Impact of the Ain Taoujdate Flexure on the Morphology of the Mikkes River Valley in the Saïs Basin (Sebou Basin, Morocco)

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Abstract. The Oued Mikkès is a left-bank tributary of the Oued Sebou, located in the Prerif region. Its watershed extends across three distinct morpho-structural units, from south to north: the western edge of the Middle Atlas plateau in the upstream section, the Saïs basin in the central part, and the Pre-Rif ridges and the Prerif in the downstream section. The central part of the basin, corresponding to the Saïs plain, is significantly influenced by active tectonics, mainly related to the Ain Taoujdate flexure. This major geological structure, with a general WNW-ESE orientation, crosses the basin and plays a key role in shaping both the hydrographic network and sedimentary deposits. The middle reach of the Oued Mikkès valley exhibits a complex morphology, directly linked to ongoing tectonic movements. These tectonic disturbances affect the riverbed slope, channel alignment, and the processes of erosion and sedimentation. Moreover, the interaction between active tectonics and regional climatic conditions contributes to shaping the current fluvial landscape. This study aims to examine the impact of the Ain Taoujdate flexure on the morphology of the middle reach of the Oued Mikkès valley, by highlighting the geomorphological and hydrological dynamics at work.

1 Introduction

Fluvial systems are closely controlled by watershed geomorphology, lithology, and active tectonics, which influence both river channel morphology and sedimentary dynamics[11]. The study of interactions between tectonic deformation and fluvial morphology is a central field in fluvial geomorphology, allowing for an understanding of how rivers respond to structural variations and environmental constraints. In regions of active tectonics, the location of flexures and faults often controls the configuration of drainage networks, the distribution of alluvial deposits, and channel morphometry.

The Oued Mikkès basin, a left-bank tributary of the Oued Sebou, is located in the Fès-Meknès region and is of particular interest for studying morpho-structural and fluvial interactions. It drains three distinct morpho-structural units: the western edge of the Middle Atlas plateau in

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its upstream section, the Saïs plain in the central part, and the Prerif highlands in the downstream section. The central part of the basin, corresponding to the Saïs plain, is strongly influenced by active tectonics, notably the Aïn Taoujdate flexure, a WNW–ESE-oriented structure that controls both the morphology of the drainage network and the distribution of sedimentary deposits. Despite several studies on the geomorphology and tectonics of the region [14, 6, 4,13], few studies have analyzed in an integrated manner the impact of tectonic deformation on fluvial dynamics and alluvial morphologies in the Oued Mikkès.
This study therefore aims to :

- Characterize the morphometry and dynamics of the Oued Mikkès channel using longitudinal and cross-sectional profiles ;
- Identify the relationships between tectonic structures (flexures and fractures) and the drainage network configuration ;
- Assess the implications of these interactions for integrated river management and environmental planning.

By combining morphometric analysis with a tectonic context, this research provides new insight into how active tectonics modulates fluvial morphology in semi-arid Mediterranean basins, thereby contributing to the understanding of fluvial processes in complex morpho-structural settings.

2 Presentation of the Study Area

The studied area, mainly located in the middle section of the basin, exhibits an altitudinal gradient ranging from 700 to 400 meters northward, with gentler slopes characterizing the Meknès Plateau. This topographic configuration, combined with the geological history of the region, reflects the basin's evolution from an ancient lacustrine environment to the present-day fluvial transition zone. The Aïn Taoujdate flexure, a major tectonic structure-oriented WNW–ESE, plays a decisive role in the morpho-structural organization of the region. It corresponds to a syn-sedimentary crustal flexure that has been active since the Miocene and continues to influence local tectonic dynamics. This structure marks a clear boundary between the Meknès Plateau to the west and the Saïs Plain to the east, controlling valley alignment and the general orientation of the drainage network. The flexure also acts as a sediment redistribution node, promoting the accumulation of alluvial deposits in sheltered areas while enhancing fluvial incision in sectors most exposed to tectonic forcing.

Thus, the Aïn Taoujdate flexure cannot be considered merely as a structural feature; it directly influences channel morphology, the spatial distribution of Quaternary and Plio-Quaternary sedimentary deposits, and governs the hydrological and sedimentary dynamics of the Oued Mikkès. This complex interaction between active tectonics and fluvial morphology makes the basin a particularly suitable site for investigating fluvial systems within complex semi-arid morpho-structural contexts (Fig. 1).

In general, the Saïs Plain, near Fez, is tectonically downthrown relative to the Meknès Plateau, which reaches elevations of approximately 1000 meters in its southern part. In contrast, the Saïs Plain lies at around 400 meters above sea level (Fig. 2). Overall, the region displays a northward-decreasing topography with an average slope of about 1.2%, culminating in an abrupt relief at the northern margin, where the plateau meets the Prerif Ridges along a tectonic contact [5].

Climatically, the study area is characterized by a Mediterranean climate with significant seasonal variations. This climate, ranging from semi-arid to sub-humid depending on the location, plays a key role in the hydrological and ecological dynamics of the region. Precipitation, mostly concentrated in the winter season, is irregular and ranges between 400

and 600 mm per year, while the summer period is marked by prolonged drought and high temperatures that can reach up to 35°C.

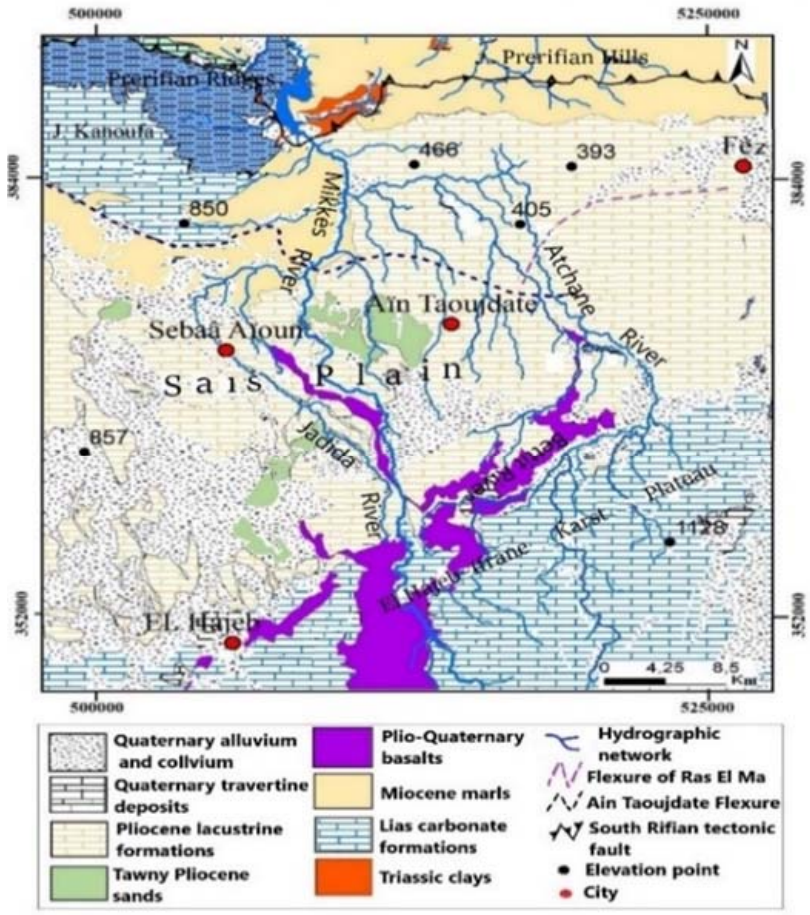

Fig. 1. Simplified geological and geomorphological sketch of the Saïs Plain (Excerpt from the Fès-Ouest geological map, scale 1:100,000)**.**

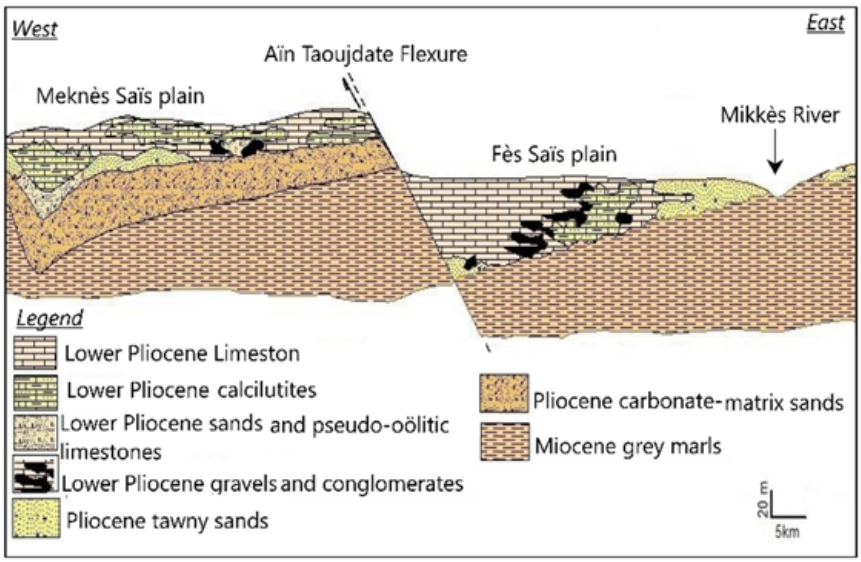

Fig.2. Schematic cross-section illustrating the position of the Mikkes Valley in relation to the Ain Taoujdate flexure and the East-West lateral facies variations in the Upper Neogene of the Saïs Basin [15].

3 Methodology and research tools

The methodology adopted in this study is based on a multidisciplinary approach combining field observations, the use of cartographic documents, satellite image analysis, and a morphometric study of river meanders.

3.1 Fieldwork

Field investigations enabled the identification of the main morphological features of the Oued Mikkès riverbed and the collection of sediment samples at several representative sites. Coarse sediment fractions were analyzed directly in the field (grain size classification, petrographic characterization, and pebble morphometry), while sand fractions were taken to the laboratory for detailed granulometric analysis. The aim is to reconstruct sediment transport dynamics in relation to the river's longitudinal profile.

3.2 Use of cartographic documents and satellite imagery

The analysis relied on various cartographic sources covering the study area include the geological map of the El Hajeb sheet at a 1:100,000 scale, the topographic maps of the Sbaa Aïoun and Bni Ammart sheets at a 1:50,000 scale, as well as satellite images from Google Earth based on missions from 2003 and 2020. These documents were processed and georeferenced using Arc GIS 10.8 software to enable the characterization of fluvial landforms, the detection of morphological discontinuities, and the monitoring of the spatial evolution of channel sinuosity.

3.3 Meander Morphometry Study

This involves the quantitative characterization and analysis of the sinuosity geometry of the riverbed by determining the main morphometric parameters [10]. (Fig. 3).

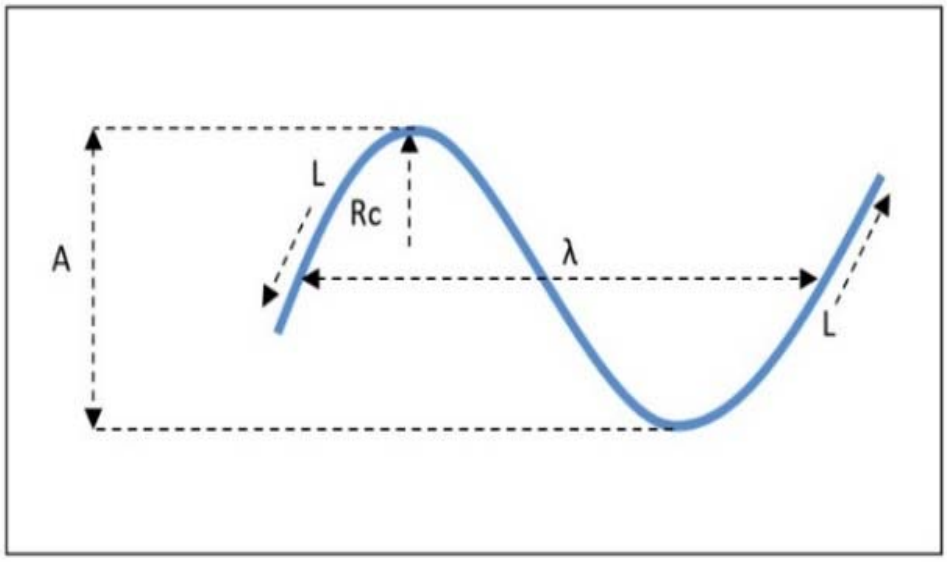

Fig.3. Main morphometric parameters of river meanders (after M. J. Selby, 1985)

λ: wavelength, A: meander amplitude, L: thalweg length between two inflection points in the same direction, Rc: radius of curvature, Is: sinuosity index (L/λ).

Meander amplitude is measured between the crests of two meander loops in opposite phases [10]. Its value is calculated by tracing the outer envelope of the meander and drawing a perpendicular line to obtain a representative average value [12]. The radius of curvature is measured by fitting a circle through the two inflection points of a complete meander loop, or by adjusting a circular arc to best match the meander shape if it is irregular. Both parameters are preferably measured in a morphologically homogeneous meander.

4 Results and Discussion

4.1 Influence of the Aïn Taoujdat flexure on the morphological characteristics of the Oued Mikkes

4.1.1 Longitudinal Profile of the River

The studied section of the Oued Mikkès, which is 58 km long, extends from the Middle Atlas plateau to the Sidi Chahed dam. It comprises two main parts : an upstream section with a moderate slope (1.47%) on the Meknes plateau, and a downstream section with a gentler slope (0.8%) in the Saïs plain (Fig.4). These two zones are separated by a steep transitional segment (23.25%) associated with the Ain Taoujdate flexure, marking a structural discontinuity that strongly influences the fluvial dynamics [9]. This break in slope and litho-structural control affects sediment transport and channel morphology, as commonly observed in fluvial systems crossing tectonic flexures [11]. The contrast in longitudinal slope and valley confinement between the Meknès plateau and the Saïs plain contributes to variability in incision, deposition patterns, and channel behavior along the course of the river [14,2].

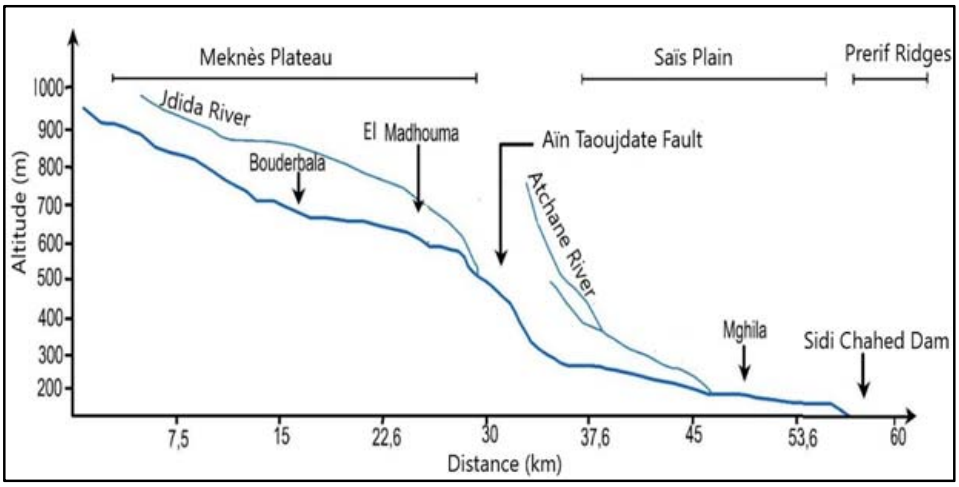

Fig. 4. Longitudinal profile of the middle section of the Mikkes River (Saïs Plain)

4.1.2 Meander Morphometry

Table.1 shows that in the Meknès Plateau, the Oued displays an average sinuosity of 1.42, indicating a sinuous channel pattern. The mean radius of curvature is 98 m, and meander amplitude ranges from 83 to 254 m, with an average of 150 m. The width of the minor channel increases downstream from the Middle Atlas to Bouderbala (12 m), then gradually decreases toward Douar Arazla (3 m), with significant variations observed in the El Madhouma area (ranging from 3 to 12 m).

Table 1. The morphometric characteristics of the Middle Mikkes

		Plateau of Meknes	Saïs Plain
Length	True length	30 km	28 km
	Straight-line distance	21km	13 km
Sinuosity		1,42	2 ,15
Longitudinal slope of the riverbed		1,47	0,8
Channel width		3	3
Wavelength		247	246
Amplitude		150	246
Radius of curvature		98	149

In the Sais plaine, the morphometric analysis shows that the downstream section of the Oued Mikkès exhibits pronounced sinuosity (average sinuosity index: 2.15), indicating a meandering pattern. The average wavelength is 246 m, the average meander amplitude is 90 m, and the mean radius of curvature reaches 149 m. The maximum channel width (58 m) is observed near the Sidi Chahed dam reservoir, where the river flows through soft marl formations.

The sinuosity of the middle course of the Oued Mikkes is mainly determined by the lithological nature of the substrate and the slope of the longitudinal profile. It results from the interplay between erosion of concave banks and sedimentation on convex banks, which promotes lateral migration of the channel. This dynamic can lead to the abandonment of meanders (oxbow lakes), locally reducing sinuosity. Downstream, in the Saïs plain near Fez, the meanders are highly unstable and frequently undergo cutoffs caused by bank erosion or flood events.

4.2 Impacts on alluvial sediment characteristics

The middle reach of the Oued Mikkès, located between the Meknès Plateau and the Saïs Plain, constitutes a key morpho-structural transition zone marked by the Aïn Taoujdate flexure. This major tectonic structure represents a clear discontinuity in the longitudinal organization of the basin and plays a fundamental role in controlling fluvial and sedimentary dynamics. Indeed, the flexure acts as a morpho-structural threshold influencing energy gradients, the river's transport capacity, and sediment deposition patterns. During flood events, characterized by high discharges and elevated specific stream power, the flexure promotes the transport of coarse materials in upstream sectors. Downstream, however, the slope break induces a progressive decrease in flow velocity, favoring the settling and accumulation of fine particles [1,14]. Such morpho-structural thresholds are widely recognized in geomorphological literature as major factors disrupting the longitudinal equilibrium of fluvial systems. They alter sediment fluxes, redistribute sediment loads, and trigger morphological adjustments in response to changing hydrodynamic conditions [11].

In the case of the Oued Mikkès, the Aïn Taoujdate flexure thus represents an energetic transition zone where the fluvial system shifts from a regime dominated by erosion and sediment transport to one characterized by sediment sorting and differential deposition. To better assess the impact of this structural discontinuity on sedimentary dynamics, sediment samples were collected from two representative sectors: the Meknès Plain, particularly in the Bouderbala area, and the Saïs Plain, immediately upstream of the Sidi Chahed Dam. These two areas, located on either side of the flexure, provide an appropriate framework for analyzing variations in sediment grain size, petrographic composition, and morphometric characteristics, as well as for evaluating the combined influence of tectonic, hydrodynamic,

and anthropogenic factors. From a granulometric perspective, pebbles collected in the Bouderbala sector are characterized by larger dimensions, with a median diameter of 50 mm and a maximum diameter reaching 90 mm, reflecting the high transport competence of the river in this reach. In contrast, pebbles from the Saïs Plain display a median diameter not exceeding 40.5 mm, indicating a progressive downstream fining of materials. This granulometric trend reflects longitudinal sediment sorting largely controlled by the Aïn Taoujdate flexure, which slows down flow velocity, reduces transport capacity, and promotes the deposition of coarser elements immediately upstream, while only finer materials are transported beyond this threshold [2]. Petrographic analysis of the pebbles further confirms this process of sedimentary selection. In both study areas, carbonate rocks are dominant, accounting for between 45% and 62% of the material, reflecting the widespread carbonate outcrops in the upstream basin of the Oued Mikkès, particularly within the Middle Atlas reliefs [9,7]. However, a clear differentiation emerges between the two sectors. The Saïs Plain is characterized by a higher proportion of sandstones and a relative decrease in dolomites and limestones. This petrographic evolution suggests selective sediment transport, whereby the most resistant lithologies or those best adapted to local hydrodynamic conditions are preferentially preserved. It also reflects progressive energy dissipation across the flexure, leading to lithological sorting associated with decreasing stream competence [3].

These lithological and granulometric differences are directly reflected in the morphometric characteristics of the pebbles. In the Bouderbala sector, pebbles exhibit a high degree of rounding, with a median roundness index of 615, as well as pronounced flattening, indicated by a flatness index of 2.3. These values reflect prolonged and energetic transport involving repeated processes of collision, abrasion, and rolling from source areas located in the highlands of the Middle Atlas [8]. Conversely, pebbles from the Saïs Plain show lower morphometric indices, with a median roundness of 579 and a flatness index of 1.9. These characteristics indicate shorter transport distances or reduced hydrodynamic energy, consistent with sedimentation under calmer flow conditions following energy loss at the Aïn Taoujdate flexure (Fig. 5). Grain-size analysis of the sandy fraction further reinforces the contrast between the two sectors. At Bouderbala, sediment texture is dominated by coarse elements, comprising 48% gravel, 36% sand, and only 15% fines, reflecting a high-energy depositional environment. The median sand diameter reaches 0.5 mm, confirming the high transport competence of the fluvial system in this reach. In contrast, the Saïs Plain exhibits a much finer sediment texture, dominated by silt and clay, which account for approximately 59% of the total sediment, with a median diameter of 0.25 mm (Fig. 6). This accumulation of fine particles is directly related to flow deceleration, further enhanced by the proximity of the Sidi Chahed Dam, which acts as a sediment trap and amplifies settling processes.

Overall, this study highlights the decisive role of the Aïn Taoujdate flexure as a morpho-structural control on sedimentary dynamics within the Oued Mikkès system. By modifying hydrodynamic conditions and energy gradients, this structure imposes a longitudinally contrasted organization of sediment deposits, ranging from upstream sectors dominated by coarse sediment transport to downstream zones characterized by fine sediment accumulation. These findings underscore the importance of integrating tectonic and morpho-structural constraints into any integrated river and hydraulic infrastructure management approach, particularly in semi-arid Mediterranean environments subject to high hydrological variability.

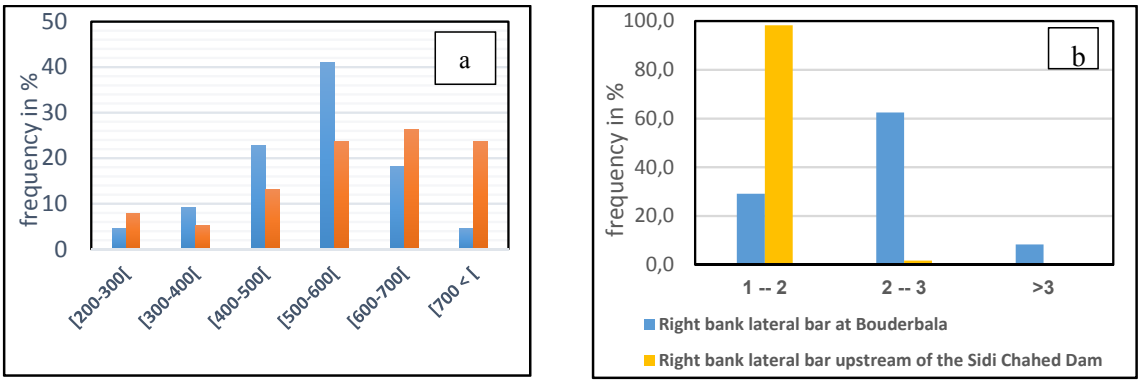

Fig.5. Rounding and flatness indices of pebbles from the low-flow channel of the Middle Mikkes a) Rounding indices, b) Flatness index

In summary, the Meknès plain corresponds to a high-energy fluvial environment, characterized by coarse sediments and active transport. Downstream, the Saïs plain forms a low-energy depositional zone favorable to the accumulation of fine particles. The Aïn Taoujdate flexure plays a major morphodynamic role by marking the structural and hydraulic transition between these two geomorphological units, thus illustrating the interaction between structural control, hydro-sedimentary dynamics, and fluvial morphology.

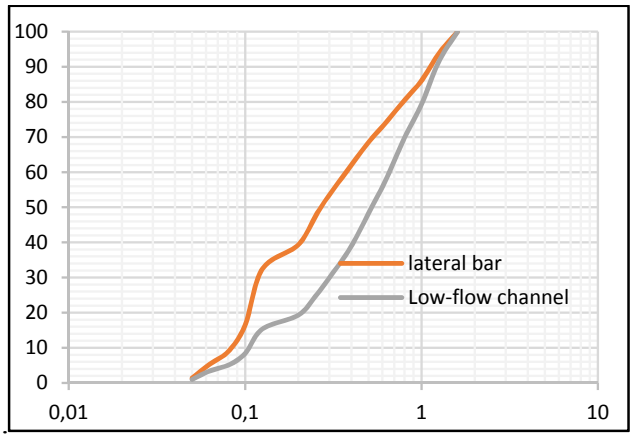

Fig.6. Cumulative curves of the grain size classes of sands from the low-flow channel and lateral bar of the middle reach of the Oued Mikkes.

5 Conclusion

The morpho-sedimentary analysis of the middle course of the Oued Mikkès based on its longitudinal profile, meander sinuosity, and the grain size of its alluvial deposits reveals the major influence of the Aïn Taoujdate flexure on fluvial dynamics. This tectonic discontinuity, located between the Meknès plateau and the Fès-Saïs plain, acts as a morpho-structural threshold that controls channel slope, sediment deposition, and meander morphology. Upstream, on the Meknès plateau, the riverbed displays a moderate slope, weakly developed meanders, and the transport of coarse material, characteristic of a high-energy environment. Downstream, in the Saïs plain, the slope decreases, sinuosity increases, and deposits become finer and more varied, reflecting a slowdown in flow and more favorable conditions for sedimentation. The Aïn Taoujdate flexure thus emerges as a key factor in the spatial organization of the Mikkes fluvial system. It regulates erosion, transport, and deposition processes, and illustrates the interaction between tectonic constraints and hydro-sedimentary dynamics in shaping fluvial landscapes.

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