchment morphology, and the interaction between surface water and groundwater significantly shape the enviromental reponse the these extreme events. In this context, the aim of this study is to explore the geological approach to undesrtanding the impact of floods and low-flow periods on surface water pollution. This involves examining the underlying physico-chemical mechanisms, the interactions among soil, water, and rock, also the implications for the environmental vulnerability and water resource management. Particular attention is given to sediment dynamic, lithological, and catchment geomorphology.

II. MATERIALS AND METHODS

A. Study area

The upper Inaouene catchment area covers a surface of 1616 km² representing approximately 31.17 % of the total Inaouene wtarshed which itself accounts for 12.92 % of the entire Sebou basin. Geographically, it is located between latitudes 33.84°N and 34.58°N, and longitudes 3.78°W to 4.91°W. It is boundes to the east

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by the middle Moulouya basin, to the northwest by the upper Ouergha basin, and the southwest by the upper Sebou basin. From a geological and structural perspective, the upper Inaouene basin lies in a geologically complex region at the intersection of three major Moroccan geological domains : the Rif domain to the north, the Meseto-Atlasic domain in the senter, and the Middle Atlas to the south. These structural units are separated by the South-Rifain trench, and east-west oriented tectonic corridor that narrows toward the east at the Touahar Pass (Rachid, 1977). The basin also extends across the Fes-Taza corridor, a miocene marl graben bordered by the Rif and Middle Atlas chains. This structural complexity is reflected in a variety of lithologies, including limestone, marl, sandstone, and clay, which exert a strong influence on the region's hydrological behavior. The topography is highly diverse, combining mountainous areas, plateaus, hills and plains. Altitude range from 1500 to 2000 meters, particularly in the Tazzeka region, leading to significant winter precipitation (up to 1000 mm/year).

These topographical and climatic conditions directly impact erosion, runoff, and infiltration processes. The morphometry of the basin further influences hydrological behavior. The main stream channel extends 85 km, with centroid-to-outlet distance of 22.15 km. The basin's maximum length and width are 58 km and 38 km, respectively. These parameters affect the concentration time, runoff velocity, and the basin's response to both flood and low-flow events. Geologically, two main types of formations are observed : Permeable formations (limestone, porous sandstone) that promote infiltration and reduce surface runoff, impermeable and unconsolidated formations (marl, clay), often assoociated with sparse vegetation cover, which enhace surface runoff and accelerate erosion. Finally the geochemical compostion of the geological formations significantly affects the physico-chemical quality of both sediments and surface waters, playing a decisive role in the basin's vulnerability to pollution.

B. Geological aspect

To assess the impact of extreme hydrological events (floods and low-flow conditions) on surface water pollution in the Upper Inaouene catchment, a multidisciplinary and integrative methodology was adopted, combining geological, and spatial analyses.

Geological Approach, detailed geological analysis was conducted, focusing on the nature and spatial distribution of lithological formations within the catchment. Particular attention was paid to key geological propreties such permeability, porosity, and fracturing which directly influence infiltration capacity, runoff behavior, and pollutant transport. Permeable formations that favour infiltration include, Jurassic limestone (blue): highly karstified, dominant in the northwest, facilitating groundwater recharge, Cretaceous formations (yellow): carbonate-rich, with moderate to high permeability, Quaternary deposits (light grey): alluvial and gravel formations, also favourable to infiltration.

In contrast, impermeable formations, including Miocene and Neogene units (pink and light green): rich in marl and clay, promoting runoff and pollutant transport, Hercynian basement (light blue): generally impermeable unless fractured, Triassic and Paleogene (red and light brown): often contain marls, gypsum, and clays, with low permeability. promote rapid surface runoff, which can enhance erosion and the transportof sediments and contaminants (Chauve et al., 2000; Margat, 1990).This geological characterization is crucial for establishing links between substratume properties and surface water vulnerability to pollution.

C. Sediment Sampling and Analysis

Physico-chemical Approach (Sediment Analysis), to substantiate the impact of geology on surface water quality, a physico-chemical analysis of sediment samples was carried out. An additional 5 samples were collected during contasting hydrological conditions flood periods and low-flow periods at representative locations along the main watercouses.

In this study, the results of the anlysis at sites in the upper reaches of the Inaouene river during the two periods April 2025 and October 2025 can be classified into two series :

series 1: Includes metals (Fe, Sr, Mn, Zn, Rb, Pb) detected at all sampled sites.

series 2: Includes metals (Cu, Ni, Cr, As, Co, Pt, Au, Sn) detected at certain sites only.

Although the Oued Inaouène watercourse flows through all the solid waste dumps in urban areas (the city of Taza, Bab Marzouka, Oued Amlil, Bouhlou), it also carries untreated wastewater, which may be the source of

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the pollution.The integration of these four complementary approaches offers a holistic understanding of the spatial dynamics of pollution risk in relation to both hydrological events and geological factors.

III. RESULTS

D. Sediment Chemical Characteristics

In the sampled sites during april 2025, Fe concentrations are consistently the highest, at around 13,000 to 16,000 mg/kg. There is a slight increase from L1 to L2, a small decrease at L3 and LH, and then a rise again at site I. Sr levels remain relatively stable, fluctuating slightly between approximately 450 and 550 mg/kg. There is a small dip at L2, L3 and site I. Mn shows a gradual increase in L1, L2 and LH (around 250 to 320 mg/kg), followed by a slight decrease at site L3 and I. Zn concentrations increase from L1 to L3 (roughly 40 to 55 mg/kg), then decline slightly at LH and I. Rb remains fairly stable, with minor fluctuations around 30–40 mg/kg across all sites. Pb has the lowest concentration. It increases from L1 to LH (about 15 to 32 mg/kg), then drops significantly at site I.

For the sampled sites during October 2025 Iron (Fe) shows the highest concentrations (≈10,000–20,000 mg/kg), with only minor fluctuations. This stability suggests a dominant lithogenic origin and consistent mineralogical composition across sites. Strontium (Sr) and Manganese (Mn) form the second concentration tier (≈300–750 mg/kg). Sr exhibits a slight increase at L2 and L3 followed by a decrease toward LH and I, while Mn remains more stable. These two elements also appear primarily lithogenic, with modest site-dependent variations.

Zinc (Zn) and Rubidium (Rb) are present at intermediate levels (≈50–80 mg/kg). Zn remains relatively stable across the sites, whereas Rb shows a small peak at L3 before decreasing toward site LH. These variations may reflect local differences in sediment grain size or clay mineral content. Lead (Pb) shows the lowest concentrations (≈10–20 mg/kg). Although generally stable, a slight increase is observed around LH. Pb's low levels and limited spatial variation indicate minimal anthropogenic enrichment.

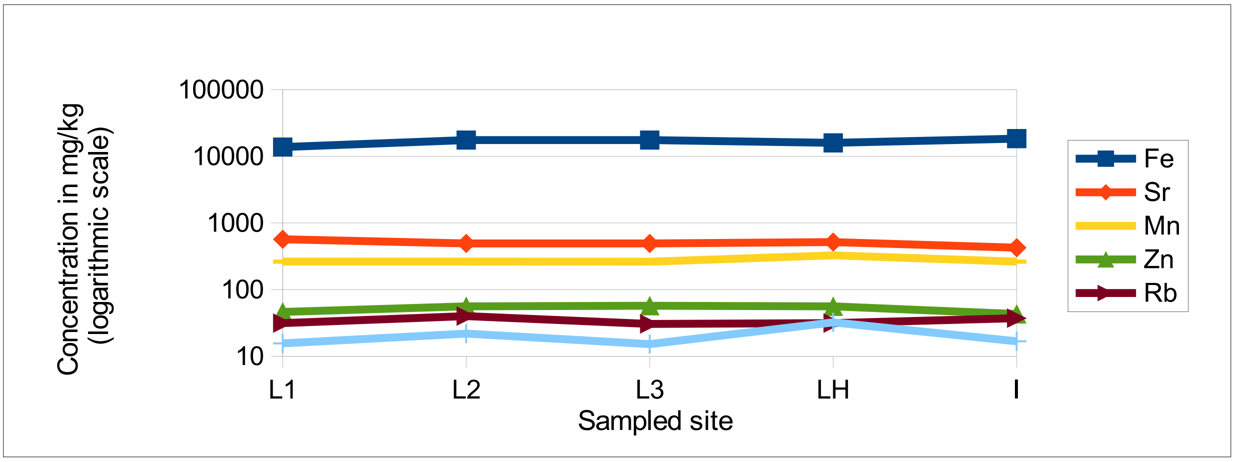

Fig 1. Spatiotemporal variation of six elements (Fe, Sr, Mn, Zn, Rb, and Pb series 1) in the sampled sites during april 2025.

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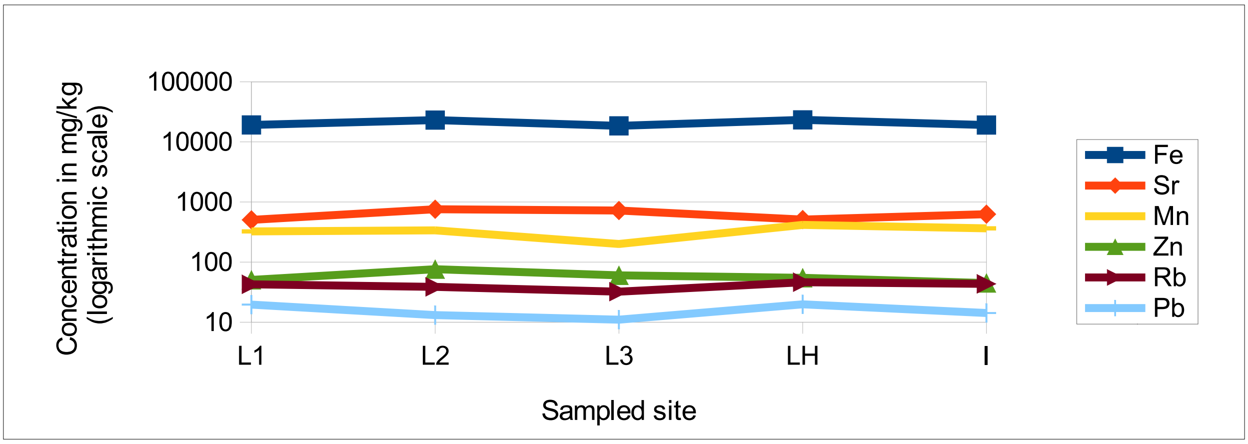

Fig 2. Spatiotemporal variation of six elements (Fe, Sr, Mn, Zn, Rb, and Pb series 1) in the sampled sites during october 2025.

A bar graph is shown for all six trace metals (Cu, Ni,Cr, As, Co and Sn) analysed at each of the five sampled locations (L1, L2, L3, LH, and I): those sampled locations metal concentrations are shown on a log scaled bar chart as well. For all measured elements, as can clearly be seen, both Cu and Ni dominate, while most other measured elements (Cr, As, Co and Sn) exist at very low and almost constant concentrations across all measured locations (cr = ~1mg/kg). Cu data shows moderate concentrations from ~30mg/kg. Significant increases in Cu concentration occur from L1 to L2. The largest concentration of Cu occurs at LH and then it decreases slightly at site I. The likely explanation for this pattern is localised differences in sediment composition or minor human induced additions of Cu. Ni has the highest concentration of all six analysed trace metals, with a very large peak concentration at L3 (~48mg/kg) with another peak concentration at site LH (~45mg/kg). The large concentration of Ni at both L3 and LH , instead of L1 & L2, possibly relates to both lithological differences (i.e., different rock types/ages due to geological processes having occurred) and anthropogenic sources that exist upstream. L1 and L2 have appreciably lower Ni concentrations than L3, LH and I. Cr, As, Co and Sn concentrations are all relatively low (close to/less than ~1mg/kg) compared to Cu and Ni concentration across the five sampled locations, and demonstrate little variation amongst measured locations, indicating all five measured elements exist in equilibrium with nature (as measured) and do not show an increasing level of enrichment.

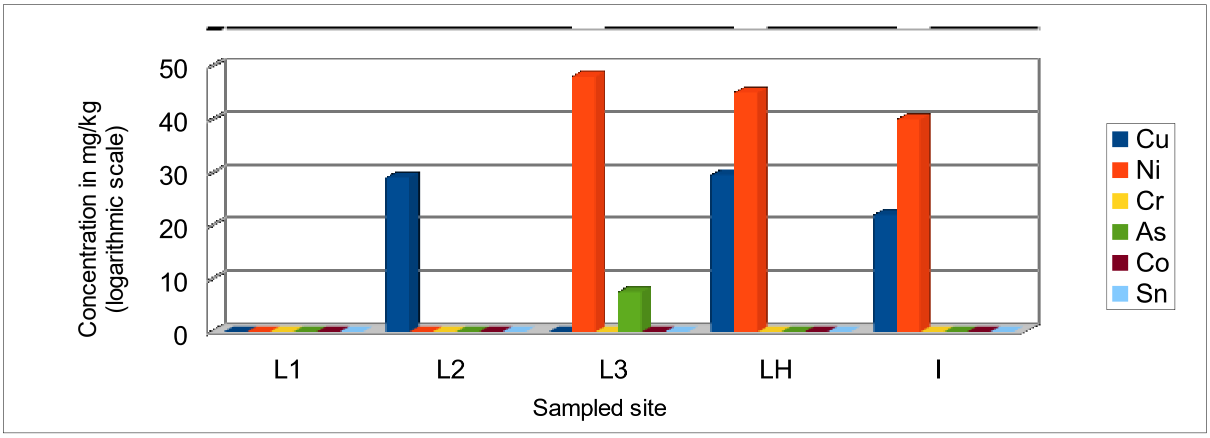

Fig 3. Spatiotemporal variation of six elements (Cu, Ni, Cr, As, Co, and Sn series 2) in the sampled sites during april 2025.

Trace metal concentration data for Cu, Ni, Cr, As, Co, and Sn. There are 4 locations (L1, L2, L3 LH and I) sampled in the river. The data has been graphed using a logarithmic scale. Just like with the first dataset, the

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overwhelming majority of trace metals are present in either Ni (Nickel) or Cu (Copper). The remaining elements are present at very low background levels. Ni (Nickel) concentrations at all locations are consistently high (40 to 60 mg/kg), with a slight peak at site L3. This uniform increase of Ni across all sites indicates a large lithogenic source or a constant source of geochemical input into the river system. Cu (Copper) concentrations vary greatly from site to site. A very low amount of Cu was found at L1 and there was a sharp increase to a moderate amount at L2. From L2 to LH Cu experienced a weaker increase and then a maximum concentration at site I. This data suggests two types of gold deposits: local geology varies and potential contribution from distinct anthropogenic activity. As (Arsenic) was the only low concentration trace metal with significant variation in that there was a distinct peak at L3 (11 mg/kg), while all other sites were close to the baseline (< 1 mg/kg). This peak detected at L3 may represent a localized geochemical anomaly or historical source.

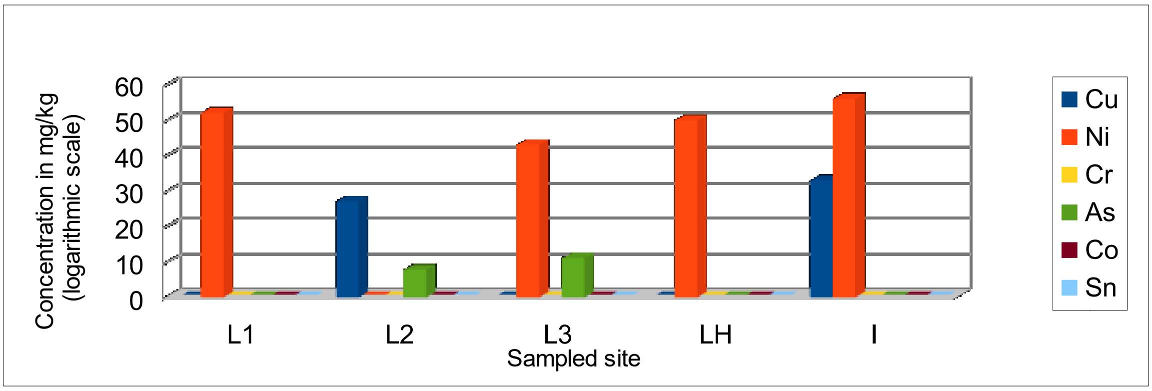

Fig 4. Spatiotemporal variation of six elements (Cu, Ni,Cr, As, Co, and Sn series 2) in the sampled sites during october 2025.

E. Water Physical Characteristics

In periods of low water, the reduction in flow accentuates the effects of point source pollution. To support these findings, a physico-chemical water quality assessment was carried out on samples from key points in the catchment area. The aim was to identify pollution indicators and assess the potential correlation between hydrological conditions and surface water quality. The main parameters analysed include pH, electrical conductivity (EC) and turbidity.

The results obtained are the results of one campaign in april 2025, except for turbidity, for which the October campaign was not carried out, given that turbidity across the study area, even in winter, is low.

The physico-chemical parameters measured at the five sampling points in the Upper Inaouéne catchment indicate clear spatial variation in water quality. I1 and L2 shows the highest electrical conductivity (4750 µS/cm), suggesting elevated ionic content and suspended solids, likely due to runoff or the presence of low-permeability formations. In contrast, I1 present no turbidity, with conductivity values of 1500 µS/cm and 2000 µS/cm respectively, reflecting differing geological substrates and mineralisation levels. The pH varies between 7.5 and 8.8, indicating slightly alkaline waters typical of carbonate-rich environments. These results, although measured under normal flow conditions, highlight the influence of lithology, infiltration capacity, and runoff on surface water quality.

F. Water Chemical Characteristics trace elements (heavy metals)

Iron concentrations in the October 2025 monitoring campaign were very low at most sites (≤0.01 mg/l). For the April 2025 campaign, concentrations above Moroccan standards (0.2 mg/l) were recorded at sites L1 and LH. These results can be explained by the presence of iron in the form of Fe^{3+}-containing salts when the pH is above 7.
Ni^{2+} is the dominant form of nickel in freshwater; for a pH < 8, its mobility increases as the pH decreases. The results recorded during the April 2025 campaign show concentrations below the limit of detection. For the October 2025 campaign, concentrations remain low at most stations except for station L1 (0.014 mg/l).

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Regarding manganese, the October 2025 campaign recorded concentrations above the detection limit at L2; these concentrations may originate from industrial waste, as this site is directly exposed to such pollution.

IV. CONCLUSION

The pollution risks and the level of contamination in the surface waters of the Inaouène wadi were assessed by analysing their physicochemical characteristics, which was one of several investigative methods employed. The study focused primarily on the physicochemical analysis of the water, including temperature, conductivity, pH, turbidity, the content of major elements, and finally the concentration of certain heavy metals in the waters of the Inaouène, such as Fe, Ni,Cu, Pb, Mn, Cr, Cd…

The concentrations of certain heavy metals were found to exceed the relevant standards, such as Fe, Ni and Mn, which are thought to be caused by both certain artisanal activitiesin the town of Taza and domestic wastewater. Furthermore, heavy metals, in addition to their possible anthropogenic origins, may have a geological origin, entering the river system via climatic erosion

This study made it possible to assess the influence of floods and low-water periods on the pollution of surface water, using a geological approach applied to the upper Inaouéne catchment. Morphometric and lithological analysis and the spatialisation of hydrogeological factors have highlighted the role of lithological nature in controlling the flow and dispersion of pollutants. Areas with loose, impermeable litholohgic formations, and high drainage density are more vulnerable to extreme hydrological events.

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