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Comparing the Impact of Climate on Tectonic and Seismic Controls of Sediment Yield: Cold-Humid vs. Hot-Dry Regions of Iran

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ABSTRACT

Aims: Over the past decades, extensive research has been conducted on basin-scale erosion evaluation models. A persistent challenge in this field is the significant discrepancy between model-estimated sediment yield (SY; t.km^{-2}.y^{-1}) and observed values at hydrometric stations. While various factors have been explored, the role of tectonic activity in controlling SY has received limited attention despite evidence highlighting its substantial influence. However, to date, no study has systematically examined how climatic conditions modulate the relationship between tectonic activity and sediment yield. This study aims to investigate the impact of tectonic indices on sediment yield across contrasting climatic regimes.

Materials & Methods: The analysis was conducted across 74 fifth-order sub-basins, distributed between two distinct climatic zones: cold-humid and hot-dry. Selected tectonic indices were correlated with measured sediment yield using regression analysis to assess their interrelationships within each climatic context.

Findings: The results reveal a significant positive linear relationship between tectonic indices and sediment yield in both climatic regions. Notably, the slope of this relationship is considerably steeper in cold-humid basins, suggesting a higher sensitivity of sediment yield to tectonic activity under these conditions compared to hot-dry environments.

Conclusion: The findings demonstrate that tectonic indices account for 44.11% to 67.48% of the variability in sediment yield in cold-humid climates, in contrast to 15.23% to 33.54% in hot-dry climates. Furthermore, the overall influence of climate on sediment production reaches up to 55% in cold-humid regions and up to 25% in hot-dry regions, indicating a stronger control under humid conditions.

Keywords: Erosion-Sediment; Climate Condition; Regression Models; Sediment Yield; Tectonic Indices.

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Introduction

Soil represents a fundamental component in regional development planning. Accurate estimation of erosion rates and soil loss serves as a critical basis for agricultural and infrastructure development strategies. Such estimation may be implemented in effective erosion control measures [1, 2]. Assessing soil erosion and sediment yield, alongside identifying the factors that influence these processes, constitutes a key responsibility for experts to generate reliable soil loss estimation. Such estimates are essential to predict the investment required to mitigate the impacts of erosion and to support sustainable land management practices.

Despite a long history of applying sediment estimation models to assess soil loss and erosion in Iran [3, 4], significant discrepancies exist between models' outputs and field measurements, revealing differences exceeding 2.5 times. Similarly, application of the Erosion Potential Method (EPM) [5] has yielded estimates that are 3.0 to 3.5 times lower than actual sediment accumulation measured in reservoirs.

In some studies [4], the amount of erosion is more than 1 to 2.5 billion tons per year, and in others, the number of 549 million tons per year has been announced. This estimate was obtained from the research conducted in 73 million hectares of watersheds in the country, with a specific sedimentation of 7.5 ($t.ha^{-1}.y^{-1}$) and a specific erosion rate of 25 ($t.ha^{-1}$). In several other studies, this rate has been reported to be up to 4 billion tons. In the Soil Conservation and Watershed Management Research Institute (SCWMRI) (2007), the erosion rate of the entire country using the EPM model [5] was estimated to be 976 million tons.

These models typically consider external factors such as rainfall and weather conditions, along with the inherent physical characteristics of the basin, including topography, lithology, soil type, and vegetation. Despite these considerations, discrepancies in calculations persist for various reasons. A significant contributing factor to these inaccuracies is the extrapolation of erosion data from small sub-basins to larger spatial scales, which may not adequately capture the complexity of broader basin dynamics. Furthermore, these models fail to incorporate other effective indicators, such as indices of tectonic activity, in their methods for estimating sedimentation rates (SY) in basins, which may result in significant forecast deficiencies. [6, 7, 8, 9, 10, 11, 12].

Several studies have linked elevated sediment yields primarily to earthquake-induced mass movements [13, 14, 15, 16]. However, other research suggests that even in tectonically stable regions, minor fluctuations in seismic activity can influence sediment yield [16]. It is reported that there has been a surge in erosion rates exceeding five times the pre-earthquake baseline. This heightened sediment response gradually declined, returning to near-background levels approximately six years after the event.

In certain seismically active regions characterized by frequent seismic activity, elevated SY has been observed even in the absence of widespread landsliding, likely due to factors such as increased surface fragmentation, accelerated weathering processes, and enhanced hillslope and channel erosion [17].

Overall, literature reviews suggest that active tectonic processes, particularly those associated with seismic activity, can disturb the equilibrium between sediment production and transport mechanisms [18, 19]. Yantis [20] demonstrated that on shorter timescales, earthquake-induced alterations to river channels can result in substantial geomorphic changes. However, to date, no studies have specifically examined the influence of various tectonic-related processes, including uplift, landsliding, fracturing, rock weathering, and subsidence, on sediment yield (SY), despite their potential significance [11, 12, 21, 22].

Malamud [23] further explored the relationship between earthquake magnitude and sediment yield (SY), specifically in the context of landslides triggered by seismic activity. Some studies have attributed the influence of tectonics on SY to processes such as uplift and associated topographic changes, which can increase slope gradients and thereby enhance sediment production [24, 25].

The geomorphic and sedimentary impacts of large earthquake-induced mass movements can persist over millennial timescales [26, 27, 28]. However, even relatively moderate seismic events ($M>4.3$) are capable of triggering landslides [23], which can significantly influence SY at the basin scale. Moreover, seismic activity and the associated fracturing of geological layers can directly enhance weathering rates and increase the susceptibility of landscapes to erosion [29, 30, 31, 32, 33, 34, 35]. These investigations suggest that earthquake-triggered landslides can generate notable pulses in SY; however, the overall significance of seismic activity in influencing long-term sediment yield remains poorly constrained [11, 12, 36, 37, 38].

Recent research [11] suggests that one contributing factor to the limited accuracy of these models may be the neglect of tectonic influences on basin sedimentation, which are rarely incorporated into SY modeling frameworks.

Various mechanisms have been proposed to explain the strong correlation between seismicity and sediment yield (SY) at regional scales [11]. This effect is not the same in different climatic conditions, where the humidity and temperature, and consequently the rate of weathering, are different. The objective of this study extends beyond examining the impact of tectonic indices on SY, and also to evaluate this effect in various climates. Particular attention is given to comparing the nature of this influence in hot-dry climates, predominant in the southern and southwestern regions, vs. that in cold-humid climates found in the northwestern and western parts of the country.

To achieve this objective, tectonic indices data were collected, including peak ground acceleration (PGA, $cm.s^{-2}$), cumulative seismic moment (M_0, $N \cdot m$), based on moment magnitude (Mw), derived from seismic records spanning 30 years (1995–2022). In addition, the "active fault density" index was introduced and applied to assess the impact of tectonic features on basin sedimentation yields (SY, $t.km^{-2}.y^{-1}$). Considering the potential influence of surrounding seismic activity, seismic parameters within a 50 km radius of each basin were collected. Finally, the regression relationships between tectonic indices and sediment yield (SY) in two different climatic zones, hot-dry and cold-humid, of the selected basins were evaluated. Based on the positive findings of this study, it is hypothesized that subsequent testing of this proposition across diverse climatic conditions would yield results applicable to enhancing the precision of SY estimation models in future applications.

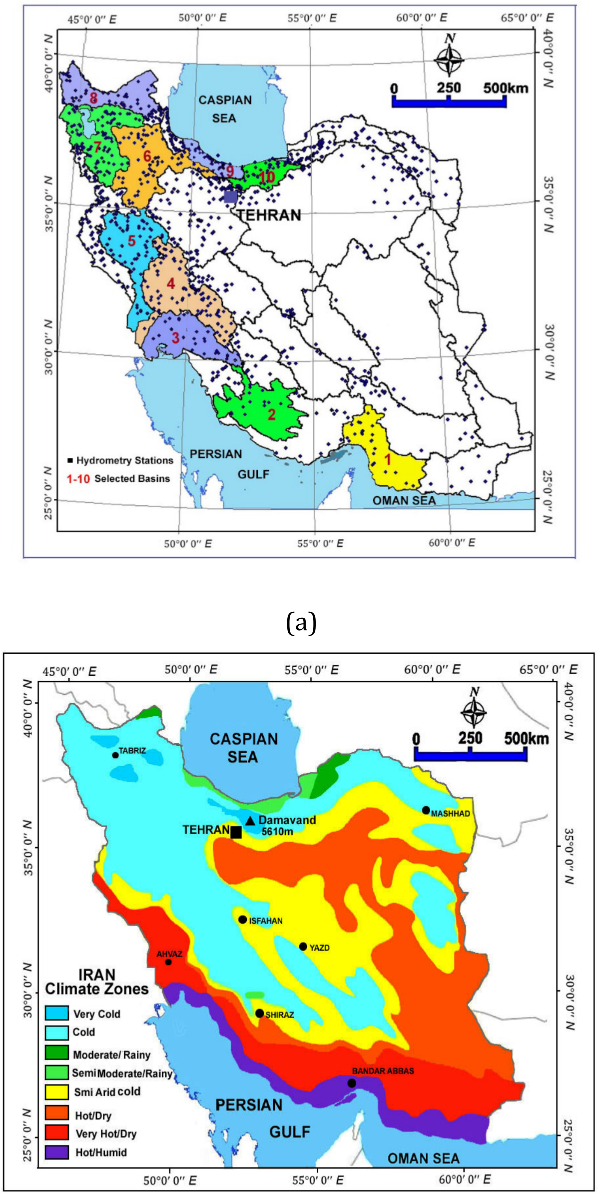
Materials & Methods

Selection of the Study Areas

Iran is divided into six major first-order watersheds, 31 second-order, and 575 fifth-order sub-basins [39] (Figure 1a). From a climatic perspective, the country comprises eight distinct climatic zones (Köppen-Geiger climate classification system) (Figure 1b), ranging from arid and semi-arid conditions in the central and eastern regions to cold-humid climates in the northwest and west. For the selection of study basins, a systematic approach was adopted to ensure that the chosen watersheds had reliable and long-term records of both runoff and sediment yield. In addition, only those basins with sufficient seismic data were selected to allow for a robust assessment of tectonic influences. These criteria ensured that the chosen basins were appropriate for examining the combined effects of climatic conditions and tectonic activity on sediment yield dynamics.

The eastern regions of Iran experience relatively strong earthquakes with significant peak ground acceleration (PGA) regularly; however, these areas are characterized by low precipitation and a scarcity of hydrological monitoring stations, resulting in limited availability of runoff and sediment data. In contrast, the western parts of the country, where more comprehensive runoff and sediment records are available, exhibit fewer occurrences of strong earthquakes. To address this spatial disparity, study areas were selected from the southern and southwestern regions with a hot-dry climate and the northern and northwestern regions with a cold-humid climate, where hydrometric and sediment measurement stations provide reliable long-term records of runoff and sediment [3, 4, 40], and where sufficient seismic data are also available. This selection strategy ensured that the basins included in the study area were suitable for analyzing the combined influence of tectonic and climatic factors on sediment yield.

Considering the objectives of this study, a total of 10 second-order watersheds, consisting of 74 fifth-order sub-basins, were selected across two major climatic zones of hot-dry and cold-humid. These basins are situated within two main geological provinces, the Zagros Fold-and-Thrust Belt in the west and southwest, and the Alborz structural zone in the north and northwest, both of which represent the country's tectonically active folded regions (Figure 2). The selection of these areas facilitates a practical assessment of how tectonic activity interacts with contrasting climatic conditions to influence sediment yield.



(a)

(b)

Figure 1) (a) Spatial distribution of the 10, second order selected basins and associated hydrometric stations: 1: Bandar Abbas, 2: Mond, 3: Zohreh, 4: Karoon, 5: Karkheh, 6: Sefidroud, 7: Urumiyeh, 8: Aras, 9: Noor, 10: Neka, (b) Climatic classification of Iran into eight major zones (Köppen-Geiger climate classification).

Geology of the Study Areas

Given the spatial distribution of the selected basins across two major tectonic provinces in Iran, the Alborz Mountain range, which extends in an east-west direction across northern Iran, and the Zagros Mountain range, which follows a northwest-southeast trend in western Iran, a brief overview of the regional geology is provided [41].

From a morphological and physiographic perspective, the Iranian Plateau lies at the heart of the Alpine-Himalayan orogenic system, a vast Cenozoic collisional belt that extends from southern Europe through Turkey, Iran, Afghanistan, Tibet, and into parts of Southeast Asia, including Myanmar and Indonesia.

Within the Iranian segment of this orogenic system, the mountainous belt is primarily composed of the Alborz and Zagros ranges as two major structural provinces. These regions are characterized by complex folding, faulting, and ongoing tectonic activity due to the northward convergence of the Arabian Plate against the Eurasian Plate. The spatial distribution of these geological provinces is illustrated in Figure 2.

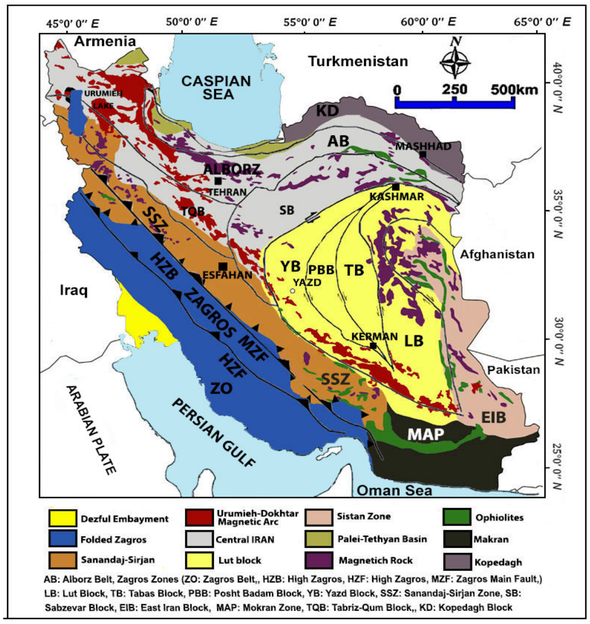


Figure 2) Simplified geological map of Iran, highlighting the major tectonic provinces, including the Alborz and Zagros Mountain Ranges.

Alborz Zone: The Alborz Zone constitutes the northern branch of the Alborz orogenic belt and forms a tectonic boundary between the southern Caspian Basin and the Iranian Plateau. It is a product of ongoing convergence along the active collision front between the Eurasian and Arabian plates. The Alborz Mountains form an extensive east-west trending mountain range in northern Iran, located immediately south of the Caspian Sea. Two distinct geological domains are recognized within the Alborz region: the northern part is bounded by the Alpine-Himalayan orogenic belt. It extends toward the Caspian depression, whereas the southern margin is defined by its contact with the Central Iranian Plateau. From a stratigraphic perspective, the pre-Paleozoic to lower Paleozoic successions in the Alborz reveal two contrasting facies; (1) shallow marine deposits characterized by evaporates, dolomite, and limestone; and (2) deep marine basin sediments, including clastic and coarse clastic deposits, flysch sequences, alkaline and sub-alkaline volcanic rocks, as well as remnants of ophiolite assemblages.

Zagros Zone: The Zagros Folded and Thrust Belt represents the southern branch of Iran's major tectonic provinces and forms a prominent topographic barrier that separates central Iran from the Mesopotamian foreland basin. This structural zone extends along the Persian Gulf coast and transitions into the Mokran accretionary prism in southeastern Iran and western Pakistan.

The geology of the Zagros Zone is characterized by two primary rock assemblages: Precambrian metamorphic basement and an overlying sedimentary cover composed primarily of Paleozoic to Cenozoic strata. Sequence stratigraphic studies indicate that this region experienced distinctive marine conditions from the pre-Cambrian through the Triassic periods.

Tectonically, the Zagros is subdivided into two main subzones, including the Zagros Thrust Zone and the Zagros Folded Zone. The latter spans approximately 10 to 65 kilometers in width and constitutes a narrow, elevated belt that includes the highest elevations within the Zagros Mountains, commonly referred to as the High Zagros. In this area, exposed rock units range in age from the late Precambrian to the Middle Triassic, reflecting a long and complex geological history shaped by both sedimentation and orogenic deformation.

Data Collection

In the selection of target basins, priority was given to those with a minimum of 500 recorded observations over 30 years for both runoff and suspended sediment load. These long-term records were essential to ensure statistical reliability and temporal consistency in analyzing sediment yield dynamics. In addition, continuous seismic data, including peak ground acceleration (PGA) and earthquake intensity (Mw), were required for the same 30-year period to enable robust assessment of tectonic influences on sediment yield. Only basins with these combined hydrological and seismic data criteria were included in the final analysis.

Runoff and Sediment of the Selected Basins

Iran maintains a national network of approximately 1300 hydrometric stations, which play a crucial role in monitoring surface water resources across the country (Figure 1). These stations collect data on river discharge (flow rate) and suspended sediment load, with measurements recorded either manually or through automated systems. However, many of these stations suffer from incomplete or discontinuous records due to various operational and logistical constraints.

To identify suitable stations for this study, an extensive review of all available data from hydrometric stations was conducted. From this dataset, 123 stations with sufficiently complete and reliable records were selected [39]. Suspended sediment load is typically measured using water sampling during flood events at regular time intervals. These data were further supplemented by filling data gaps using the rating curve method, based on research conducted by the Soil Conservation and Watershed Management Research Institute of Iran. By cross-referencing these hydrological datasets with seismic records spanning the period 1995 to 2022, a final set of 10 second-order basins, consisting of 74 5th-order sub-basins, was identified. Throughout the selection process, care was taken to ensure that downstream measurements were not significantly influenced by upstream dams or other flow regulation structures, thereby preserving the natural hydrological and sediment conditions of the basins.

Tectonic Index of the Selected Basins

Tectonic activity within a basin can induce gradual, significant changes in its physiography over time. Sudden seismic events resulting from active faults, along with associated phenomena such as fault-related fracturing, stream displacement or diversion, widespread landsliding, debris flows, and ground shaking, directly contribute to increased sediment production. The selection of appropriate tectonic indices to represent these complex processes for each basin posed one of the key challenges of this study. Tectonic indices can be derived from a range of geomorphic, seismological, and structural characteristics measured or observed within a basin, requiring careful consideration to ensure their relevance and applicability in sediment yield modeling in different climates.

In this study, three key tectonic indicators were selected to represent the influence of seismic activity on sediment yield: earthquake magnitude (expressed as moment magnitude, Mw), peak ground acceleration (PGA) for each recorded event, and the density of active faults within each basin. These parameters were chosen based on their relevance to tectonic forcing and the availability of reliable data. It is important to note, however, that seismic activity alone does not fully capture all aspects of tectonic influence on erosion and sedimentation processes within a basin. While most previous studies have relied on parameters such as PGA and earthquake intensity across various scales to characterize basin seismicity, these metrics may not comprehensively reflect the broader spectrum of tectonic effects, including long-term uplift, crustal deformation, or structural controls on landscape evolution.

Iran has been classified into various seismic zones based on multiple seismotectonic frameworks. According to one widely recognized classification [42], the country is divided into six major seismotectonic provinces: Azerbaijan, Alborz Mountains, Kopeh Dagh, Central Iran, Zagros Mountains, and Mokran (Figure 3, solid black lines). These regions are delineated based on differences in tectonic setting, crustal structure, and seismic behavior.

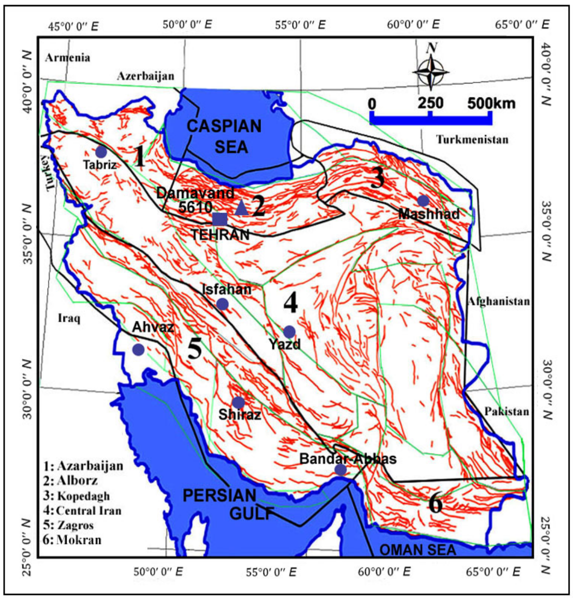


Figure 3) Simplified tectonic map of Iran, displaying the six major seismotectonic regions (outlined by solid black lines), with further subdivision into seismic sub-zones (narrow green lines). Active faults are represented in red [42].

In addition, each of the six primary seismotectonic zones is further divided into smaller seismic subzones (Represented by narrow green lines in Figure 3), reflecting spatial variations in earthquake distribution, recurrence intervals, and localized tectonic conditions. This sub-division enhances the resolution of regional seismicity patterns and facilitates a more nuanced evaluation of tectonic influences on geomorphic and sedimentary processes across different physiographic settings.

Seismic data for the study regions were compiled from multiple national and international sources. Domestic seismic networks and institutions such as the Institute of Geophysics at the University of Tehran (IRSC) [43], the International Institute of Earthquake Engineering and Seismology (IIEES) [44], the Seismological Research Center, and the Seismic Monitoring Network of the Ministry of Roads and Urban Development (BHRC) [45], provided key data sets. In addition, international databases, including the Strong Motion Database hosted by earthquake data banks, the Pacific Earthquake Engineering Research Center (PEER) [46], and the Strong Motion Database, were utilized to supplement and validate the regional seismic records.

Earthquake Magnitude (Intensity)

An earthquake's magnitude is directly related to the amount of energy released during rock rupture. The greater the amount of stored elastic strain energy in the crust at the time of failure, the higher the magnitude of the resulting earthquake. Additionally, earthquake magnitude is influenced by the mechanical strength of the involved rock mass; stronger rocks require greater stress to induce failure, and consequently release more energy upon rupture.

In some previous studies [14, 15, 17], researchers have used cumulative seismic moment (M_0) as an indicator of the integrated effect of both minor and major earthquakes on landscape weakening and erosion processes. Given the spatial nature of sediment yield (SY) and other variables analyzed in this study, it was essential to compile spatially distributed seismic data for each basin. To this end, earthquake moment magnitudes (Mw) were extracted from a 30-year dataset spanning the period of 1995 to 2022. Considering that seismic effects can extend beyond basin boundaries, seismic events occurring within a 50 km radius around each basin were included in the analysis.

Subsequently, the cumulative seismic moment (M_0) for each basin was calculated using the empirical relation proposed by Kanamori, Eq. (1) [47]:

$$\mathrm{Mw} = (\mathrm{Log}_{10}\mathrm{M}_0 - 9.1)/1.5 \qquad \text{Eq. (1)}$$

Where Mw is the earthquake moment magnitude and M_0 is the cumulative seismic moment. This approach enabled the quantification of the total seismic energy input over time, providing a robust tectonic index for assessing its influence on sediment yield across different climatic settings.

Peak Ground Acceleration (PGA) of the earthquakes

Peak ground acceleration (PGA) is closely related to earthquake magnitude, and thus, the frequency and intensity of seismic events generally show a strong correlation with major earthquakes [48]. As a result, PGA serves as a reliable indicator of overall seismic activity in a given region. While earthquake magnitude (Mw) is a derived parameter based on ground accelerations recorded by seismographs at various scales, the direct use of PGA can provide sufficient accuracy when assessing the influence of seismic activity on sediment yield (SY).

Ground acceleration plays a critical role in inducing disturbances within surface soil layers and subsurface geological formations in river basins. In this study, peak ground acceleration (PGA, expressed in $cm.s^{-2}$) was extracted for the selected period (1995–2022) from seismic databases covering the study basins. Given the spatial nature of SY data, it was necessary to assign a representative seismic acceleration value to each basin over the study period. To achieve this, cumulative PGA values recorded within a 50 km radius of each basin during the 30 years were measured. These values were then normalized relative to standard gravitational acceleration (981 $cm.s^{-2}$) to generate a dimensionless seismic acceleration score for each basin. This normalization allowed for meaningful comparisons across basins with varying seismic exposure.

Fault Density of the Basins

In addition to the two seismicity-based tectonic indices, Peak Ground Acceleration (PGA) and earthquake moment magnitude (Mw), fault density ($m.km^{-2}$) was also assessed as a third tectonic indicator in this study. To evaluate the influence of active faulting on sediment yield (SY), the most recent active fault map of Iran, provided by the Geological Survey of Iran (Figure 3), was utilized. Using GIS tools, the total length of active faults within each of the 74 fifth-order basins was measured. Fault density for each basin was then calculated by dividing the total length of active faults (m) by the corresponding basin area (km^2). This approach provided a quantitative measure of tectonic deformation intensity at the basin scale. It allowed for comparative analysis of fault-related influences on sediment production across different climatic and geological settings.

Findings

In this study, the relationships between various tectonic indices including peak ground acceleration (PGA, $cm.s^{-2}$), cumulative seismic moment (M_0, N.m) derived from moment magnitude (Mw) [11, 12], and active fault density ($m.km^{-2}$) and sediment yield (SY, $t.km^{-2}.y^{-1}$) over 30 years

(1995–2022) we investigated. Regression analyses were conducted using SPSS and Excel software to explore these relationships across two distinct climatic zones: hot-dry and cold-humid, within selected basins. The results in cold-humid are illustrated in Figures 4 through 6.

Figure 4 illustrates the relationship between peak ground acceleration (PGA) and sediment yield (SY) under cold-humid climatic conditions.

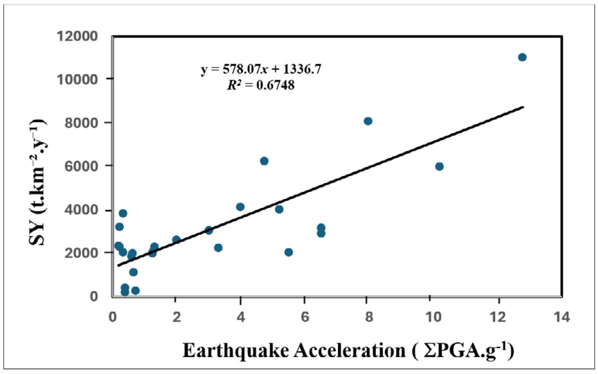


Figure 4) The relationship between peak ground acceleration (PGA) during earthquakes and sediment yield (SY) in cold-humid regions.

The best-fit linear regression model reveals a moderate to strong positive correlation, with a coefficient of determination (R^2=0.6748). This suggests that approximately 67.48% of the variability in SY can be explained by its linear association with PGA. The positive slope of the regression line indicates that as PGA increases, so does SY, underscoring the significant influence of seismic activity on sediment production in cold-humid environments.

Figure 5 presents the regression plot depicting the relationship between earthquake intensity, represented by moment magnitude (Mw), and sediment yield (SY) in the same climatic region. The fitted regression line shows a positive linear trend, with R^2 = 0.5101, implying that about 51% of the variation in SY can be attributed to earthquake magnitude. While this reflects a moderate correlation, it also highlights the potential influence of additional controlling factors such as lithology, topography, and hydrological processes on sediment generation.

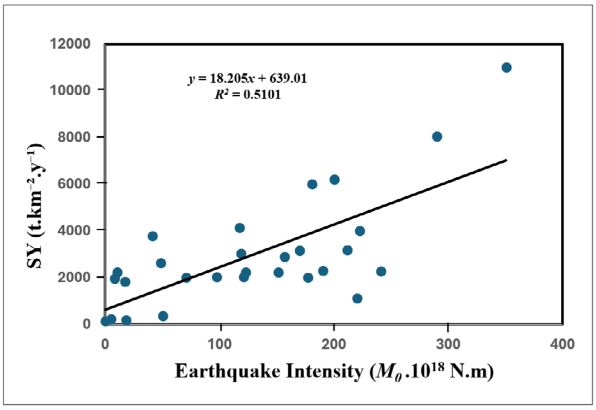


Figure 5) The relationship between earthquake intensity (M_0) and sediment yield (SY) in cold-humid regions.

Figure 6 displays the relationship between active fault density and sediment yield (SY) in cold-humid regions. A positive correlation is evident, as indicated by the upward slope of the regression line, suggesting that higher fault densities are generally associated with increased sediment yields. However, some scattered data points indicate that not all high-fault-density areas correspond uniformly with elevated SY values. The coefficient of determination (R^2 = 0.4417) indicates that around 44.17% of the variation in SY can be explained by fault density, pointing to a moderate relationship and emphasizing the role of other geomorphic and environmental controls.

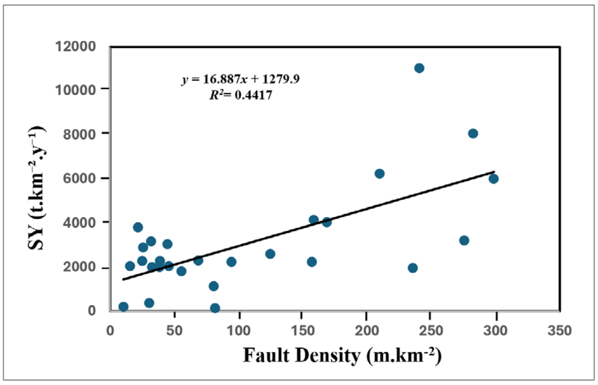


Figure 6) The relationship between fault density (m.km^{-2}) and sediment yield (SY) in cold-humid regions.

Regression analyses for the hot-dry regions are presented in Figures 7 to 9, revealing generally weaker but still statistically significant correlations compared to the cold-humid zones.

Figure 7 shows the relationship between peak ground acceleration (PGA) and sediment yield (SY) under hot-dry climatic conditions. The scatter plot suggests a moderate positive correlation, indicating that increases in PGA are associated with corresponding rises in SY. The linear regression model yields a slope of 379.89, implying that each unit increase in PGA corresponds to an average increase of 379.89 t.km^{-2}.y^{-1} in sediment yield. However, the relatively low coefficient of determination (R^2 = 0.1523) indicates that only about 15.23% of the variation in SY can be explained by PGA. This suggests that while seismic activity exerts a measurable influence on sediment mobilization in hot-dry environments, other factors such as lithological characteristics, land use patterns, or hydrological dynamics likely play more dominant roles.

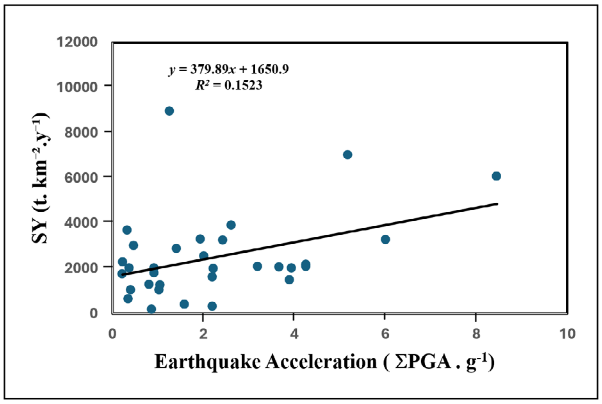


Figure 7) The relationship between earthquake acceleration (PGA) and sediment yield (SY) in hot-dry regions.

Figure 8 presents the relationship between earthquake magnitude (M_0) and sediment yield (SY) in the hot-dry climatic zone.

A positive correlation is observed, with the regression line showing a slope of 10.079. This implies that each unit increase in M_0 corresponds to an approximate increase of 10.079 t.km^{-2}.y^{-1} in SY. The R^2 value of 0.3354 indicates that roughly 33.54% of the variation in SY can be attributed to earthquake magnitude. Although this reflects moderate explanatory power, it also underscores the importance of other contributing factors such as local geomorphology, rock type, and climate variability. Nonetheless, the statistically significant relationship confirms the influence of seismic activity on sediment production even in hot-dry regions.

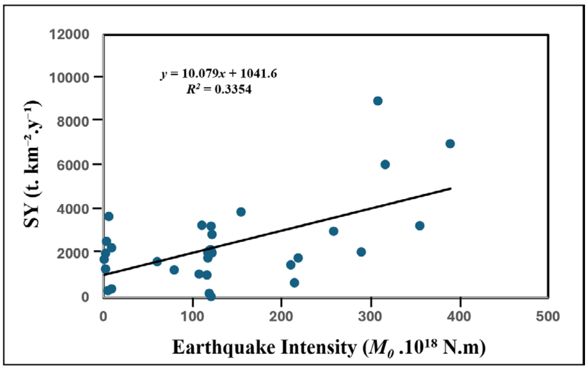


Figure 8) The relationship between earthquake intensity (M_0) and sediment yield (SY) in hot-dry regions.

Figure 9 illustrates the relationship between active fault density and sediment yield (SY) in hot-dry areas. A positive correlation is evident, with a regression slope of 14.7, indicating that a unit increase in fault density corresponds to an average rise of 14.7 t.km^{-2}.y^{-1} in SY. The coefficient of determination (R^2=0.1755) suggests that approximately 17.55% of the observed variation in SY can be attributed to fault density. While this represents a relatively modest explanatory power, the statistically significant relationship demonstrates that tectonic activity, particularly faulting, continues to exert a measurable impact on sediment production in hot-dry environments, albeit one modulated by other environmental and geological variables.

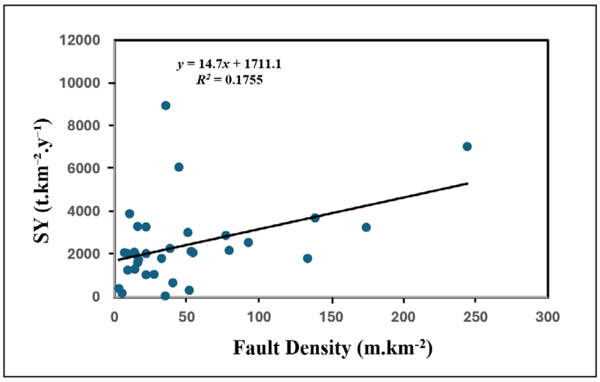


Figure 9) The relationship between fault density (m.km^{-2}) and sediment yield (SY) in hot-dry regions.

Discussion

Assessing soil erosion and sediment production, along with identifying the factors that influence these processes, has long been a main theme in erosion science, sediment dynamics, and soil conservation research. Despite decades of employing sediment estimation models to evaluate soil loss both in Iran and globally, significant discrepancies persist between modeled predictions and field-based measurements. For instance, a specific research project in Iran reported modeled estimates exceeding field observations by more than 2.5 times [3]. Furthermore, a comprehensive national study conducted by the Soil Conservation and Watershed Management Research Institute, which applied the Erosion Potential Method (EPM) [5] to estimate sedimentation rates in all major basins in the country [4], found that modeled erosion rates were 3.0 to 3.5 times higher than observed sediment yields in specific basins. Recent studies [11] suggest that one contributing factor to the limited accuracy of such models may be the omission of tectonic influences on basin sediment processes that are rarely included in conventional sedimentation modeling (SY) frameworks.

Over the past decade, various mechanisms have been proposed to explain the relationship between tectonic activity and sediment production at regional scales [11,49]. This study investigates this relationship in selected basins located in the southern, southwestern, and northwestern regions of Iran, characterized by distinct tectonic and climatic settings.

The findings indicate that tectonic effects on sediment yield in Iran, situated within the Alpine-Himalayan orogenic belt, can be positive, with significant variability across different climatic zones. Therefore, the objective of this research extends beyond merely examining the influence of tectonic indices on SY; it also aims to comparatively assess this influence under contrasting climatic conditions: hot-dry climates, predominant in the southern and southwestern regions, versus cold-humid climates in the northwestern and western parts of the country.

To achieve this, data on three key tectonic indices were compiled from seismic records spanning 30 years (1995–2022): peak ground acceleration (PGA, cm.s^{-2}), cumulative seismic moment (M_0, N.m), derived from moment magnitude (Mw), and active fault density (m.km^{-2}). The impact of these three tectonic indices on basin-scale sediment yield (t.km^{-2}.y^{-1}) was systematically analyzed.

Regression analyses were conducted to evaluate the relationships between tectonic indices and sediment yield in the two contrasting climatic zones. The results of these statistical analyses, detailing the strength and nature of these relationships, are presented in the "Findings" section and summarized in Table 1 as Eqs. (2) to (7). The influence of climate on the relationship between tectonic indices exhibits marked spatial variability, particularly when comparing cold-humid and hot-dry environments. These differences underscore the interplay between tectonic forcing and climatic conditions in controlling sediment dynamics and modulating landscape responses to seismic events. As summarized in Table 1 (Eqs. (1) and (2)) and illustrated in Figures 4 and 7, the impact of peak ground acceleration (PGA) on sediment yield (SY) reveals a positive linear relationship across both climatic regimes, with the best-fit regression equations provided for each. In these equations, y represents basin sediment yield, and x denotes tectonic variables, including PGA, seismic intensity (M_0), and active fault density.

In cold-humid regions, the relationship between PGA and SY is characterized by a strong positive correlation, with a regression slope indicating high sensitivity of sediment production to changes in seismic acceleration. The coefficient of determination (R^2 = 0.6748) suggests that approximately 67% of the variance in SY can be explained by variations in PGA. This pronounced response likely arises from a combination of climatic and environmental factors typical of cold-humid settings, such as elevated soil moisture, sparse vegetation cover, and weak or poorly consolidated surface lithology, which collectively enhance slope instability and promote erosion during seismic shaking. Consequently, even moderate seismic events can trigger substantial sediment mobilization, emphasizing the critical role of climate in amplifying tectonically driven geomorphic processes.

In contrast, in hot-dry regions (Figure 7), while a positive correlation between PGA and SY persists, the relationship is considerably weaker. Only about 15.23% of the variability in SY is attributable to PGA, as indicated by the lower R^2 value. The relatively flat slope of the regression line reflects reduced sensitivity, whereby increases in seismic acceleration result in only modest increases in sediment yield compared to a cold-humid climate. This response may be attributed to factors such as limited water availability, reduced soil moisture, greater surface armoring, and enhanced sediment cohesion, all of which constrain erosion and limit sediment mobilization despite seismic forcing.

These contrasting patterns highlight the importance of climatic context in modulating the geomorphic response to tectonic activity, demonstrating that prevailing climate conditions strongly mediate the efficiency of seismic energy in driving sediment production.

The attenuated sedimentary response observed in hot-dry regions can be attributed to climatic limitations inherent to such environments. Unlike cold-humid regions, where frequent and intense rainfall or snowmelt rapidly mobilize loose sediments following seismic disturbances, hot-dry regions are characterized by low and infrequent precipitation. This significantly restricts the potential for effective sediment transport, which typically occurs only during rare, high-intensity storm events. Although sparse vegetation cover and weak soil structure in hot-dry zones contribute to slope instability, the scarcity of water limits surface runoff and thereby reduces the efficiency of sediment delivery to fluvial systems, resulting in lower overall sediment yields (SY).

A comparative assessment of the influence of earthquake intensity on SY across the two climatic regimes (Figures 5 and 8, Table 1, Eqs. (3) and (4)) reveals a positive linear relationship between seismic moment (M_0) and SY, with the best-fit regression equations provided in Table 1. In these equations, y denotes basin sediment yield and x represents earthquake intensity, expressed as seismic moment (M_0). In cold-humid regions (Figure 5), the relationship underscores the significant impact of seismic energy on sediment production. Seismic moment, as a measure of the total

Table 1) A summary of data analysis of the effect of climate conditions on tectonically related SY.

Tectonic Index	Climate condition	Equation	Eq. No.	R^2
Earthquake Acceleration (PGA)	Cold-humid	y=578.07x+1336.7	(2)	0.675
	Hot-dry	y=379.89x+1650.9	(3)	0.152
Earthquake Intensity (M_0)	Cold-humid	y=18.21x+639.0	(4)	0.510
	Hot-dry	y=10.08x+1041.0	(5)	0.335
Fault Density	Cold-humid	y=16.89x+1279.9	(6)	0.442
	Hot-dry	y=14.70x+1711.1	(7)	0.176

Note: y in Eqs. (2)-(7) is the sediment yield (SY, $t.km^{-2}.y^{-1}$), x in Eqs. (2) and (3) are the earthquake peak ground acceleration (PGA, $cm.s^{-2}$), x in Eqs. (4) and (5) is the cumulative seismic moment (M_0, N·m), x in Eqs. (6) and (7) are the active fault density ($m.km^{-2}$), and R^2 is the coefficient of determination in regression analysis.

energy released during an earthquake, reflects the potential for extensive landscape disruption through intense ground shaking and surface faulting. The steep slope of the regression line indicates a high sensitivity of SY to seismic intensity, suggesting that even moderate-magnitude earthquakes can induce substantial increases in sediment yield. This heightened geomorphic response is likely facilitated by rapid surface runoff and the prevalence of weak, water-saturated soils that are highly susceptible to failure. The coefficient of determination (R^2 = 0.5101) indicates that approximately 51% of the variability in SY can be explained by changes in seismic moment, emphasizing the importance of earthquake magnitude as a primary control on sediment dynamics in these environments.

In contrast, the regression relationship between M_0 and SY in hot-dry regions (Figure 8) also exhibits a positive correlation, but with a notably gentler slope and a lower R^2 value of 0.3354, implying that only about 33.5% of the variability in SY is accounted for by seismic intensity. This reduced slope reflects a lower sensitivity of sediment production to seismic energy in hot-dry climates. While seismic activity in these regions can still fracture bedrock and destabilize it, the absence of frequent or sustained precipitation limits the immediate entrainment and transport of displaced material. Consequently, the geomorphic response is often delayed and subdued, with mobilized sediment accumulating in hillslope or alluvial storage zones until rare, high-magnitude rainfall events provide the necessary hydrological forcing for downstream transport.

In cold-humid settings, earthquake commonly triggers landslides and other mass-wasting processes, particularly on slopes already preconditioned by high soil moisture. Water plays a critical role in amplifying these effects by reducing shear strength in soils and promoting rapid overland flow, thereby enhancing both sediment mobilization and conveyance. In contrast, in a hot-dry climate, the same seismic impulses may initiate rockfalls or surface fracturing, but without sufficient runoff, the displaced material remains largely in place. This decoupling of sediment production from transport leads to a lagged and less efficient sediment flux, underscoring the pivotal role of climate in regulating the connectivity between tectonic forcing and landscape evolution.

A comparative analysis of the influence of fault density on sediment yield (SY) under two distinct climatic regimes, cold-humid and hot-dry (Figures 6 and 9, Eqs.

(5) and (6)), reveals a positive linear relationship between fault density and SY, with corresponding regression equations provided in Table 1.

In cold-humid regions (Figure 6), the relationship between fault density ($m \cdot km^{-2}$) and SY is best described by a linear regression model, where y represents basin sediment yield and x denotes fault density. The positive slope of the regression line indicates that increasing fault density is associated with higher sediment production. This suggests that even moderate tectonic activity, expressed as a denser network of active faults, can significantly enhance sediment mobilization. The coefficient of determination ($R^2 = 0.441$) indicates that approximately 44.17% of the variability in SY can be explained by fault density, underscoring its role as a key tectonic control on erosion and sediment flux in these environments. Faults act as zones of structural weakness, promoting rock fracturing, reducing geotechnical stability, and thereby enhancing hillslope erosion and deposit generation.

In contrast, the relationship between fault density and SY in hot-dry regions (Figure 9) is considerably weaker, as evidenced by a flatter regression slope (Table 1), where y again represents SY and x denotes fault density ($m.km^{-2}$). Although the correlation remains positive, the reduced slope reflects a lower sensitivity of sediment yield to tectonic structuring. With an R^2 value of 0.1755, only about 17.55% of the variability in SY is attributable to fault density in these hot-dry environments, highlighting the limited explanatory power of tectonic indices when considered in isolation.

This attenuated response likely arises from the interplay between climatic constraints and surface processes. While sparse vegetation and inherently weak surface materials in hot-dry regions may increase susceptibility to erosion, the scarcity of moisture limits both chemical and physical weathering rates and restricts the development of sustained surface runoff. Although fault zones can channel and concentrate water during rare, high-intensity rainfall events, thereby accelerating localized weathering and enabling episodic sediment transport, the overall efficiency of sediment delivery to channels remains low. Moreover, the absence of continuous hydrological connectivity often results in sediment storage on hillslopes or within alluvial fans, delaying downstream flux.

Despite these limitations, tectonic structures in hot-dry landscapes still play a critical role in preconditioning the terrain for erosion. Fracture networks along fault zones reduce rock mass integrity and increase exposure to weathering, while minimal vegetation cover diminishes root reinforcement, further destabilizing surface materials. Consequently, when extreme precipitation occurs, the combination of pre-weakened substrates and intense runoff can trigger abrupt and sometimes dramatic sediment mobilization events. Nevertheless, the overall sediment flux remains constrained by climatic aridity, which limits the frequency and duration of flows capable of sediment transport.

In summary, while fault density exerts a measurable influence on sediment production across both climatic settings, its geomorphic impact is strongly modulated by climate. In cold-humid regions, high moisture availability and efficient hydrological coupling amplify the erosional effects of tectonic structuring. In contrast, in hot-dry regions, despite the presence of structural vulnerabilities, the lack of sustained runoff dampens the translation of tectonic forcing into measurable sediment yield, resulting in a more muted and delayed landscape response.

Conclusion

This study demonstrates a significant influence of tectonic activity on sediment yield (SY), while also highlighting the critical role of climate in modulating the magnitude of this effect. It further underscores that climatic conditions play a key role in shaping landscape responses to tectonic indices. In cold-humid regions, strong correlations were observed between SY and tectonic indicators such as peak ground acceleration (PGA), seismic moment magnitude (M_0), and fault density. These relationships are primarily driven by high soil moisture and frequent rainfall, which enhance surface runoff and facilitate rapid sediment mobilization following seismic events.

In contrast, hot-dry climates, despite exhibiting comparable levels of structural instability due to earthquakes and faulting, exhibit weaker correlations between tectonic drivers and sediment yield. The reduced efficiency of sediment transport in arid environments is mainly attributable to limited precipitation, which restricts sustained surface flow and delays geomorphic responses until rare, high-intensity rainfall events occur.

Collectively, these findings emphasize the necessity of integrating both tectonic and climatic variables when analyzing sediment dynamics and modeling long-term landscape evolution. From a practical standpoint, an understanding of how climatic conditions mediate tectonic forcing can significantly improve predictive models used in hazard assessment, watershed management, and post-earthquake recovery planning.

One major limitation in applying the results of this study to refine sediment yield models is the scarcity of reliable runoff and sediment data in tectonically active basins. Existing station records often lack sufficient continuity and temporal coverage. Data gaps are typically addressed through statistical imputation methods, which introduce uncertainty into model estimates. This highlights the need for enhanced monitoring systems capable of generating high-quality, continuous datasets at representative stations.

Beyond improving data reliability, the observed climate-dependent variability in tectonic impacts on sedimentation suggests that this research should be extended across major and sub-regions of the climatic classification framework. Doing so would allow for the derivation of region-specific correction factors to improve sediment yield models. Given the relatively comprehensive understanding of sediment production drivers gained through model calibration efforts, future work should involve replicating this analytical framework across diverse climatic zones, extracting correction coefficients, and subsequently updating existing models accordingly.

As a next step, a rigorous validation program should be implemented to test the performance of the modified models through careful monitoring of runoff and sediment yield. Once their accuracy is confirmed, these improved models can be generalized to all river basins across the country, accounting for variations in tectonic activity, climatic conditions, and other factors influencing sediment dynamics.

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