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Research Article

Morphometric and spatial analysis of incised river channels in the southern Caspian Sea coastal plain (Mazandaran, Iran)

Reza Esmaili *

Department of Geography, Faculty of Humanities and Social Sciences, University of Mazandaran, Babolsar, Iran

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Abstract

River incision, which refers to the vertical lowering of the riverbed, plays a significant role in adjusting river channels. This process is driven by a range of factors, including tectonic activity, climatic variations, sea level changes, hydrological dynamics, and anthropogenic influences. This study investigates the spatial pattern and morphometric characteristics of incised river channels on the southern Caspian Sea coastal plain, focusing on Mazandaran Province, Iran. Using ALOS PALSAR digital elevation model (DEM), Google Earth imagery, field survey, and GIS-based morphometric analysis, 160 cross-sections across 17 rivers were assessed. The analysis applied non-parametric statistical tests and spatial autocorrelation methods to examine incision depth patterns and their relationships with geomorphic units, tectonic structures, and sea-level changes. Results reveal a mean incision depth of 4.7 meters, with significantly deeper incisions in alluvial fans than to coastal plains. Incision depth decreases downstream, showing a strong inverse correlation with elevation. Also, no significant differences were observed in the average incision depth among the different rivers. Except for the Caspian Fault, proximity to faults had no significant impact on incision depth. Moran's *I* statistics indicate that the incised river channels exhibit a strong clustering pattern. The findings highlight the dominant role of Caspian Sea base-level fluctuations during the late Holocene in shaping incision patterns, while tectonic factors appear more influential near mountain fronts. These insights are critical for geomorphological understanding, river management, flood mitigation, restoration efforts, and regional planning in this dynamic region.

Keywords: Caspian Sea, Coastal plain, Incised river, Mazandaran

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* Corresponding author E-mail address: r.esmaili@umz.ac.ir

Introduction

River incision is the process of vertically cutting into the riverbed. This process plays a crucial role in adjusting the river's vertical dynamics and substantially influences the evolution of the river's geomorphological landscapes. Numerous studies on river incision indicate that various factors, including tectonics (Lavé and Avouac, 2001; Whittaker et al, 2007; Hu et al, 2016; Zhang et al, 2018; Wu et al, 2020; Ma et al, 2023), climate (Wobus et al, 2010; Dey et al, 2016; Malatesta et al, 2018; Lu et al, 2020; Wang et al, 2024), sea level fluctuations (Blum and Aslan, 2006; Bowman et al, 2010; Vital et al, 2010), hydrology (Wyżga et al, 2016; Binh et al, 2021; Hosseinzadeh et al, 2025), and anthropogenic activities (Pollock et al, 2007; Martín-Vide et al, 2010; Esmaili et al, 2013; Huang et al, 2014; Aringoli et al, 2015), contribute to this process. Tectonic forces significantly influence river incision through uplift and subsidence processes. In tectonically active regions, uplift increases river gradients, enhancing the river's erosive power and leading to deeper incision. Climatic factors, especially changes in precipitation and temperature, affect river discharge and sediment load and can influence the river incision (Hosseinzadeh and Esmaili, 2014). Tectonic movements and climate operate as independent forcing factors, and their interaction can result in either opposing or, at the very least, complex impacts on river morphology (Wang et al, 2024). Sea-level fluctuations significantly impact river incision by modifying the base level. The base level is an external controlling factor for river systems, whether for rivers flowing into oceans and seas or at a local scale, such as a lake or a larger river (Faulkner et al, 2016). During periods of sea-level fall, rivers experience an increased gradient, which enhances their erosive capacity and promotes incision.

However, incision can occur through two main mechanisms: downstream progression and upstream progression. Downstream degradation, often caused by climatic factors, typically involves a decrease in the bed material load or an increase in water discharge. In contrast, upstream degradation, usually of tectonic origin, is generally the result of a fall in base level (Fryirs and Brierley, 2012; Ma et al, 2023). Human impacts, such as dam construction, river channelization, sediment extraction, land-use changes, and others, significantly contribute to the above mechanisms in river incision processes. While there are many causes of river channel incision, the morphological effects and hazards associated with incised channels tend to be similar across various physiographic environments (Simon and Rinaldi, 2006). Floodplains along rivers play a crucial role in dispersing the energy of flood flows. In incised rivers, where the riverbed is deep and the banks are high, flood flows with varying return periods become concentrated within the channel. This concentration increases the stream power, which can result in undercutting and erosion of the riverbanks (Brierley and Fryirs, 2005). However, concentrating the flow within the channel can be an advantage in reducing flood risk by preventing water from spreading to surrounding areas. Lowering of groundwater levels, structural damage, ecological degradation, and reduced floodplain function are among the problems that occur in incised river channels (Hosseinzadeh et al, 2025). Given the various drivers that can influence the formation and modification of incised channels, any disturbance caused by natural or anthropogenic causes, whether rapid or very slow over a long time, can cause instability of this type of river (Simon and Rinaldi, 2006). Therefore, understanding the processes affecting incised rivers is essential for river restoration and rehabilitation planning, construction of infrastructure, and river management. The southern coastal plains are located between the Alborz Mountains and the Caspian Sea. Therefore, they have been affected by the tectonic uplift of the Alborz Mountains (Djamour et al, 2010; Ballato et al, 2015; Rashidi et al, 2023) and Caspian Sea level changes (Lahijani et al, 2009; Kakroodi et al, 2012). Additionally, abundant rainfall, permanent and steep rivers, and widespread settlement of urban and rural areas can potentially be effective in river incision. Paluska and Degens (1992) have mentioned the cause of river channel incision in the southern plains of the Caspian Sea due to the strength of river floods, i.e., the hydrological factor. Additional studies conducted on the rivers incision in the Caspian plain in the Sefidrud Delta (Yamani and Kamrani, 2010), the Neka

River in Mazandaran Province (Emadodin, 2014), and the southwestern rivers of the Caspian Sea in Gilan Province (Hajikarimi et al, 2021) revealed that the tectonic factor was dominant in the upstream areas of the plain and near the mountain front, and in the downstream areas of the river, fluctuations in the Caspian Sea water level played a more significant role. The rivers of the southern Caspian Sea plain are often incised, making the study of river channel incision in this region particularly significant due to its distinctive environmental, geomorphological, and socio-economic challenges. Hence, this research focused on performing a spatial and statistical analysis of the incised rivers in the area.

Study Area

The Arabian-Eurasian plate collision zone is considered part of the Alpine-Himalayan orogenic belt. The initial collision between the Eurasian and Arabian plates began in the late Eocene (Ballato et al, 2015) and intensified during the Miocene (Allen et al, 2004). Intraplate regions, such as the Alborz-Talesh range and subzones of the Iranian Plateau, gradually experienced structural deformation. This process ultimately led to the subduction of the South Caspian Basin plate beneath the Eurasian plate along the Aspheron sill (Rashidi et al, 2023). The southern Caspian coastal plain is located between the Alborz and Talesh mountain ranges and the Caspian Sea. This study focuses on a region of this plain located in Mazandaran province (between the Caspian Sea and the Alborz Mountains, Fig. 1). The length of the Mazandaran Plain is 300 km, its width varies from 1 to 45 km, and its area is 4800 km^2. The Mazandaran Plain is located in the Caspian-Alborz tectonic zone. During the Quaternary period, the Caspian Sea level experienced significant fluctuations, characterized by repeated transgressions and regressions that resulted in the deposition of diverse marine, terrestrial (rivers), and transitional (e.g., deltas, lagoons) sediments (Esmaili, 2025). Alluvial and fluvial sediments primarily cover the upper sections of the plain, while the middle and lower sections consist of a combination of marine, wetland, and coastal deposits. There are several faults in the region, the most important of which is the Khazar Fault. The Fault is a 600 km long thrust fault that separates the Alborz margin from the southern Caspian coastal plain (Nazari et al, 2021). The Alborz Mountains are the source of many rivers that cross the coastal plain and flow into the Caspian Sea. The most important of these rivers include the Haraz, Tajan, Talar, Babol Rood, and Neka Rood, each with a basin area of less than 5,000 Km^2. The Alborz Mountain range includes several peaks between 3,500 and 4,000 meters, with Damavand Peak being the highest at 5,610 meters. In contrast, the Caspian Sea coastline, at -27 meters above sea level, is the lowest elevation in the region. The significant elevation difference between the Alborz Mountains and the Caspian Sea's base level has resulted in a steep longitudinal profile and powerful flood flows. The coastal plain of Mazandaran receives an average annual precipitation of 980 mm, which decreases from west to east (Mazandaran Meteorology General Office). In mountainous regions, precipitation progressively decreases towards the south, reaching an average of 300 mm.

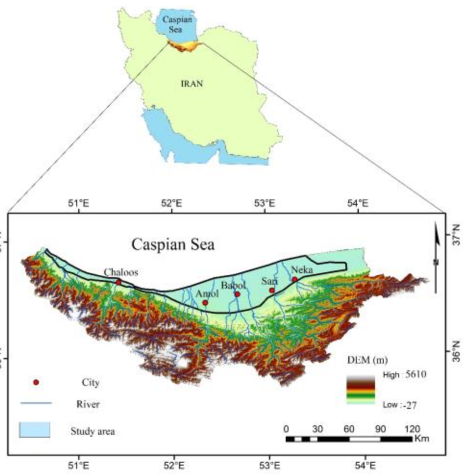

Fig. 1: Location of the study area, Mazandaran coastal plain

Materials and Methods

In the present study, rivers of the southern Caspian Sea plain (Mazandaran Province) were evaluated for incision analysis. The river channels were mapped using Google Earth and the ALOS (Advanced Land Observing Satellite) PALSAR (Phased Array Type L-band Synthetic Aperture Radar) digital elevation model, which has a resolution of 12.5 meters. A total of 160 cross-sections from 17 rivers were drawn in HEC-RAS and Arc GIS software. River cross sections were randomly extracted at regular intervals of 1 to 3 km and were located as far away from urban areas as possible. The cross-sections were verified at several points along the river channel with field mapping and terrestrial mapping. The location of these cross-sections was identified as point data on the map. The normality of the data distribution was initially assessed, and based on this, non-parametric statistical tests were used to examine the differences in variables. The cross-sections were separated according to their location in the two prominent landforms of alluvial fan and coastal plain (Fig. 2), and were tested and compared using the Mann-Whitney test. The Kruskal-Wallis test was used to compare incised channels among different rivers. The relationship between river incision from upstream to downstream was assessed with Spearman's correlation coefficient. In certain rivers, statistical analyses could not be conducted due to an insufficient number of cross-sections (fewer than 5). This limitation has led to discrepancies in the total section count. To analyze how faults influence river incision, fault layers were derived from geological maps of the region at a 1:100,000 scale, provided by the Geological Survey of Iran (Fig. 3). A 500-meter buffer was then created on both sides of each fault line. Consequently, the incision data were divided into two groups: points located within the fault buffer and points outside the fault buffer. These two sets of values were compared using the Mann-Whitney test. Spatial autocorrelation quantifies the similarity between neighboring features and is a key concept in geographical studies (Kondo, 2016). Global spatial autocorrelation methods evaluate the features' pattern as clustered, random, or dispersed (Prasannakumar et al, 2011). Moran's *I* statistic is a widely recognized measure of global spatial autocorrelation. Higher Z-scores and lower P-values in Moran's *I* index signify stronger spatial correlations and highlight the presence of spatial clustering. This method was applied to analyze the spatial distribution of incised channels within the area. Finally, geostatistical and point interpolation techniques were utilized to map the spatial distribution of incised channels.

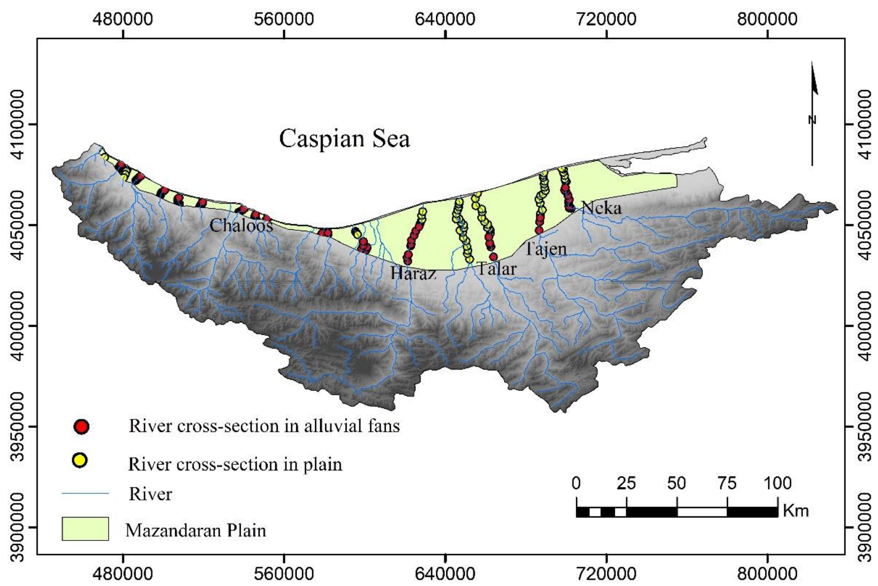

Fig. 2: Locations of river cross-sections classified into alluvial fan and plain within the study area

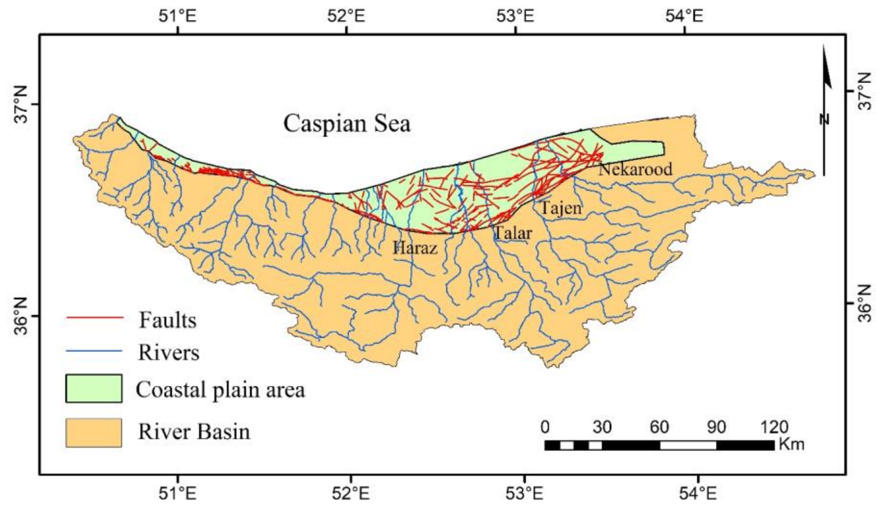

Fig. 3: Fault distribution map in the study area

Results and Discussion

Results

The normality of data distribution was tested both for the total dataset and each river individually. For the total dataset, consisting of over 50 samples, the Kolmogorov-Smirnov method was used, yielding a significance value of 0 (Sig: 0), which confirmed that the data did not have a normal distribution. For rivers with fewer than 50 samples, the Shapiro-Wilk method was applied (Table 1). These findings revealed that the incision values of several rivers deviated from a normal distribution, requiring non-parametric tests for statistical analysis. The mean depth of the incised river channels was calculated from the total cross-sections of the sample to be 4.7 meters, with the minimum and maximum values being 1 and 8.7 meters, respectively (Fig. 4).

To compare the incision values in the alluvial fans and coastal plain, the hypotheses H_0 and H_1 were expressed as follows:

H_0: The depth of river incision in alluvial fans and coastal plains is not different ($H_0: \mu_1 = \mu_2$).

H_1: The depth of river incision in alluvial fans and coastal plains is different ($H_1: \mu_1 \neq \mu_2$).

The average depth of river incision was calculated as 5.1 meters for Alluvial Fan Rivers and 4.1 meters for coastal plain rivers. Mann-Whitney test was performed for this hypothesis, and the value of Sig: 0 was obtained, which indicates rejection of the null hypothesis. This result indicates a significant difference in river incision depths between the alluvial fan and the coastal plain.

Table 1: Normality test for the incision depth variable in the study area.

ivers	**Statistic**	**df**	**Sig**
Neka	.849	17	.011
Tajen	.886	17	.040
Talar	.945	17	.376*
Babol	.937	16	.315*
Haraz	.931	14	.319*
Chaloos	.922	7	.482*
Galandrood	.883	5	.325*
Kheyr rood	.902	5	.421*
Tilrood	.769	7	.020
Kazemrood	.640	6	.001
Azadrood	.701	6	.006
Shirrood	.915	7	.429*
Cheshmeh	.883	5	.325*
Chalakrood	.818	7	.062*
Alluvial Fans	0.23	85	.00
Coastal plain	0.204	63	.00

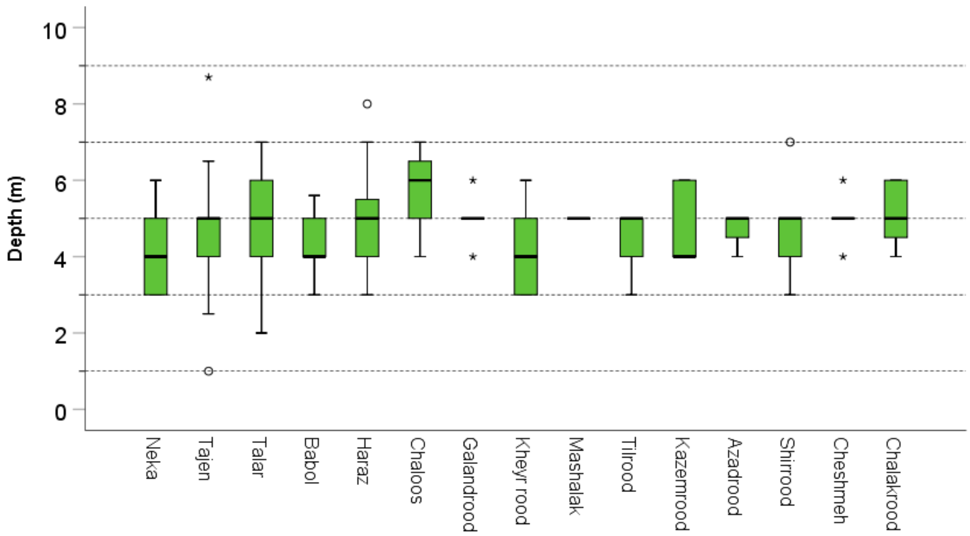

Fig. 4: Box plot of channel incision depth in the Mazandaran Plain Rivers

To evaluate the differences in channel incision depths across various rivers, the following hypothesis was proposed:

H_0: The mean incision depth is similar in the rivers studied.

H_1: The mean incision depth varies among the rivers studied (at least one case is different from the others).

The hypothesis was tested using the Kruskal-Wallis method, which yielded a significance value (Sig) of 0.176. Given that the p-value is above 0.05, there is no evidence to reject the null hypothesis, implying that incision depths among the rivers are not significantly different.

Assuming that incision depths are greater at upstream cross-sections and decrease downstream, the cross-sections were ranked accordingly. Spearman's correlation coefficient was applied to examine the relationship between incision depths from upstream (foothills) to downstream (coastline). The results indicated a significant inverse correlation for most rivers (Table 2), highlighting a decrease in incision depth along the downstream direction.

The following hypothesis was proposed to analyze the impact of faults on river incision:

H_0: There is no difference in the mean of river incision between areas located near faults and those farther away ($H_0: \mu_1 = \mu_2$).

H_1: The mean of river incision varies between areas located near faults and those farther away ($H_1: \mu_1 \neq \mu_2$).

The average incision depth in areas near faults was calculated to be 4.86 m and in non-fault areas to be 4.68 m. Based on the Mann-Whitney U test, the value of Sig: 0.323 was obtained, which is greater than the significance level of 0.05 and indicates that the null hypothesis is not rejected. Thus, there is no significant difference in the incision depth in these two areas.

Table 2: Spearman correlation coefficients for the relationship of river erosion depth from upstream to downstream

Rivers	**Neka**	**Tajen**	**Talar**	**Babol**	**Haraz**	**Galandrood**	**Keyrrood**	**Chalos**	**Tilrood**	**Kazemrood**	**Azadrood**	**Shirood**	**CheshmehKyleh**	**Chalakrood**
Spearman Correlation	-0.85	-0.83	-0.46	-0.16	-0.79	-0.22	-.097	-0.9	-0.78	-0.83	-0.7	-0.92	-0.22	-0.77

The z-score value of the Moran *I* statistic for the incision depth data was calculated as 5.9 with a p-value of 0, which indicates that the distribution of the river incision pattern in the region is not random and has a strong cluster pattern (Fig. 5).

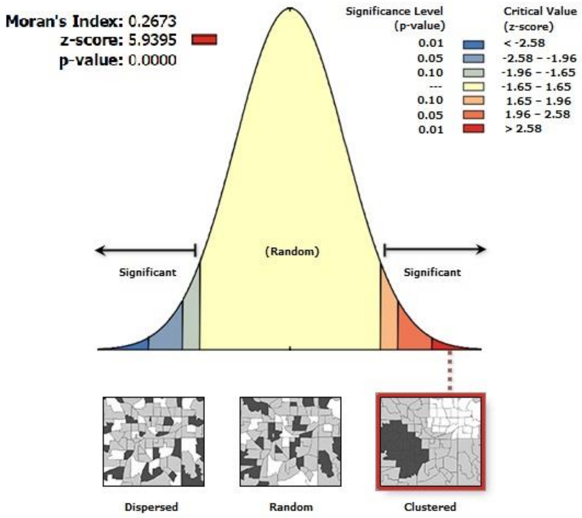

Fig. 5: Diagram of the global Moran *I* index for river incision depth in the study area.

The map illustrating incision depth reveals that values exceeding 6 meters are observed in the Tajan, Talar, and Haraz alluvial fans located in eastern Mazandaran (Fig. 6). Incision depths ranging from 4 to 5 meters dominate the central regions of the eastern Mazandaran plain, while depths between 4 and 6 meters are characteristic of the western portion of the Mazandaran plain (Fig. 7). In the downstream areas of the eastern Mazandaran plain, incision depths decrease to less than 4 meters.

Discussion

The effects of base level changes on river systems are complex. At least ten variables play a role in them, divided into three groups: base level controls, geological factors, and geomorphological controls (Schumm, 1993). Based on these characteristics and their combination, rivers are modified by erosion, deposition, river planform changes, and channel widening and narrowing. The slope of the continental shelf is also an effective factor in these changes. The slope of the coastal plain in eastern Mazandaran is less than the slope of the shelf, so in such a case, the river performs bed incision to reach a state of equilibrium. In the western Mazandaran plain, due to the extension of alluvial fans to the sea, the slope of the plain is high and is almost similar to the slope of the shelf; in such, a case, the river expands downstream but, no significant incision or deposition occurs during the period of sea level fall (Shcumm, 1993; Blum and Törnqvist, 2000). Therefore, changes in sea level cannot be simply interpreted as incision following a fall and deposition following a rise. In the case of the plains leading to the Caspian Sea, this complexity is further increased due to large, rapid, and frequent sea-level fluctuations.

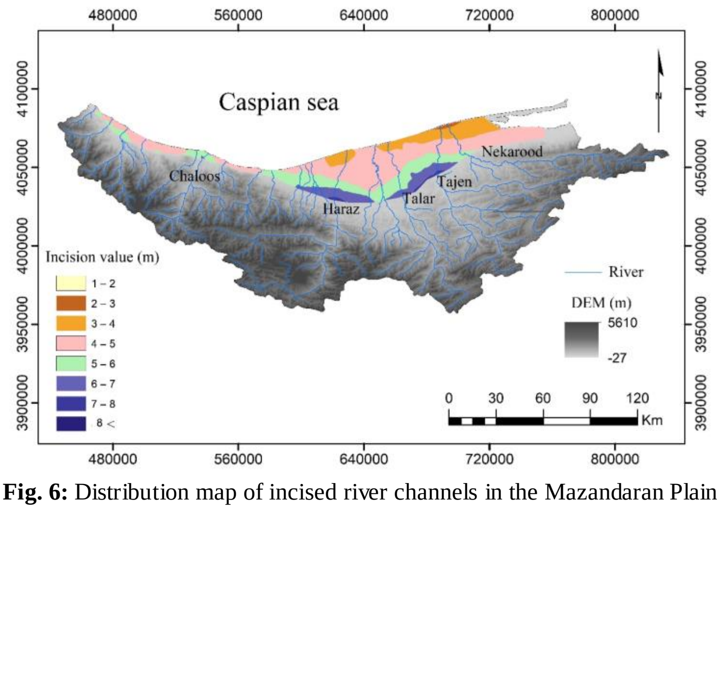

Fig. 6: Distribution map of incised river channels in the Mazandaran Plain

The Caspian Sea level experienced significant fluctuations during the late Quaternary, ranging from +50 meters during the early Khvalynian highstand to -113 meters during the Mangyshlak lowstand (12-8 ka) (Koriche et al, 2022; Kakroodi et al, 2012). After the Mangyshlak regression, the sea level rose and fluctuated between -32 and -18 meters during the Holocene (Rychagov, 1997; Lahijani et al, 2009). Coastal landforms and associated deposits above 0 meters ASL are classified as Early Khvalynian, while those between 0 and -17 meters fall under Late Khvalynian (Dolukhanov et al, 2010). Several alluvial fans extend west of the Mazandaran Plain near the current coastline. The Haraz alluvial fan, which is the largest alluvial fan in the Mazandaran Plain, extends to a height of -10 meters. This suggests that the river deposition was dominant after the Khvalynian transgression and during the Holocene. Therefore, the depth of the incised channels does not perfectly align with the contour lines. The Caspian Sea level has experienced a maximum range of changes exceeding 15 meters over the past 2,200 years. The highest recorded level was -22 meters around 50 BC and AD (during the mid-Parthian period), while the lowest level reached -40 meters by the mid-Sasanian period (around 600 AD) (Leroy et al, 2022). In the eastern sections of the Mazandaran Plain, the distance between these two levels changed by 5 to 8 Km, whereas in the western part of the plain, the change was between 1 and 3 km. During the Little Ice Age (LIA), from 1350 to 1850, the Caspian Sea level varied between -21 and -28 meters above sea level (Naderi Beni et al, 2013).

Fig. 7: Incised river channels in the study area: a: Lavij Rood alluvial fan; b: Mashlak river (Nowshar), c: middle part of the plain (Babol Rood); and d: downstream of the plain (Tajen river).

The study results indicate that the depth of the incised channels, both near and far from the faults, does not show a significant difference. The faults in the plain area are mainly hidden and have been identified by geophysical measurements, so no clear knickpoint indicating the effect of the fault on the local bedrock has been observed. In contrast, the situation is different for the Khazar fault, which is the most significant active fault in the region and lies at the border of two tectonic plates. According to research, the minimum uplift rate of the Khazar fault is estimated to be 2 mm per year (Nazari et al, 2021). Djamour et al. (2010)

reported the uplift rate of the Khazar fault to be ~6 mm/year in the western part and 2-3 mm/year in the eastern part, indicating different fault behavior in these two segments. However, no significant difference in the depth of the river incision channels was observed in the eastern and western parts of the Mazandaran Plain. The uplift of river terraces and asymmetric terraces is among the effects of this fault on the border between the mountains and the plain. Using dating techniques for river terraces can effectively aid in reconstructing the Quaternary environment of this plain. Although the plain area is subsiding relative to the Alborz Mountains, no evidence of tilting of sedimentary layers has been observed in the plain area. In summary, it can be stated that the incised channels in the upstream areas of the plain, particularly in the alluvial fans, resulted from a combination of Khazar fault activity and Caspian Sea level fluctuations. In the middle and lower sections of the plain, the incision was influenced primarily by changes in the Caspian Sea level in the late Holocene. The results of this study are consistent with similar studies of rivers in the southwest region of the Caspian Sea in Gilan Province (Yamani and Kamrani, 2010; Hajikarimi et al, 2021) and the Neka River in eastern Mazandaran (Emadodin, 2014). In addition, the Gorganrood River, which flows in an east-west direction in Golestan Province and enters the Caspian Sea, has also been incised, which is far from the Khazar fault and parallel to it, which highlights the role of changes in the base level of the Caspian Sea in the incised of this river. The average incised depth of the river channel in the study area was calculated to be 4.7 m, which is similar to the measurements of Emadodin (2014) of 4-5 m and Hajikarimi et al. (2021) of approximately 5 m. However, in some river sections, land surveys reveal depths exceeding 10 meters, potentially due to human interventions (gravel mining), riverbank characteristics (fine-grained, cohesive sediments and dense vegetation), or errors in the digital elevation model.

Conclusion

Incised river channels are a common feature in the fluvial geomorphology of the southern Caspian Sea plains. The spatial analysis of these rivers based on their morphometry was investigated in the present study. The findings indicated that, on the whole, the incision depth exhibits minimal variation across the entirety of the plain's surface. Also, the incision of different rivers is similar and has a strong clustering pattern. However, the amount of incision in alluvial fans and coastal plains has differed significantly, and this relationship shows a high correlation from upstream to downstream. Overall, it seems that changes in the base level of the Caspian Sea, especially in the late Holocene, have played a more important role in the formation of these incised river channels, and tectonic factors have played a role mainly in the vicinity of the Khazar fault. However, the role of human intervention in the river channels of the region, which has caused incision and aggradation, is undeniable and requires further studies. Given the morphological similarity of incised channels in the region, there is a need to develop regional protocols for flood management, determining river and floodplain boundaries, restoration programs, and determining exploitation criteria, etc., to ensure optimal management of these rivers and maintain integrity in planning and implementation.

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