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Hydro-physical characterization of contrasting urban and natural soils in a semi-arid basin: Implications for water transfer in Bouskoura, Morocco

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ABSTRACT

Urbanization modifies soil conditions and may alter the partitioning of rainfall between surface runoff and subsurface water transfer, particularly in semi-arid environments. This study characterizes the hydro-physical properties of soils under contrasting land-use conditions in the Bouskoura Basin, Morocco. Four site-specific soil samples representing dense urban, peri-urban, industrial, and natural forest environments were analyzed for particle-size distribution, natural water content, bulk and dry density, and Atterberg limits. Total porosity was estimated from dry density using an assumed particle density of 2650 kg m^{-3}. The results show clear differences in particle-size composition and measured hydro-physical properties among the investigated sites. The industrial sample contains the highest gravel fraction (25%), whereas the natural forest sample has the highest fine-particle fraction (48.2%). Dry density ranges from 1540 to 1671 kg m^{-3}, with the highest value occurring at the natural forest site. Natural water content ranges from 4.4% to 12.5%. These observations indicate contrasting soil conditions among the investigated land-use settings that may influence water storage and subsurface transfer. However, infiltration rate, hydraulic conductivity, and groundwater recharge were not directly measured; therefore, hydrological implications are interpreted as potential effects rather than quantified processes. The study provides a site-specific hydro-physical baseline for future investigations of infiltration, runoff, and groundwater recharge in the rapidly urbanizing Bouskoura Basin.

Keywords: hydro-physical properties, urban soils, soil texture, soil moisture, porosity, semi-arid basin, Bouskoura, Morocco.

INTRODUCTION

Urbanization is one of the most significant drivers of land-use change in semi-arid regions, where water availability is already limited and highly variable (Carlson et al., 2011; Cotti, et al., 2022). The conversion of natural soils into compacted or partially sealed urban surfaces alters the functioning of the soil–water system, particularly within the unsaturated zone that governs infiltration and groundwater recharge processes (Lerner, 2002; Scanlon et al, 2006; Borgwardt et al, 2021; Fletcher, et al, 2024). In such environments, changes in soil hydro-physical properties may influence surface runoff generation and subsurface water fluxes.

The hydro-physical characteristics of soils, including texture, water retention capacity, and natural moisture content, play a central role in regulating infiltration processes (Rattan lal et al, 2004; Rahmati, et al, 2018). Fine-textured soils, especially those rich in clay, tend to exhibit high water storage capacity but limited permeability, which constrains vertical percolation toward deeper soil layers and aquifers (Ben Slimene, et al., 2015; Assouline, 2013; Shuster et al, 2021). These variations influence pore connectivity and hydraulic behavior in the vadose zone, thereby controlling the partitioning of rainfall between infiltration and surface runoff (Beven et al, 2013).

Although the impacts of urbanization on runoff dynamics and flood risk have been extensively investigated, the role of soil hydro-physical variability in urban hydrological systems remains less documented, particularly in semi-arid settings. Many studies rely on static soil parameters or simplified representations of impervious surfaces, overlooking the temporal dynamics of soil moisture and its interaction with soil texture and compaction (Ludovic et al, 2013). This gap limits the ability to accurately assess infiltration efficiency and potential groundwater recharge in urbanized basins.

The Bouskoura Basin, located south of Casablanca in Morocco, constitutes a relevant case study to address these issues. The basin is characterized by rapid urban expansion, a semi-arid Mediterranean climate with strong seasonal rainfall variability, and the predominance of clayey to silty soils. Previous investigations have reported increasing runoff coefficients and reduced infiltration associated with urban development in the basin (El Garouani, et al., 2017; Benjelloun, et al., 2021). However, the hydro-physical behavior of urban soils and the seasonal dynamics of soil moisture within the unsaturated zone have not yet been comprehensively analyzed from a hydrogeological perspective.

The objective of this study is to characterize and compare the hydro-physical properties of soils collected from contrasting land-use environments in the Bouskoura Basin. Specifically, the study aims to: characterize particle-size distribution, natural water content, density, and Atterberg-limit properties; estimate total porosity from dry density; compare these properties among dense urban, peri-urban, industrial, and natural forest sites; and discuss their potential implications for water storage and subsurface water transfer. Because direct measurements of infiltration, hydraulic conductivity, and groundwater recharge were not conducted, the hydrological interpretation is intentionally qualitative and does not attempt to quantify these processes.

The contribution of this study is primarily empirical and site-specific. Rather than proposing a new infiltration model or a new hydraulic method, the study establishes a comparative hydro-physical baseline for contrasting soil environments within the Bouskoura Basin. By documenting differences in particle-size distribution, natural water content, density, and estimated porosity across urban, peri-urban, industrial, and natural settings, the study provides initial evidence that can guide subsequent field-scale investigations of infiltration and groundwater recharge in this semi-arid and rapidly urbanizing environment.

MATERIALS AND METHODS

Study area

The Bouskoura Basin is located south of Casablanca, northwestern Morocco, between latitudes 33.45°N and 33.55°N and longitudes −7.55°W and −7.40°W. The basin covers an approximate area of ≈120 km² and drains toward the Atlantic coastal system. Topography is characterized by low relief, with elevations ranging from 40 to 160 m a.s.l. and gentle slopes generally below 5%, which favor rapid surface runoff during intense rainfall events (El Garouani, et al., 2017).

The climate of the basin is semi-arid Mediterranean, characterized by strong interannual and seasonal rainfall variability (Cantón et al., 2001; Scanlon et al, 2006). Mean annual precipitation ranges between 300 and 400 mm, with more than 70% of rainfall occurring between October and March. Rainfall events are typically short and intense, frequently exceeding 20–30 mm per event, which enhances runoff generation under low infiltration conditions (Benjelloun, et al., 2021). Mean annual temperature is approximately 18–20 °C, with summer maxima exceeding 30 °C, leading to high potential evapotranspiration and prolonged soil drying during the dry season.

From a hydrogeological perspective, the basin is underlain by Plio-Quaternary formations composed mainly of marls, clays, silts, and locally sandy deposits. The soil cover is dominated by clayey to silty textures, with clay contents commonly exceeding 35–45%, which confer high water retention capacity but low permeability (Hillel, 1998; Assouline, 2013). These soil characteristics strongly influence infiltration processes and regulate water storage within the unsaturated zone. The thickness of the unsaturated zone varies spatially but generally ranges between 2 and 10 m, depending on local topography and lithology.

Land-use analysis indicates that urban areas have expanded rapidly over the last two decades. Built-up surfaces increased from approximately 15–20% in the early 2000s to more than 45–50% after 2020, resulting in significant soil sealing and compaction. This urban expansion has been associated with an increase in runoff coefficients, reported to range between 0.4 and 0.6 in highly urbanized sub-areas, compared to values below 0.25 in less disturbed zones (El Garouani, et al., 2017; Benjelloun, et al., 2021). These changes have led to a reduction in effective infiltration and groundwater recharge potential.

Overall, the Bouskoura Basin represents a representative semi-arid urban catchment where climatic constraints, fine-textured soils, and rapid urbanization jointly control infiltration processes and subsurface water fluxes. The combination of low permeability soils, strong seasonal soil moisture variability, and increasing imperviousness makes the basin particularly suitable for investigating soil hydro-physical controls on runoff and groundwater recharge (Figure 1).

Sampling device and hydrogeological context

Four site-specific soil samples were collected manually on 6 November 2025 from selected contrasting land-use environments within the Bouskoura area, including dense urban (S1), expanding peri-urban (S2), industrial (S3), and natural forest (S4). The sampling locations were selected to represent contrasting soil environments rather than to provide a statistically representative sampling of the entire basin. The sampling depths were not identical among sites. S1 was sampled over a depth interval of 0–150 cm, whereas S2, S3, and S4 were sampled from 0–30 cm. This difference in sampling depth should be considered when comparing the measured properties, as the samples do not represent identical vertical soil intervals. Following collection, the samples were labeled and transported to the laboratory for physical characterization.

The laboratory characterization included particle-size distribution, natural water content, soil density, and Atterberg limits. Particle-size distribution was determined by sieve analysis according to Moroccan standard NM 13.1.008, while soil classification was performed using the LCPC classification method. Natural water content was determined by the oven-drying method according to Moroccan standard NM 13.1.152. Soil density was determined using the cutting-ring, mould, and water-immersion method according to Moroccan standard NM 13.1.119. Atterberg limits were determined according to Moroccan standard NM 13.1.007, including the liquid limit determined using the cup method and the plastic limit determined by the rolling method. The

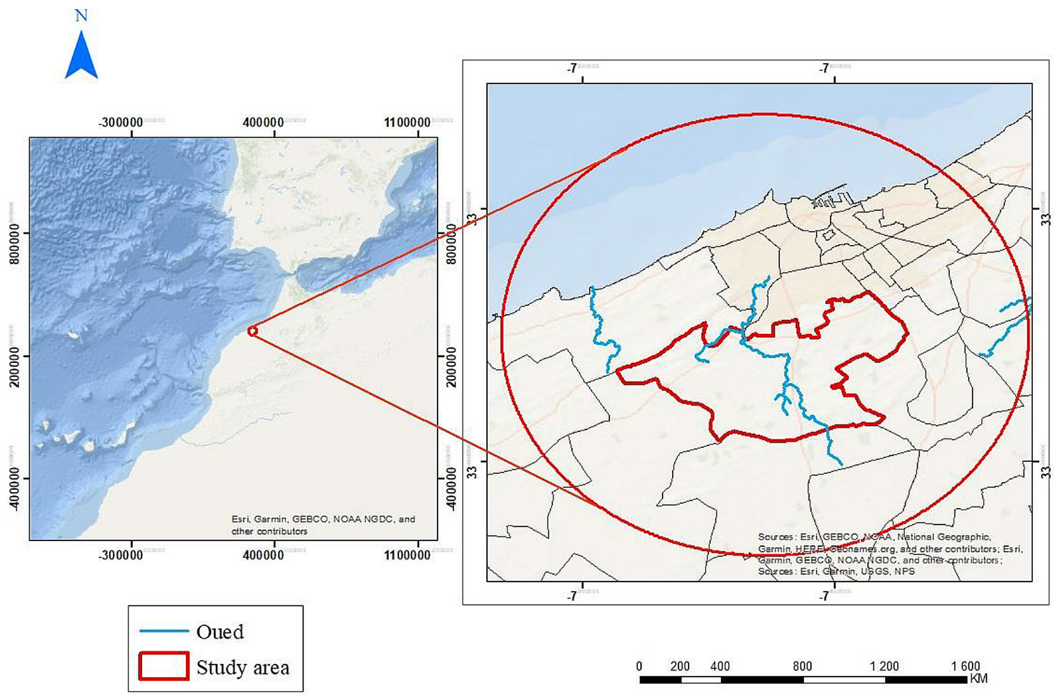

Figure 1. Location of the Bouskoura commune on a map of Morocco

liquid-limit test was performed using a grooving tool, with a cup drop height of 10 mm.

For the present dataset, the available Atterberg-limit results are reported as recorded in the laboratory results. Where the plastic-limit test did not yield a measurable plastic limit, the result is reported as non-plastic (NP) rather than converted to an assumed numerical value. Accordingly, no numerical plastic-limit or plasticity-index values are inferred where they are not directly available from the original laboratory records (Table 1, Figure 2).

Detailed information on the manufacturer and model of the laboratory equipment, as well as the corresponding calibration and quality-control records, was not preserved in the available archived documentation. Consequently, these details cannot be retrospectively verified and are not reconstructed or assumed in the present study. The analytical procedures are therefore reported according to the laboratory records and the referenced Moroccan standards available for the original analyses. This limitation should be considered when assessing the reproducibility of the reported measurements.

The reported analytical results are supported by the available electronic laboratory worksheets and calculation records for the four investigated soil samples (S1–S4). These records contain the analytical measurements and calculations used to obtain the reported results. However, the available documentation does not allow the number and nature of independent replicate determinations to be verified for all analyzed parameters. Consequently, the available measurements are not treated as statistically independent replicates, and no missing replicate information has been reconstructed or inferred.

Parameters analyzed and hydrogeological justification

Particle-size distribution was used to characterize the textural composition of the investigated soils and to discuss its potential implications for water retention and transmission. Natural water content was measured to describe the moisture condition of each sample at the time of collection. Bulk and dry density were determined to characterize the physical state of the samples, while total porosity was estimated from dry density using an assumed particle density of 2650 kg m^{-3}. Atterberg limits were used to characterize the consistency and plasticity of the fine fraction. These measurements were interpreted as indirect indicators of potential water-transfer behavior; direct hydraulic properties were not measured.

Interpretation approach

The measured properties were compared descriptively among the four sampling sites to identify contrasts in soil texture, moisture condition, density, and estimated porosity. These contrasts were then discussed in relation to their potential implications for water storage and subsurface transfer. Because hydraulic conductivity and infiltration rate were not measured, the analysis does not establish causal relationships between the measured soil properties and actual infiltration or recharge rates (Figure 3).

Data availability

The laboratory data supporting this study are available as electronic worksheets for the four investigated soil samples (S1–S4), including the analytical measurements and associated calculation records. These archived files constitute the available underlying laboratory documentation for the results reported in this study.

RESULTS AND DISCUSSION

Hydro-physical properties of the studied soils

The hydro-physical characteristics of the studied soils are summarized in Table 2. Laboratory

Table 1. Location and characteristics of samples

Sample	Coordinates (Lat, Long)	Depth (cm)	Zone type
S1	33.46 N ; -7.45W	0–150	Dense urban area
S2	33.47 N ; -7.45W	0–30	Expanding peri-urban area
S3	33.46 N ; -7.44W	0–30	Industrial estate
S4	33.46 N ; -7.45 W	0–30	Natural area/Bouskoura forest

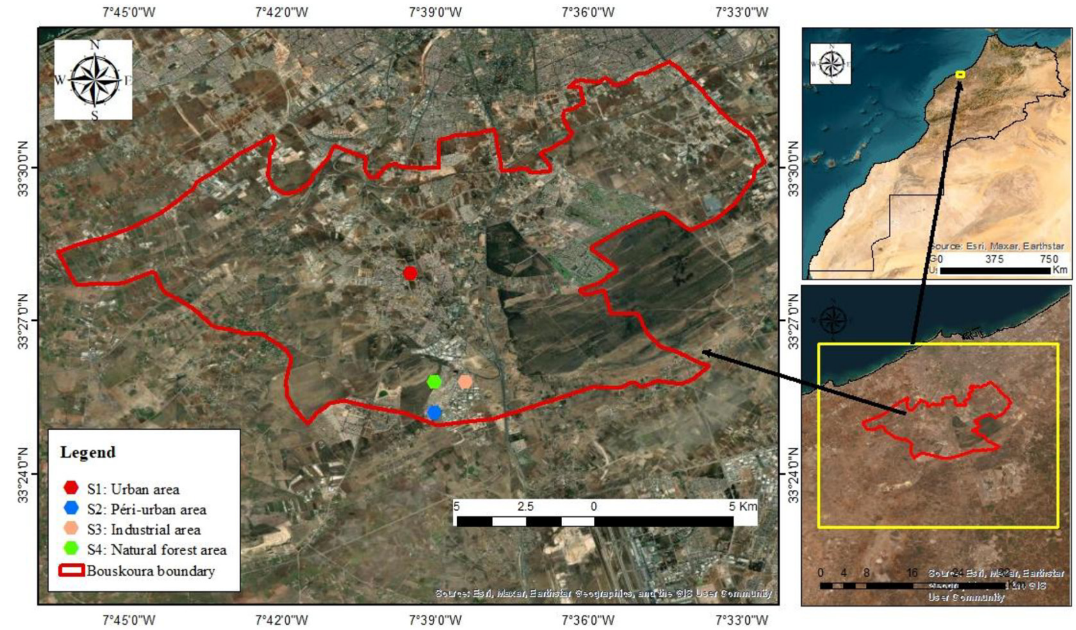

Figure 2. Location of the study area and spatial distribution of soil sampling sites (S1–S4) within the Bouskoura commune, Morocco

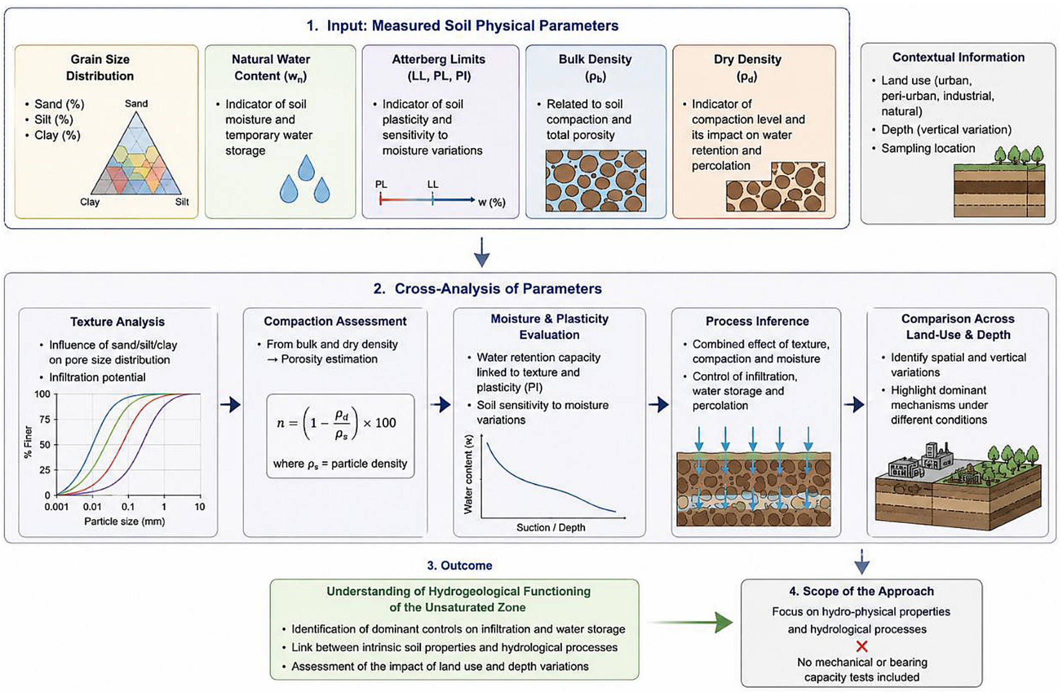

Figure 3. Interpretation approach

Table 2. Atterberg limits and plasticity classification of the studied soil samples

Sample	Liquid limit, WL (%)	Plastic limit, WP	Plasticity index, IP
S1	27	NP	NP
S2	18	NP	NP
S3	19	NP	NP
S4	23	NP	NP

analyses revealed noticeable spatial variability between the different sampling environments of the Bouskoura Basin. The proportion of fine particles (<0.08 mm) ranges from 21.2% in the industrial site (S3) to 48.2% in the natural forest area (S4) (Figure 6 and Figure 7). The measured properties differed among the four investigated sites, in texture and hydrological behavior between urbanized and natural environments.

The urban (S1) and peri-urban (S2) soils are mainly characterized by silty sand textures (ML according to the USCS classification), with sand fractions reaching 63.6% and 63.8%, respectively (Figure 4 and Figure 5). These soils contain moderate proportions of fines (33.4% for S1 and 28.2% for S2), reflecting partially disturbed and reworked urban materials. In contrast, the industrial soil (S3) exhibits a more heterogeneous granulometric composition with a relatively high gravel content (25%), suggesting the presence of anthropogenic filling materials and coarse reworked deposits associated with industrial activities. The natural forest soil (S4) presents the highest proportion of fine particles (48.2%) and a lower sand fraction (40.8%), indicating a finer and more cohesive soil structure.

Grain size analyses revealed a predominance of fine particles, mainly composed of silts and clays, associated with variable proportions of sand and gravel depending on the sampling location. The high proportion of fine particles suggests relatively low hydraulic conductivity and limited vertical infiltration capacity. Fine-textured soils generally possess smaller pore spaces, which slow down water percolation and favor temporary water retention within the upper soil horizons (Hillel, 1998; Rawls et al., 1982). Under intense rainfall conditions, these characteristics may contribute to temporary surface saturation and increased runoff generation.

Spatial variability in grain size distribution also reflects the influence of land-use conditions on soil structure and hydrological response. In the natural forest environment, vegetation cover and reduced anthropogenic disturbance help preserve more stable soil organization and infiltration processes. In contrast, urbanized areas exhibit disturbed soil structures associated with surface compaction and reduced infiltration efficiency (Gregory et al., 2006; Shuster et al, 2021; Zhang et al, 2020).

Bulk density values range between 1600 and 1744 kg/m³, while dry density varies from 1540 to 1671 kg/m³. The highest dry density was measured in the natural forest soil (S4), while the urban, peri-urban, and industrial soils (S1–S3) exhibited lower values. Therefore, dry density alone does not provide direct evidence of greater compaction in the urbanized sites. In urban and industrial environments, anthropogenic disturbance may nevertheless modify soil structure and pore connectivity through construction activities, artificial filling, machinery traffic, and repeated surface disturbance. Such structural modifications may affect effective water transfer even when differences in bulk or dry density are not pronounced (Gregory et al., 2006; Shuster et al, 2021).

Porosity values vary from 36.9% in S4 to 41.9% in S3. Although this range remains relatively limited, slight porosity reductions in compacted urban soils may significantly influence infiltration processes by decreasing effective pore space available for water transfer. Similar relationships between soil compaction, porosity reduction, and infiltration limitation have been reported in semi-arid urban environments, where anthropogenic disturbance strongly modifies near-surface hydrological functioning (Gregory et al., 2006).

Natural moisture content also varies considerably between sampling sites, ranging from 4.4% in the natural forest area (S4) to 12.5% in the industrial site (S3). The relatively high moisture content measured in S3 may reflect localized water accumulation within heterogeneous disturbed layers. In contrast, the lower moisture content observed in the natural area likely reflects more stable drainage conditions and progressive infiltration promoted by vegetation cover and limited anthropogenic disturbance.

The available Atterberg-limit results indicate that the investigated samples were classified as non-plastic (NP) based on the recorded plastic-limit and plasticity-index results. The measured liquid-limit values ranged from 18% to 27%. Because the available laboratory records do not provide numerical plastic-limit values for these samples, the plastic limit and plasticity index are reported as NP rather than assigned numerical values. Therefore, no numerical value of zero is assumed for either the plastic limit or the plasticity index. These results indicate non-plastic behavior under the reported test conditions, but they should not be used solely to infer swelling potential, hydraulic conductivity, or infiltration behavior (Figure 8, Table 3).

Overall, the obtained hydro-physical properties indicate that soil texture, density, porosity, and moisture conditions collectively control infiltration capacity and water transfer processes within the Bouskoura Basin.

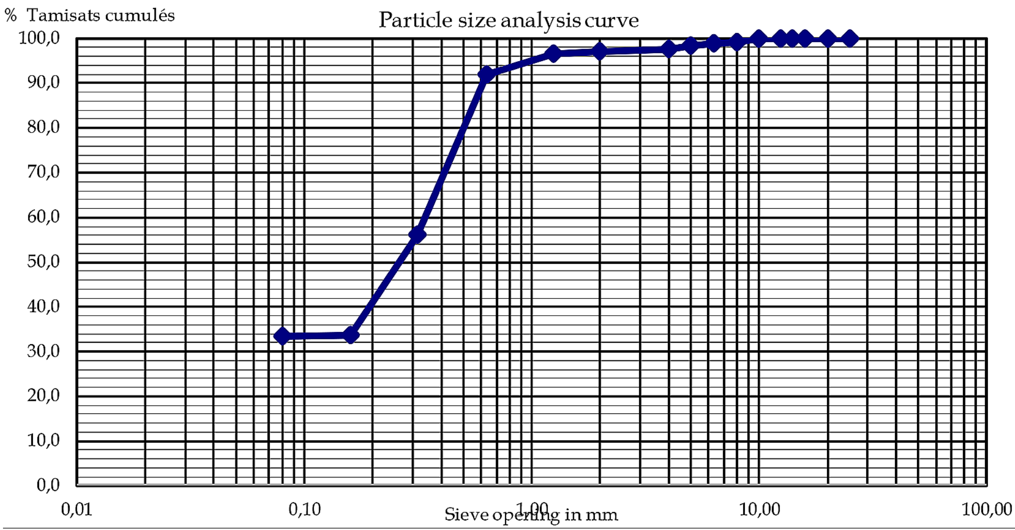

Figure 4. Granulometric curve of soil sample S1 (dense urban area)

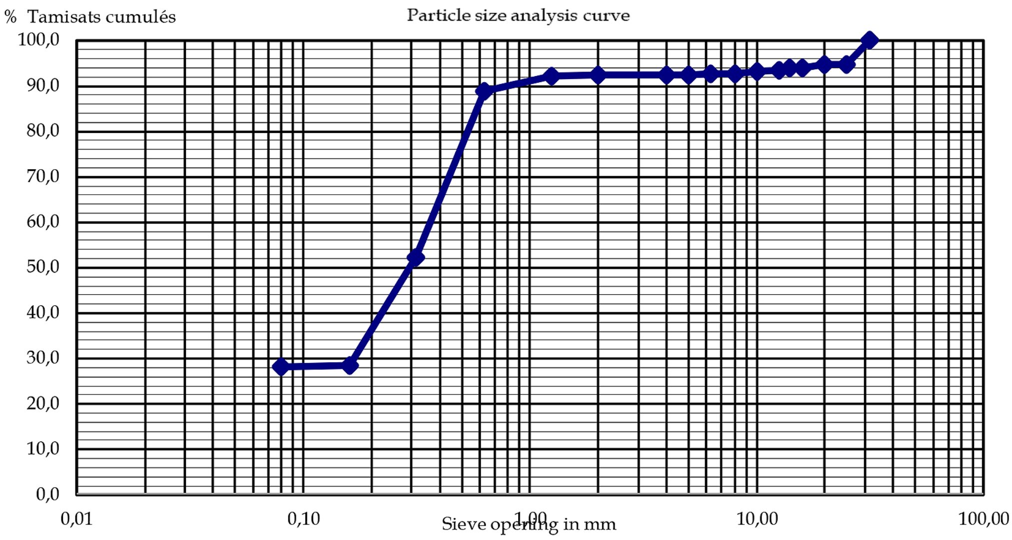

Figure 5. Granulometric curve of soil sample S2 (expanding peri-urban area)

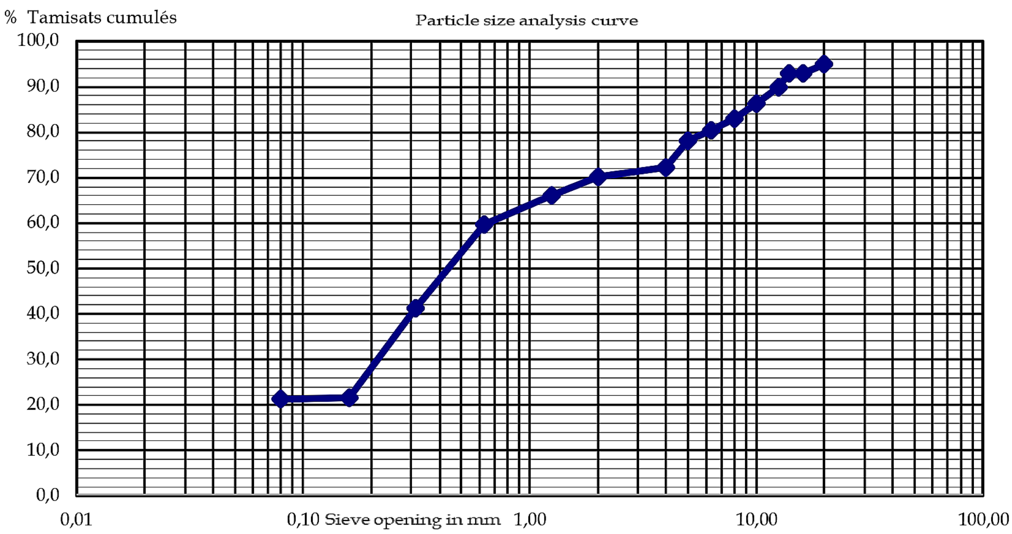

Figure 6. Granulometric curve of soil sample S3 (industrial area)

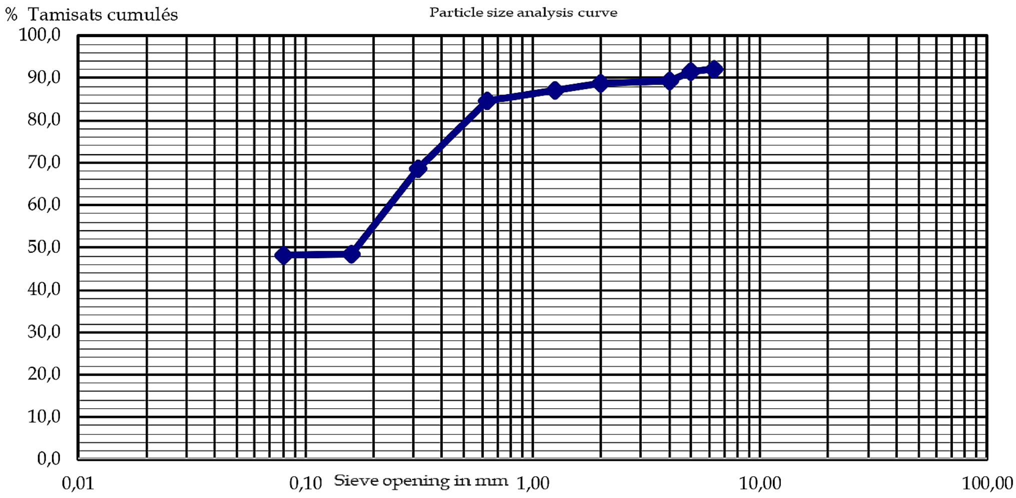

Figure 7. Granulometric curve of soil sample S4 (natural area / Bouskoura forest)

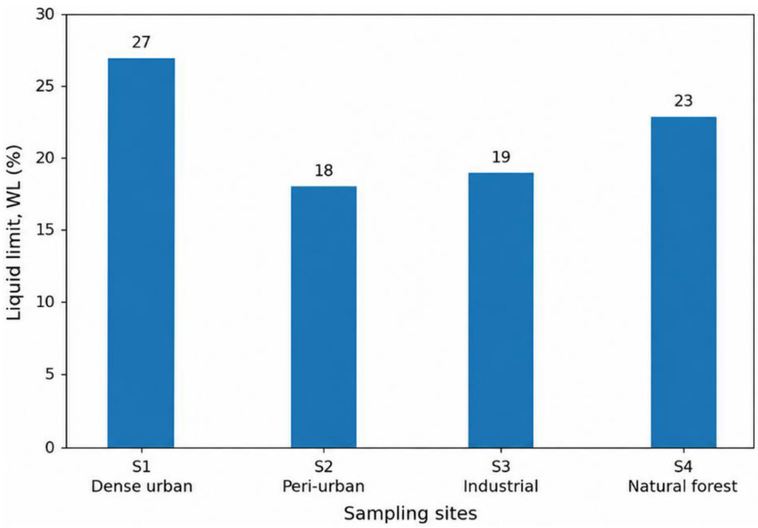

Figure 8. Liquid-limit values measured for the four investigated soil samples.

Table 3. Hydro-physical and granulometric properties of the studied soils in the Bouskoura Basin

Sample	Site type	%Fines (<0.08 mm)	%Sand (0.08–2 mm)	%Gravel (2–20 mm)	Texture (USCS)	WL (%)	Bulk density (kg/m³)	Dry density (kg/m³)	Moisture content (%)
S1	Dense urban area	33.4	63.6	3	ML – Silty sand	27	1668	1560	6.9
S2	Expanding peri-urban area	28.2	63.8	3	ML – Silty sand	18	1600	1550	7.9
S3	Industrial estate	21.2	48.8	25	ML – Silty sand, coarser	19	1730	1540	12.5
S4	Natural area / Bouskoura forest	48.2	40.8	8	ML – Silty sand, finer fraction dominant	23	1744	1671	4.4

Plastic-limit and plasticity-index results are reported as non-plastic (NP) and are therefore not represented as numerical values

Estimated porosity and implications for water transfer

The total porosity of the soils was estimated from dry density values using the following relationship:

$$n = 1 - \frac{\rho d}{\rho s} \quad (1)$$

where: n is total porosity, ρd is dry density, ρs is particle density assumed equal to 2650 kg/m³.

Estimated porosity values ranged from 36.9% in the natural forest soil (S4) to approximately 42% in the urban and industrial soils (S1–S3). Although urban soils exhibit relatively high total porosity, this does not necessarily indicate higher infiltration potential. In urbanized environments, soil compaction and anthropogenic disturbance may reduce pore connectivity and limit effective water transfer despite the presence of void spaces. In contrast, the natural soil likely presents a more stable pore network favorable to progressive infiltration and water retention.

However, estimated total porosity represents the total fraction of void space and does not directly quantify infiltration capacity or hydraulic conductivity. Therefore, differences in estimated porosity among the four sampling sites should not be interpreted as direct evidence of differences in infiltration or groundwater recharge. Direct measurements of infiltration rate and hydraulic conductivity would be required to establish such relationships.

Influence of land use on infiltration-related properties

The observed differences among the sampled land-use settings suggest that urbanization contributes to soil compaction within the Bouskoura Basin. Variations in granulometric composition, dry density, moisture content, and estimated porosity reflect the combined effects of natural soil conditions and anthropogenic disturbance associated with urbanization and industrial activities.

Urban and peri-urban soils (S1 and S2) are characterized by sandy-silty textures with moderate fines content and relatively high dry density values. The observed characteristics of urban and peri-urban soils are consistent with potential effects of anthropogenic disturbance on soil compaction and pore structure, which may reduce effective infiltration. In densely urbanized environments, anthropogenic disturbance and partial surface sealing can alter pore connectivity and limit vertical water transfer within the unsaturated zone. Similar effects of anthropogenic disturbance on infiltration-related soil properties have been reported in several semi-arid and Mediterranean urban catchments, where land-use change significantly modifies runoff generation and groundwater recharge processes.

The industrial soil (S3) exhibits a more heterogeneous granulometric composition characterized by a significant gravel fraction (25%). The relatively high gravel fraction observed at S3 (25%) indicates a markedly coarser particle-size composition compared with the other investigated sites. This coarse fraction may influence the arrangement and distribution of soil pore spaces and, consequently, the potential movement of water through the soil. However, preferential flow was not directly measured in the present study, and the observed particle-size distribution alone is insufficient to establish the occurrence or magnitude of preferential flow.

S4 provides a natural reference condition characterized by the highest fine-particle fraction and the lowest estimated total porosity. These properties indicate a distinct soil condition, but they are insufficient to establish its actual infiltration capacity without direct hydraulic measurements. The lower estimated porosity observed in S4 does not necessarily indicate lower infiltration potential, as pore continuity and soil structure may play a more important role than total porosity alone in controlling effective water transfer.

These observations demonstrate that infiltration-related properties in the Bouskoura Basin are controlled not only by soil texture but also by land-use conditions and anthropogenic alteration of soil structure. Urbanization tends to modify the balance between infiltration, water retention, and surface runoff generation, particularly under semi-arid climatic conditions characterized by short-duration and high-intensity rainfall events. Consequently, the hydrogeological response of urban soils cannot be interpreted solely from granulometric parameters, but must also consider compaction effects and pore connectivity within the unsaturated zone.

Hydrogeological implications for runoff and groundwater recharge

The measured differences among the four studied sites provide a basis for discussing the potential hydrological implications of soil variability within the Bouskoura Basin. However, these results do not constitute direct measurements of infiltration, surface runoff, or groundwater recharge. Soil texture, natural water content, dry density, and estimated total porosity can influence water storage and transmission, but the magnitude and direction of these effects also depend on hydraulic conductivity, pore connectivity, soil structure, antecedent moisture conditions, surface sealing, and rainfall characteristics. These hydraulic variables were not directly measured in the present study. Nevertheless, previous studies have shown that soil compaction and surface disturbance associated with urbanization can modify soil structure and pore connectivity, potentially affecting the partitioning of rainfall between infiltration and surface runoff, particularly during short-duration and high-intensity rainfall events in semi-arid environments (Gregory et al., 2006; Scanlon et al, 2006; Fletcher, et al, 2024).

Accordingly, the urban and peri-urban samples should not be interpreted as having demonstrably lower infiltration rates than the natural forest soil. Rather, their measured physical characteristics indicate contrasting soil conditions that may influence water storage and transmission and therefore warrant further hydraulic investigation. In particular, the industrial sample, characterized by a relatively high gravel content and natural water content, represents a distinct soil condition whose hydraulic behavior cannot be inferred from particle-size distribution alone. This is consistent with the need to consider the combined effects of soil physical properties and structural characteristics when assessing water movement in urbanized environments (Fletcher, et al, 2024).

The natural forest sample provides a useful reference condition for future comparative investigations. Its relatively higher fine-particle content and lower estimated total porosity may affect water storage and movement; however, these characteristics alone cannot be used to establish whether groundwater recharge is higher or lower than at the urban and industrial sites. In semi-arid environments, groundwater recharge is often associated with episodic rainfall events, and the effective transfer of water through the unsaturated zone depends on soil hydraulic properties and rainfall conditions (Scanlon et al., 2006). Therefore, direct measurements of infiltration rate and hydraulic conductivity, together with information on soil structure and rainfall response, would be required to establish the relationships between the observed soil properties and infiltration or recharge processes.

Overall, the results highlight the hydro-physical heterogeneity of soils within the Bouskoura Basin and provide an initial basis for assessing their potential role in urban hydrological processes. Rather than demonstrating a direct effect of land-use change on infiltration or groundwater recharge, the findings identify contrasting soil conditions that may contribute to differences in water storage and transfer. Further hydraulic characterization would therefore be valuable for evaluating how soil variability interacts with urbanization, rainfall, runoff generation, and groundwater recharge in this semi-arid basin.

The hydro-physical variability observed among the investigated soils may have implications for water-transfer processes within the Bouskoura Basin. In urbanized and industrialized environments, soil compaction and surface disturbance have been associated in previous studies with reduced infiltration and enhanced surface runoff, particularly during short-duration and high-intensity rainfall events characteristic of semi-arid climates (Gregory et al., 2006; Fletcher, et al, 2024) . However, infiltration and runoff were not directly measured in the present study; therefore, these relationships are considered potential hydrological implications rather than demonstrated effects at the investigated sites.

Previous studies have shown that modifications in infiltration conditions may influence groundwater recharge by affecting vertical water transfer through the unsaturated zone (Scanlon et al, 2006). In semi-arid environments, where recharge commonly occurs during episodic rainfall events, changes in soil structure may potentially influence the partitioning of rainfall between surface and subsurface pathways (Scanlon et al., 2006; Fletcher et al., 2024; Hajhouji et al., 2022). In the present study, however, neither infiltration rate nor groundwater recharge was directly measured, and the observed soil properties alone are insufficient to quantify these processes.

The natural forest sample (S4) provides a contrasting reference condition characterized by a relatively high fine-particle fraction and distinct density and porosity values compared with the other investigated samples. These properties may influence water storage and transfer, but they do not demonstrate greater infiltration or subsurface water-transfer capacity. In particular, total porosity does not provide information on pore connectivity or hydraulic conductivity. Therefore, the hydraulic behavior of S4 relative to the urban and industrial samples cannot be established from the available measurements alone.

Overall, the results demonstrate hydro-physical contrasts among the four investigated land-use settings but do not establish a direct causal relationship between land use and hydrological response. The observed differences may potentially influence water storage and transfer; however, their effects on infiltration, runoff generation, groundwater recharge, and flood response cannot be quantified from the present dataset. Direct hydraulic and hydrological measurements would be required to evaluate these processes.

Figure 9 provides a conceptual interpretation of the potential relationships between land-use conditions, soil disturbance, measured hydro-physical properties, and water-transfer pathways. The observed differences in texture, density, moisture content, and estimated total porosity indicate contrasting soil physical conditions among the investigated sites. These properties may influence water storage and transfer; however, their effects on infiltration, surface runoff, and groundwater recharge were not directly measured in this study. Therefore, the framework should be interpreted as a conceptual representation of potential hydrological implications rather than as evidence of demonstrated hydraulic responses.

Study limitations

This study has several limitations that should be considered when interpreting the results. First, the analysis is based on four site-specific samples representing contrasting land-use settings. The limited number of sampling locations and the absence of independent field replicates prevent statistical generalization to the entire Bouskoura Basin or to the corresponding land-use classes. The results should therefore be considered exploratory and site-specific.

Second, the sampling depths were not identical among sites, which may introduce a vertical

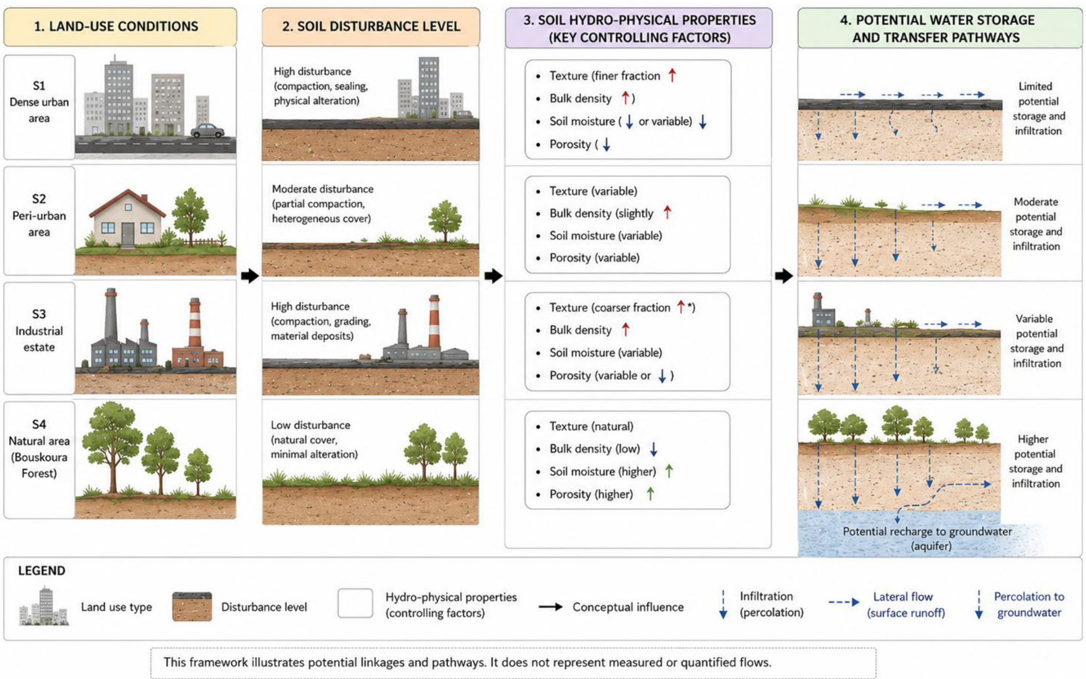

Figure 9. Conceptual framework linking land-use conditions, soil hydro-physical properties, and potential water-transfer pathways in the Bouskoura Basin

sampling effect when comparing the measured properties. Third, natural water content was measured at the time of sampling and does not provide a seasonal time series; consequently, no conclusions regarding seasonal soil-moisture dynamics can be drawn from these measurements.

Fourth, infiltration rate, saturated or unsaturated hydraulic conductivity, pore connectivity, and groundwater recharge were not directly measured. The implications discussed in this study therefore represent qualitative interpretations based on hydro-physical indicators rather than quantified hydraulic responses.

Finally, total porosity was estimated using an assumed particle density rather than measured directly. Future studies should increase the number of sampling locations, include independent field and laboratory replicates, standardize sampling depths, conduct direct infiltration and hydraulic-conductivity measurements, and monitor soil moisture over multiple seasons. These improvements would allow the relationships between urbanization, soil properties, infiltration, runoff, and groundwater recharge to be tested quantitatively.

A further limitation concerns the availability and completeness of the original laboratory records. Although electronic laboratory worksheets and analytical results are available for the four investigated soil samples, the archived documentation does not provide verifiable information on the number and nature of independent replicate determinations for all analyzed parameters. Consequently, the reproducibility of individual laboratory determinations cannot be independently assessed in terms of replicate-level variability. The results should therefore be considered documented site-specific observations rather than a statistically replicated dataset.

In addition, detailed equipment specifications and calibration and quality-control records were not available in the archived laboratory documentation; therefore, these aspects of the analytical procedures could not be independently verified.

CONCLUSIONS

This study provided a comparative hydro-physical characterization of four soil samples collected from contrasting land-use environments in the semi-arid Bouskoura Basin, Morocco. The investigated sites differed in particle-size distribution, natural water content, bulk density, dry density, and estimated total porosity. The industrial sample was characterized by a relatively high gravel fraction, whereas the natural forest sample contained the highest proportion of fine particles.

The measured dry density values did not show a systematic increase in the urbanized sites, with the highest value recorded at the natural forest site. Therefore, the present results do not provide sufficient evidence to conclude that urbanization systematically increases soil compaction in the investigated locations. Similarly, the estimated porosity values cannot be directly interpreted as infiltration capacity because pore connectivity and hydraulic conductivity were not measured.

The study nevertheless provides a useful site-specific baseline for comparing hydro-physical conditions under contrasting land-use settings. These differences may have implications for water storage and subsurface transfer, but their effects on actual infiltration, runoff generation, and groundwater recharge remain to be quantified. Future work should therefore combine a larger and replicated sampling network with direct infiltration tests, hydraulic-conductivity measurements, seasonal soil-moisture monitoring, and hydrological observations. Such an integrated approach would provide a stronger basis for quantifying the influence of urbanization on water-transfer processes in the Bouskoura Basin.

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