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Global warming-driven soil desiccation and hydrological decline in Namangan foothills, Uzbekistan

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Abstract

The foothills of Central Asia are climate-sensitive transition zones where persistent warming is driving a "warming–drying paradox"—water resources decline even as rainfall holds steady because evapotranspiration exceeds precipitation. This study assessed long-term hydroclimatic change in the Namangan foothills of eastern Uzbekistan as an indicator of climate-induced aridification by integrating meteorological records (1881–2022), river runoff data (1951–2021), and Landsat-derived soil moisture maps (1990–2023). The results showed a clear warming trend alongside only a slight rise in precipitation. Between 1990 and 2023, the area of dry soils increased nearly eightfold, while river runoff fell by more than 50% after 1951. Rising temperatures intensify evapotranspiration, reduce soil moisture, and weaken the hydrological regime. Mid-mountain foothills act as early indicators of hydrothermal change under continental warming, underlining the need for adaptation focused on evaporation control, soil moisture conservation, and catchment-scale water management.

Keywords: Aridification; Climate change; Foothill hydrology; Namangan; Soil moisture

1. Introduction

Climate change intensifies hydrological imbalances in arid and semi-arid regions, disrupting the balance among soil moisture, water availability, and ecosystem stability.[1,2] These changes are particularly evident in Central Asia, one of the fastest-warming regions globally, where temperature increases exceed the global average and have significantly altered precipitation patterns, snowmelt dynamics, and evapotranspiration regimes.[3-5] These changes are already reshaping water balance, vegetation patterns, and agricultural productivity in the region.[6,7] Despite recent technological advances in agriculture, food production in the region over the past decade has been significantly affected by rapid climatic changes that include droughts and extreme flood events.[6,8]

Fu *et al.*[9] reported that the rice yield in China declined by one-twelfth over the last two decades due to extreme rainfall events. Similarly, Li *et al.*[10] reported that the reduction of global rice yield is associated with severe flooding. In addition, several studies have shown that rice yield has significantly declined globally due to severe drought conditions.[11-14] As one of the most important staple foods in the world,[15,16] reduced rice yield indicates the broader impacts of climate extremes, with similar trends observed across different agricultural systems.[17-19]

In addition to climate change, land use and land cover changes due to increasing population present another major challenge to food security.[20-23] Therefore, the pressure on food production has rapidly increased over time, and achieving many of the United Nations Sustainable Development Goals has become unrealistic due to their links with food production.

Foothill environments, which form transitional zones between irrigated plains and mountain catchments, are particularly sensitive to climatic changes.[24] Acting as both climatic buffers and ecological connectors, they play an important role in regional hydrology and land productivity.[25] However, despite their importance, most studies on hydroclimatic change in Central Asia have focused on major river basins and lowland irrigation systems.[26-28] The foothill zone, where climatic gradients, soil processes, and land-use pressures intersect, remains neglected and comparatively understudied.[29] Its response to ongoing global warming offers critical insights into the onset and development of aridification across continental drylands.

Therefore, this study presents an integrated spatiotemporal analysis of climatic and hydrological changes in the Namangan foothills of eastern Uzbekistan—a transitional zone linking the Fergana Valley with the Kurama–Chatkal ranges. Long-term meteorological records (1881–2022), river discharge data (1951–2021), and Landsat-derived soil moisture maps (1990–2023) were used to assess how continued warming has altered the region's hydrothermal balance.

This study advances hydroclimatic research in Central Asia in three ways. First, most regional assessments have concentrated on the transboundary Amu Darya and Syr Darya basins or on lowland irrigation systems. In contrast, the foothill (adir) belt that mediates between mountain catchments and irrigated plains has rarely been examined in its own right. Second, few studies pair instrumental records spanning more than a century (from 1881) with multidecadal satellite observations of soil moisture. In this study, the two are analyzed together so that long-term climatic forcing and its terrestrial expression can be linked directly. Third, by adding river discharge data to the same analytical frame, the study traces a single warming, soil-drying, and runoff sequence within one transitional landscape rather than inferring it across disparate datasets. The distinct contribution of this study is therefore the integration of long-term observational climatology with satellite-derived soil moisture analysis and hydrological records to characterize foothill aridification at a scale that regional studies have largely overlooked.

Accordingly, the study pursues three objectives: to quantify long-term trends in temperature, precipitation, and the resulting change in evaporative demand; to map the spatiotemporal evolution of soil moisture and the extent of dry land between 1990 and 2023; and to assess whether the decline in foothill river discharge is consistent with the observed warming and soil-drying signals. These objectives correspond to the three propositions developed in Section 2.3 and are revisited in Section 5.

2. Related work

2.1. Regional drought regime in Uzbekistan's plains and foothills

Drought is a typical climatic feature in Uzbekistan, particularly in the plains and foothill zones where dry spells occur during spring and summer in most years. Figure 1 shows the drought-affected terrain, such as sparse vegetation cover and erosional forms.

These arid and semi-arid environments are representative of Central Asia's broader continental climate, which is characterized by sharp thermal contrasts, low annual rainfall, and high evapotranspiration.[27] Native steppe vegetation has adapted to this environment by completing its life cycle before the onset of extreme summer heat.[30] In contrast, cultivated crops, especially those grown

Figure 1. Semi-arid foothill landscape in Namangan region (Source: Authors)

under rainfed conditions, remain highly vulnerable to soil moisture loss.[31] In many parts of the region, rainfall decreases sharply by late May and often ceases by early June. As temperatures rise, soil moisture declines rapidly, resulting in widespread soil moisture depletion that affects crop development and dries exposed land surfaces.[32] Only deep-rooted xerophytes such as the *Alhagi* genus and *Artemisia absinthium* L. can survive through the summer months in the drier foothill areas.[33] In addition, the region's characteristic garmsel winds, which are hot and desiccating gusts, accelerate surface drying and soil erosion.[34]

The duration of drought varies with elevation.[35] Soil drought typically begins below elevations of 250 m above mean sea level in early April and extends to 300–400 m above mean sea level by early May. Meanwhile, atmospheric drought typically lasts 10–30 days per season and may extend up to 50 days in extreme years.[36] Although irrigation can reduce soil moisture deficits in cultivated areas, it cannot prevent atmospheric drought caused by increased temperatures and low humidity between irrigation events.[37] This leads to a hydrothermal imbalance that limits agricultural productivity and increases land degradation in marginal areas. Recent initiatives in the Namangan region have introduced adaptive practices such as water-efficient irrigation, mulching, and terracing to enhance soil moisture retention and reduce soil salinity.[38] Although these measures are local in scale, they represent a broader regional response to hydrological stress, aimed at stabilizing the foothill ecosystems that function as agricultural frontiers and climatic buffer zones.[27]

2.2. Climate, soil, and hydrological interactions

Understanding the interaction between climate change, soil processes, and hydrological balance has become an important focus in Earth system science. Global evidence shows that the hydrosphere and pedosphere are closely linked within a rapidly warming atmosphere. Over the past few decades, studies have shown that changes in temperature and precipitation are not isolated processes, but are part of a feedback system that links soil moisture, evapotranspiration, and energy balance across different scales.[39] The increasing variability in this system is affecting both the stability of natural ecosystems and the sustainability of agricultural systems, especially within continental regions where climatic extremes are more pronounced.

Recent studies have examined how these dynamics vary spatially. Global soil moisture records since 1980 reveal mixed drying and wetting trends in surface soils, while root-zone soils exhibit pronounced drying across inhabited semi-arid regions.[40] This uneven pattern is attributed to rising air temperatures, increased evaporation, and anthropogenic activities, especially irrigation, which alter soil-water balance at landscape scales. These findings suggest that climatic and human drivers are closely linked and interact in shaping hydroecological changes. This interaction is increasingly recognized as the key feature of aridification in the 21st century.

Various frameworks have been proposed to explain global changes in water availability, with two main

hypotheses receiving widespread attention. One suggests that the hydrological cycle is intensifying unevenly, with wet regions becoming wetter and dry regions drier, while the other proposes a general trend of aridification as evapotranspiration exceeds precipitation.[41] Both interpretations are supported by evidence, but their applicability depends on geographic context. The first hypothesis explains regional differences driven by atmospheric circulation, while the second is more applicable to inland continental regions, where even modest warming can lead to significant moisture loss. The "warming–drying paradox," now widely discussed in hydrology, reflects this contrast. It describes situations where precipitation increases while drought conditions intensify. This pattern has been observed in many parts of Central Asia, including the Namangan foothills.

Recent studies have evaluated the interactions between climate and soil, which provide further insight into these land-atmosphere processes. As CO_2 concentrations increase, soil moisture enters transitional regimes that enhance land-atmosphere feedbacks and local heat sensitivity.[42] As soils dry, surface energy partitioning shifts towards sensible heat, increasing thermal gradients and reducing humidity, creating a feedback that accelerates aridification. Studies on soil profiles also reveal that hydrological processes leave physical features such as capillary fringes, clay films, and biogenic channels, which reflect past moisture conditions and flow intensity.[43] These findings highlight that soil is not only affected by climate change but also provides valuable insights into the impacts of climate change.

At finer scales, technological interventions such as drip fertigation systems have been shown to reduce these effects by improving soil moisture distribution within the root zone and increasing water-use efficiency.[44] These examples illustrate that human actions can either exacerbate or mitigate climate impacts, depending on management practices. However, even adaptive practices are often not sufficient to offset the overall trend of rising temperatures. Global datasets also indicate that the expansion of transitional soil moisture conditions reflects a growing extent of regions highly sensitive to hydroclimatic changes.[40,42]

This sensitivity is particularly evident in Central Asia, which has been recognized as one of the fastest-warming continental regions.[5] In this region, the combined effects of anthropogenic warming, glacier retreat, and inefficient water management have altered both natural and agricultural hydrology. Over the past thirty years, declining snow cover, groundwater depletion, and surface water diversion have led to recurring droughts interspersed with short wet spells. Remote-sensing analyses show that droughts in Central Asia are intensifying and shifting spatially, with the most severe aridity observed in the lower reaches of the Amu Darya and Syr Darya basins.[28] These patterns, once seasonal, are now becoming a more prominent feature of the regional climate.

Recent attribution studies have evaluated the underlying mechanisms driving these changes. The increase in agricultural drought since the early 1990s has been linked to the combined influence of human forcing and internal climate variability associated with the Interdecadal Pacific Oscillation.[26] This interaction between global ocean oscillations and local water scarcity helps explain why Central Asia experiences strong hydrological variability despite small changes in precipitation. The pattern also indicates that aridification cannot be attributed solely to anthropogenic factors, as natural climate variability can amplify or mitigate these effects. However, projections indicate that even favorable oscillatory phases, i.e., different phases of a large-scale climate oscillation, will not offset ongoing drying, highlighting important challenges for water management in Uzbekistan and neighboring countries.

From a socio-ecological perspective, these continental trends are closely linked to a long history of human adaptation and vulnerability. Archaeological and palaeoenvironmental studies show that changes in moisture availability have constrained agricultural expansion and settlement in the steppe and foothill environments of Central Asia.[32] In recent decades, this constraint has re-emerged as a major challenge. Regional studies report widespread rangeland degradation, overgrazing, and salinization as direct consequences of climatic stress compounded by inefficient irrigation and land-use change.[27] In Uzbekistan, where irrigated agriculture plays a major role in rural livelihoods, these pressures have encouraged the adoption of water-saving agrotechnology. Large-scale implementation of efficient irrigation systems, mulching, and terracing has helped reduce soil salinity and improve water infiltration in foothill areas.[37,38]

The Namangan region, located between the fertile Fergana Valley and the Kurama–Chatkal ranges, illustrates the link between climatic vulnerability and human adaptation. Local studies indicate that climate change, declining water availability, and soil degradation have become major threats to sustainable agriculture in Uzbekistan.[45] In foothill regions, these pressures are further intensified by geoecological processes, including soil erosion and progressive drying associated with unsustainable irrigation practices. Studies on rainfed horticulture further highlight the unstable productivity

of non-irrigated systems under increasing hydrothermal imbalance.[31] These findings place Namangan within a broader Central Asian pattern in which water scarcity, energy dependency, and agricultural adaptation are closely interconnected.[46]

Thus, the literature highlights several key points. First, soil moisture acts as both a driver and an indicator of climatic transformation. Second, continental regions such as Central Asia are highly vulnerable to droughts influenced by both anthropogenic forcing and natural variability. Third, human responses, whether technological, agronomic, or policy-based, can mitigate these impacts but cannot reverse them. These broader processes are reflected in the Namangan foothills through increasing temperatures, declining soil moisture, and changing land use. They provide an opportunity to examine the interactions among climate, soil, and society, not as separate components, but as an interconnected system of feedbacks undergoing continued change.

2.3. Conceptual basis, objectives, and propositions

Building on these insights, this study adopts an integrated hydroecological approach, viewing soil moisture as a key link between climatic forcing and hydrological response. This approach aligns with the broader climate–soil feedback framework, which suggests that warming-induced reductions in soil moisture increase surface heating and suppress evapotranspiration, thereby intensifying regional aridification. Within this framework, the Namangan foothills can be considered a transitional hydroecological system in which small changes in temperature or land use can lead to significant hydrological changes.

The study also draws on the aridification feedback hypothesis discussed in recent hydrological studies, particularly the idea that continental drylands are experiencing stronger land–atmosphere coupling.[41,42] In this context, Namangan illustrates how global-scale warming–drying mechanisms are manifested regionally under specific topographic and land-use conditions. The study does not aim to statistically test these theories but instead uses them as a basis for interpreting the observed environmental changes.

Based on the reviewed literature and regional evidence, this study is guided by the following three main propositions:

I. Rising temperatures in the Namangan foothills have intensified the hydrothermal imbalance in which increasing evaporative demand exceeds precipitation.
II. Declining soil moisture and spatial drying patterns reflect the combined effects of climatic and anthropogenic factors, influenced by land use and elevation.
III. Depleted river flow in foothill areas linked to soil drying indicates a weakening of the region's natural water-buffering capacity.

Together, these propositions place the "Namangan case" within ongoing global discussions on hydroclimatic vulnerability and ecological resilience in arid continental regions. The study provides a location-specific perspective on how local environmental systems respond to, amplify, or partially adapt to ongoing climatic aridification.

3. Methods

3.1. Study area

The study was conducted in the foothills of the Namangan region, located in the northeastern Fergana Valley in eastern Uzbekistan (Figure 2). Situated at the southwestern foothills of the Tien Shan Mountains, the region marks the transition from flat lowlands to uplands. This geographic location is sensitive to climatic and hydrological changes.[34] The climate of the area is arid to semi-arid and continental, with hot summers and relatively mild winters. Average summer temperatures range from 26 °C to 30 °C and can exceed 40 °C during extreme heat conditions. Annual precipitation is limited to an average of 250–400 mm and falls mainly during winter and spring. In recent decades, increasing air temperatures have been recorded in the region, consistent with the ongoing global warming.[6]

Hydrological conditions in the foothills are characterized by seasonal streams and shallow groundwater, fed primarily by meltwater and seasonal precipitation. These water sources are essential for local ecosystems and agricultural activities. However, rising temperatures have increased evaporation and reduced water availability, contributing to a gradual decline in surface and groundwater resources.[6,47]

The soils in the Namangan foothills are predominantly gray and gray-brown sierozem soils that are very sensitive to moisture loss. Under warming and drought conditions, these soils dry out quickly and are susceptible to depletion. Natural vegetation is characteristic of semi-arid steppe and foothill environments and is highly sensitive to changes in soil moisture. Overall, the Namangan foothills provide an ideal setting for investigating the impacts of global warming on soil moisture depletion and hydrological regimes under arid and semi-arid conditions.

The Namangan foothills were selected because they encompass, within a compact area, the conditions under which foothill aridification is most likely to become evident: a steep climatic gradient from roughly 250 m to more than 1,000 m in elevation, moisture-sensitive sierozem soils, and a dense mosaic of rainfed and irrigated land that

Figure 2. Location of the Namangan region in Uzbekistan[48]

depends on seasonal foothill runoff. The region is among the most intensively cultivated parts of the Fergana Valley and is inhabited by a large rural population; therefore, changes in soil moisture and river flow can quickly affect agricultural productivity and water availability. This makes it a sensitive and policy-relevant setting for detecting early hydrothermal change. The foothill area covers approximately 402 km^2; however, no official population records are available for this area.

This study integrates long-term meteorological observations, satellite remote sensing, and hydrological data to examine the spatiotemporal dynamics of climate change, soil moisture, and river discharge in the Namangan foothill (adir) region of eastern Uzbekistan. The analysis combines instrumental records from regional meteorological stations with multitemporal Landsat imagery and historical hydrological datasets to identify climate-driven environmental changes between 1951 and 2023.

3.2. Meteorological and satellite data

Observed meteorological data covering the period of 1881–2022 were obtained from the Namangan and Pop meteorological stations of the Uzhydromet network. Monthly and annual air temperature and precipitation averages were analyzed to identify trends and anomalies across two climatic intervals (1881–1960 and 1961–2022), and an additional interval representing the recent period (2001–2022). Linear trend analysis and comparative statistics were used to quantify temporal variations and to assess regional deviations from the mean global warming patterns.

To evaluate soil moisture dynamics, four cloud-free Landsat images were acquired from the USGS Earth Explorer database for 1990, 2000, 2010, and 2023. All images were geometrically corrected, radiometrically calibrated, and atmospherically adjusted using standard preprocessing procedures in ArcGIS Pro. Soil moisture was assessed through two complementary spectral indices: i) the normalized difference moisture index (NDMI), calculated from the near-infrared and shortwave-infrared bands, and ii) the normalized difference vegetation index (NDVI), derived from the red and near-infrared bands. NDMI was used to estimate surface soil moisture content, while NDVI provided indirect validation through vegetation vigor. Based on the relative spectral responses, index thresholds were defined to classify the surface into four moisture categories: dry, slightly dry, moist, and very moist.

Only scenes free of cloud contamination over the study area were retained, and images were drawn consistently from a late-spring to early-summer acquisition window so that phenological stage and solar geometry were comparable across dates and short-term seasonal variability did not confound the multidecadal comparison. Surface-reflectance products from the Landsat archive were used to reduce inter-sensor differences among the Thematic Mapper, Enhanced Thematic Mapper Plus, and Operational Land Imager sensors. The four reference years were selected to provide an approximately decadal sequence across the satellite observation era, spanning the earliest usable coverage of the study area (1990) and the most recent cloud-free scene (2023). This spacing is sufficiently long for multidecadal changes to emerge while keeping the number of scenes small enough to ensure consistent processing.

The two indices (NDMI and NDVI) were used jointly because they reflect complementary aspects of the surface-moisture signal. NDMI responds directly to water content in soil and canopy through the contrast between the near-infrared and shortwave-infrared bands. NDVI tracks vegetation vigor, which integrates the effects of plant-available water over the preceding growth period. Using them together reduces ambiguity that may arise when either index is interpreted individually, for example, when distinguishing genuinely dry bare soil from sparse but healthy vegetation.

Spatial classification was performed through supervised maximum-likelihood methods, guided by ground-truth references and visual interpretation of high-resolution Google Earth imagery. Each classified dataset was projected to a common coordinate system (WGS 84, Zone 42N) and clipped to the delineated foothill boundary. Post-classification change detection was applied to assess temporal transitions among moisture classes. The resulting thematic maps were used to quantify the areal extent of soil moisture zones and to trace the upward or downward shifts of the aridity boundary over time.

Boundaries between the four moisture categories were defined based on the training statistics rather than fixed global thresholds. Training samples for dry, slightly dry, moist, and very moist. surfaces were digitized from field knowledge of the area and high-resolution Google Earth imagery, with the NDMI and NDVI distributions of these samples setting the decision limits of the maximum-likelihood classifier. Classification quality was checked qualitatively against independent reference points interpreted from high-resolution imagery of the corresponding period.

3.3. Hydrological data and usage

Hydrological data, including annual discharge records from five major foothill rivers (Norin, Kosonsoy, Podshaotasoy, G'ovasoy, and Chodaksay) for the 1951–2021 period, were obtained from the Ministry of Water Resources of Uzbekistan. Regression trend analysis was conducted to detect long-term changes in flow volume, while interannual variability was assessed through time-series visualization. These hydrological datasets were integrated with climatic and soil moisture data to evaluate the correlation between hydrological depletion and terrestrial drying.

Before analysis, the discharge series were screened for gross inhomogeneities and gaps, and records from gauging stations (hydrological posts) with major documented breaks were treated with caution. Because these foothill rivers also supply irrigation, the interpretation of runoff decline explicitly considers upstream abstraction, reservoir operation, and agricultural diversion alongside the climatic signal, so that the observed trend is not attributed to warming alone (see Section 5).

Finally, findings from the meteorological, satellite-based, and hydrological data were synthesized to provide an integrated interpretation of climate-driven environmental change in the Namangan foothills. This triangulated evidence enables identification of the feedback sequence that links atmospheric warming, soil desiccation, and hydrological decline, providing a robust empirical foundation for assessing the region's growing drought vulnerability.

3.4. Statistical analysis

Temporal trends in temperature, precipitation, and discharge were estimated by ordinary least-squares linear regression, and the magnitude of change was expressed as the difference between period means (1881–1960 versus 1961–2022, and the recent 2001–2022 interval). The direction and consistency of each trend were compared across stations and rivers to minimize the influence of station-specific artifacts. The monotonic increase in temperature and the monotonic decline in discharge reported below are the kinds of trends that non-parametric trend statistics like the Mann–Kendall test and Sen's slope estimator are designed to detect. Because the original station and gauge spreadsheets underlying these series were not available for reanalysis, formal Mann–Kendall and Sen's slope estimates are not reported here, and this constraint is noted in Section 6. The correspondence among the warming, soil-drying, and discharge records was assessed by comparing the timing and direction of the three signals rather than using a single correlation coefficient, given their differing temporal resolutions.

4. Results

Temperature and precipitation trends from long-term observations were first evaluated to assess regional warming patterns, followed by satellite-based mapping of soil moisture dynamics and an evaluation of multidecadal changes in river discharge.

4.1. Climatic and hydrological changes in the Namangan foothills

The early (1881–1960) and recent (1961–2022) climatic periods were compared using long-term temperature records from the Namangan and Pop meteorological stations (Figure 3). In both areas, average January temperatures increased by approximately 3 °C, indicating warming during winter. February temperatures also increased by 1.8 °C and 2 °C in Namangan and Pop, respectively, suggesting shorter and milder winters. In Namangan, mean monthly temperatures for March, May, August, September, October, November, and December increased by more than 1 °C, while other months showed smaller increments. In Pop, warming was less uniform, with March, April, June, and November showing slight temperature increases (<1 °C), while July, August, September, and October experienced a small reduction of 0.2 °C–0.6 °C. These contrasting responses reflect the influence of topographic variation, aerosol conditions, and land–atmosphere interactions.

Overall, the annual mean temperature increased by 1.2 °C and 0.6 °C at Pop, with the lower-altitude Namangan station warming at nearly twice the rate. This pattern suggests that lowland and lower-foothill environments are more sensitive to anthropogenic heat accumulation and reduced evaporative cooling. During the last two studied decades (2001–2022), this trend strengthened, with the mean annual temperature increasing by 2 °C at Namangan and 1.4 °C at Pop relative to the pre-industrial baseline (1881–1960). Both values exceed the global mean warming rate of ~1.1 °C.[49] Such increased warming is common in arid continental regions where surface albedo, soil dryness, and low atmospheric moisture feedback amplify local warming effects.

Despite the increase in temperature, precipitation has shown a slight increasing trend, with Namangan and Pop stations recording increases of 20 mm and 16 mm, respectively. However, these small increases are insufficient to offset higher evaporation and prolonged dry seasons. Atmospheric evaporative demand has increased by approximately 5–8%, leading to an increased hydrothermal deficit and reduced soil moisture across the foothill region. This pattern reflects a warming–drying paradox, in which higher rainfall occurs alongside increasing aridity due to rising temperatures and increased evaporation. This hydrothermal imbalance helps explain the soil drying observed in satellite and hydrological analyses.

4.2. Mapping and analysis of soil moisture dynamics (1990–2023)

Datasets were corrected for atmospheric effects and co-registered to ensure consistency. Four thematic maps are presented here to illustrate the gradual spatial changes in soil moisture conditions (Figures 4–7). In 1990, the foothill region showed a relatively balanced hydrothermal regime. Humid and semi-humid soils covered around 40% of the area, primarily in the central and northeastern foothills near stream valleys, while dry soils comprised only 6% of the area and were confined to the western lowlands (Figure 4).

In 2000, drying became evident, with dry zone of the area, especially along the Kosonsoy and Podshaotasoy basins, while the area of very moist zones decreased (Figure 5).

By 2010, dry soils covered 36% of the foothill zone, extending upslope to elevations of 600–800 m (Figure 6). The extension of dry conditions to higher elevations indicates that evaporative losses have begun to exceed the natural moisture-retention capacity.

By 2023, nearly 47% of the foothill area was classified as dry or very dry, while very moist had decreased to only 12%. Moisture-rich areas were mainly found along riverbanks and on upper slopes, indicating an eightfold increase in dry soils since 1990 (Figure 7).

Spatially, elevation zones of 400–800 m are the most affected, where intensive land use, vegetation loss, and high temperatures collectively contribute to increased soil drying and degradation. In contrast, upper slopes above 1,000 m retain slightly higher moisture levels due to cooler conditions and snowmelt. The spatial pattern is consistent with the observed meteorological trends, indicating feedback among warming, soil drying, and vegetation decline.

4.3. Hydrological response (1951–2021)

Long-term hydrological data from five rivers, namely Norin, Podshaotasoy, Kosonsoy, G'ovasoy, and Chodaksay, show consistent declines in water availability over the past 70 years. Flow records exhibit high interannual variability but a clear overall decline. The largest reductions occurred in the Kosonsoy and Podshaotasoy basins, with more than a 50% decrease in discharge since the 1960s. The Norin River, which has a larger catchment and glacial inputs, remained comparatively stable, while the G'ovasoy and Chodaksay rivers displayed moderate but persistent

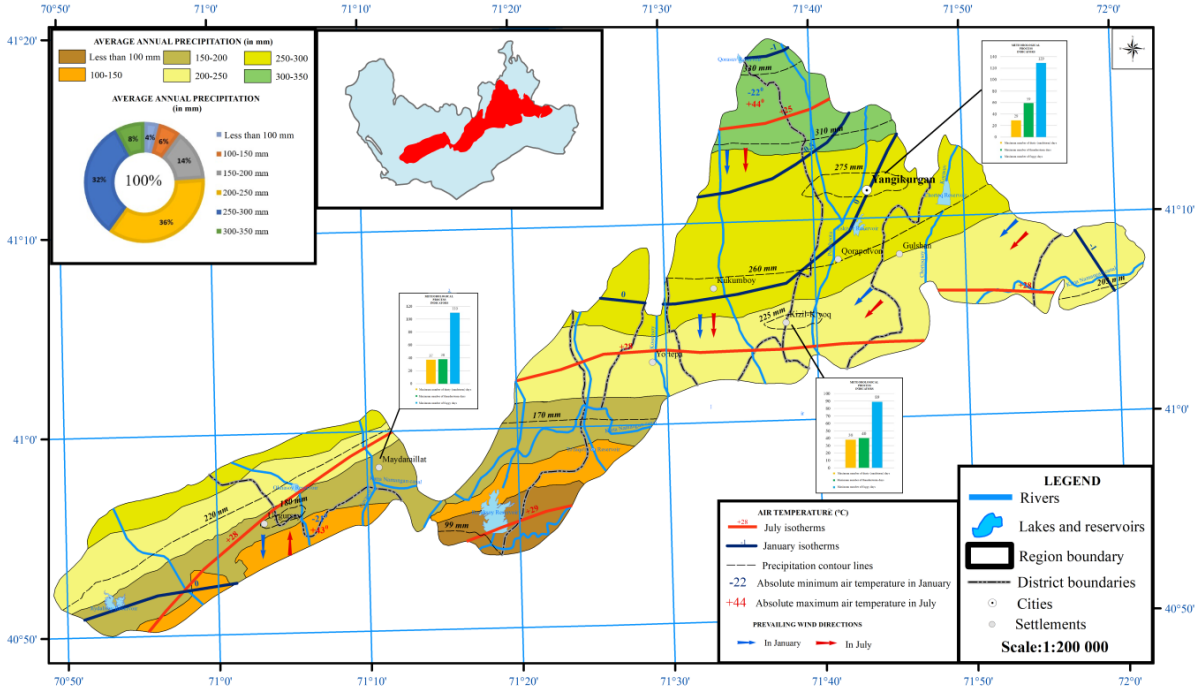

Figure 3. Climatic map of Namangan foothills showing temperature and precipitation gradients. A warmer climate was recorded in the west, while a cooler climate was recorded in the northeast.

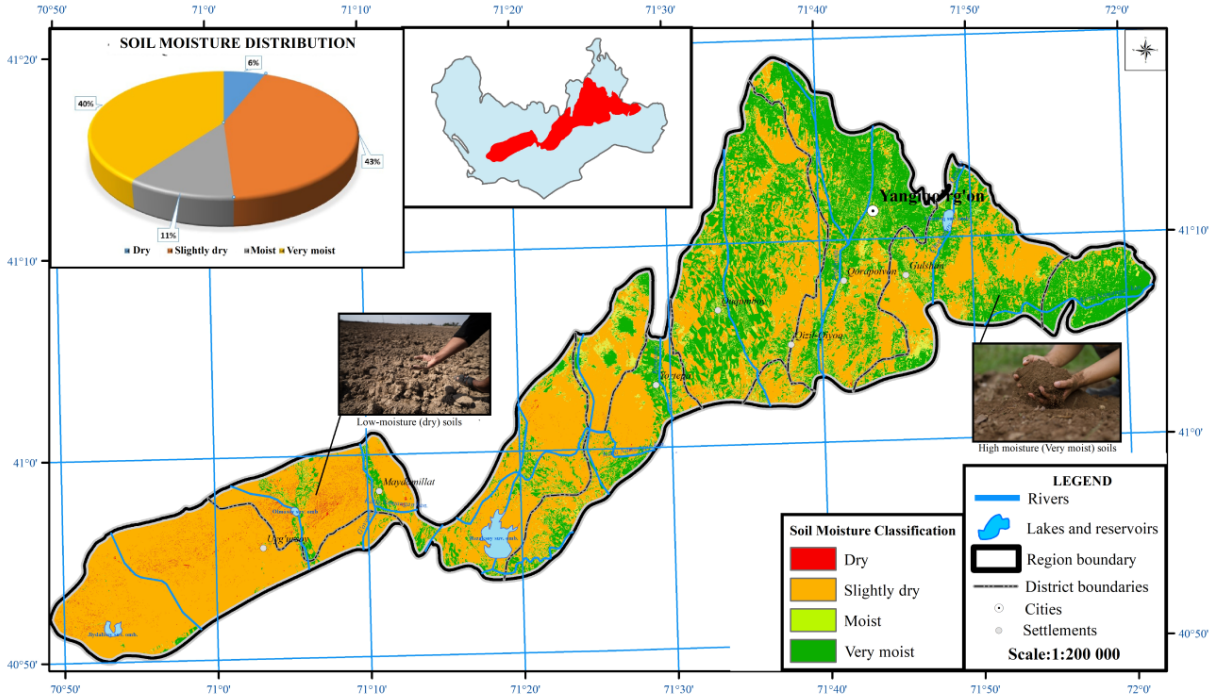

Figure 4. Map of natural soil moisture in the foothill areas of Namangan region (1990)
Note: Moist and very moist soils dominated the central and northeastern foothills near river channels, while dry soils were confined to the western lowlands.
Source: Authors' analysis based on Landsat-8 data (1990).

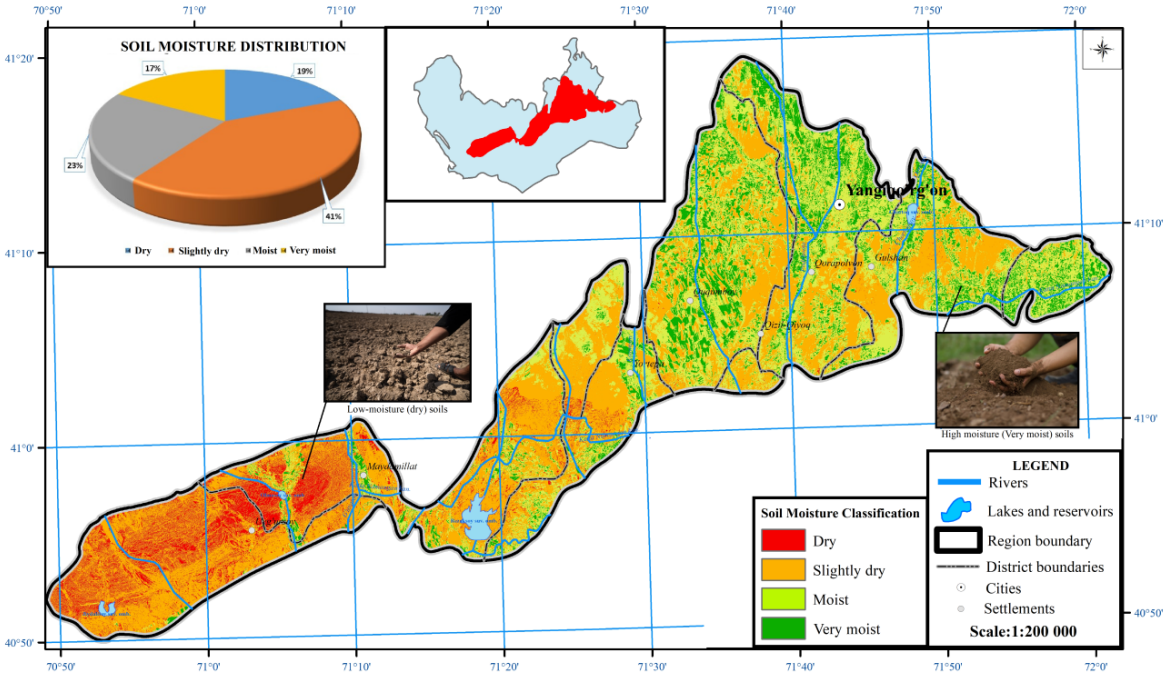

Figure 5. Map of natural soil moisture in the foothill areas of Namangan region (2000)
Note: The expansion of dry and slightly dry soils along the Kosonsoy and Podshaotasoy valleys indicates declining water infiltration and shorter wet periods.
Source: Authors' analysis based on Landsat-8 data (2000).

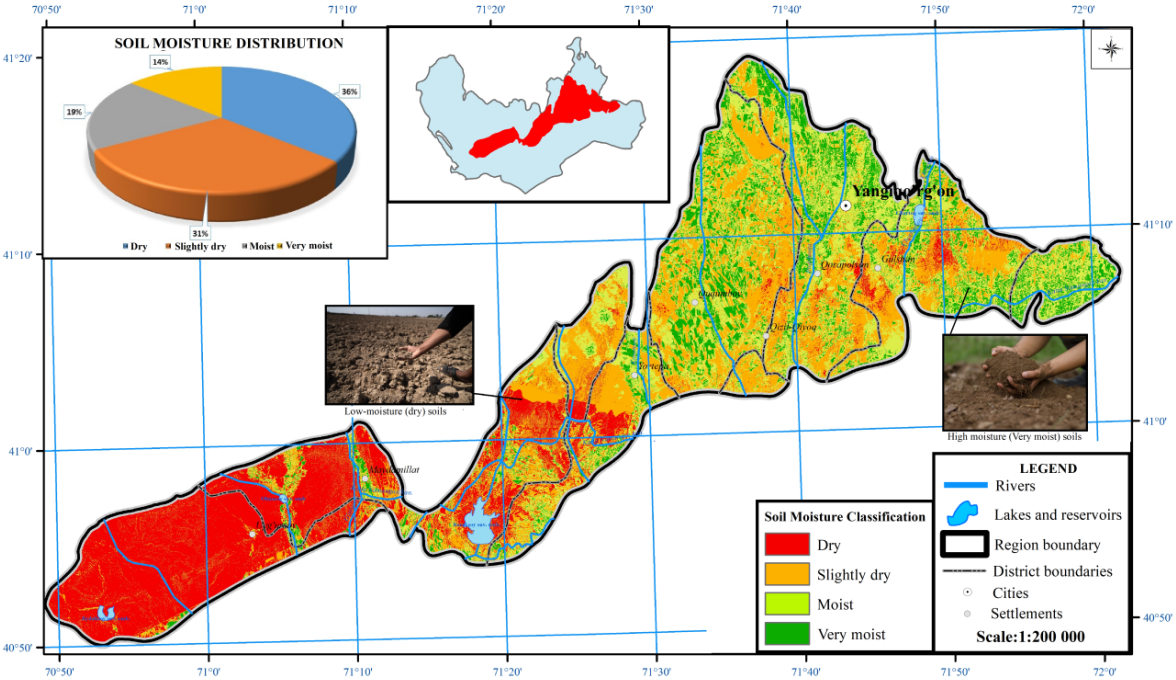

Figure 6. Map of natural soil moisture in the foothill areas of the Namangan region (2010)
Note: Aridity increased and extended to mid-elevation zones (600–800 m), revealing an upward expansion of drought-affected areas.
Source: Authors' analysis based on Landsat-8 data (2010).

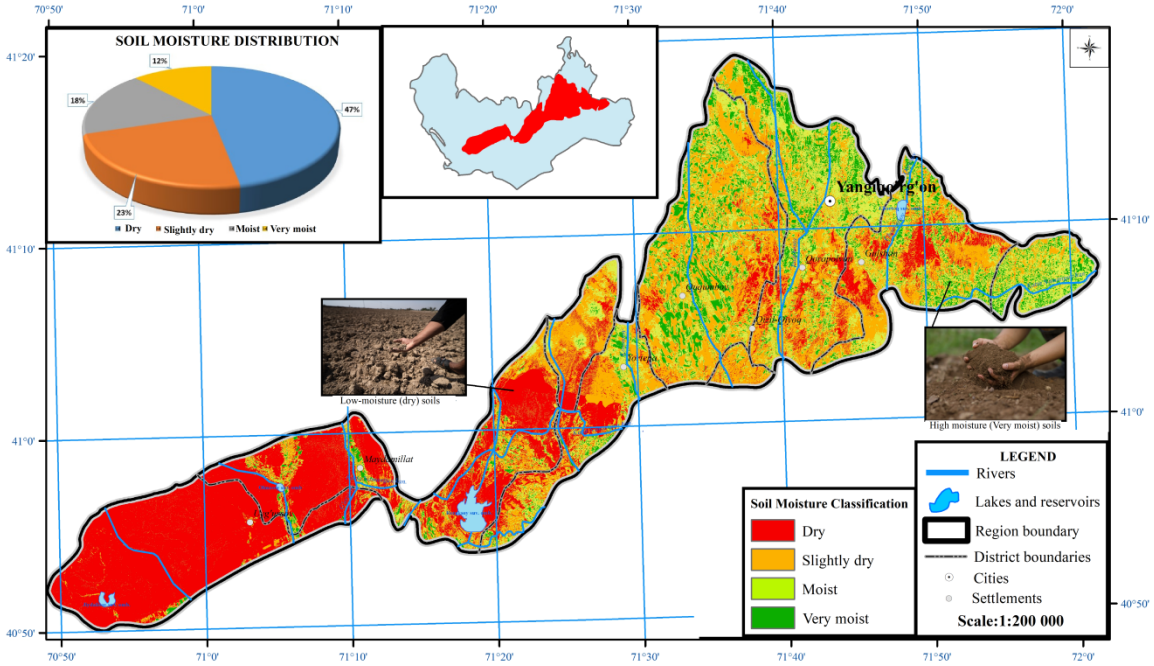

Figure 7. Map of natural soil moisture in foothill areas of Namangan region (2023)
Note: Dry and slightly dry soils dominated most of the foothill region, with humid zones confined to narrow riparian corridors and isolated upper slopes.
Source: Authors' analysis based on Landsat-8 data (2023).

declines. Detailed discharge data are provided in Figures A1–A5.

These results indicate a region-wide reduction in runoff driven by increased air temperature, reduced snowmelt, and increased irrigation demand. The timing of this hydrological decline is closely associated with the expansion of dry-soil areas and the warming trend observed in meteorological records. The relationship between lower river discharge and reduced soil moisture demonstrates the weakening of the region's hydrological buffering capacity.

5. Discussion

Building on these empirical patterns, the Namangan foothills show a distinct and increasing climatic-hydrological imbalance, consistent with broader aridification trends observed across Central Asia. Continued warming, even with slight increases in precipitation, has altered the soil–water–energy equilibrium. This change reflects a warming–drying paradox, where thermal forcing exceeds hydrological input. The foothill region therefore acts not only as a transitional zone but also as a system that amplifies continental hydrothermal change, where climate, land use, and soil processes interact to influence water availability. The agreement among meteorological, satellite, and hydrological data suggests that the foothill region is transitioning from a semi-arid to an arid regime. This transition is consistent with continental-scale drying trends observed across the interior of Asia.[5,26]

These outcomes directly address the three propositions set out in Section 2.3: the increasing hydrothermal imbalance in which evaporative demand outpaces precipitation (Proposition I), the joint climatic and anthropogenic influence on soil drying across land use and elevation (Proposition II), and the coupling of depleting river flow to soil desiccation and a weakened water-buffering capacity (Proposition III). The evidence presented below supports all three propositions, while showing that their relative influence varies between the smaller rain- and snow-fed catchments (Kosonsoy, Podshaotasoy, G'ovasoy, and Chodaksay) and the larger, partly glacial Norin system.

While the observed warming in the Namangan foothills is consistent with global findings that continental regions are warming faster than the global average, it also reveals a local effect related to elevation and land-surface interactions. Although some Central Asian basins have shown stable or slightly increasing precipitation,[28] the results from the Namangan region indicate that these increases are offset by higher evapotranspiration, consistent with

the global "aridification" hypothesis of Zaitchik *et al.*[41] The weak relationship between precipitation and soil moisture content suggests that the regional hydroclimate is governed more by energy flux and soil-atmosphere coupling than by precipitation variability. This finding is supported by Liu *et al.*,[25] who identify temperature and evaporation as the primary drivers of long-term soil moisture change, even in regions where rainfall variability is low.

The combined decline of soil moisture and river discharge highlights a strong land-hydrology feedback. The increase in dry and very dry soils from 6% to nearly half of the foothill zone between 1990 and 2023 has resulted in a multidecadal decline in river flow, which is most pronounced in the smaller Kosonsoy and Podshaotasoy basins. These changes suggest a cascading process where, as soils dry, water infiltration decreases, vegetation cover declines, and surface runoff becomes more rapid but less sustained, reducing baseflow recharge. Similar links between warming, soil drying, and depletion of streamflow have been reported in other arid mountain-front regions.[28,39] However, this study in the Namangan region shows that small, non-glacial catchments are sensitive to temperature increases. Therefore, the foothill region serves as an early warning zone for hydrological stress in continental drylands, where even minor hydrothermal changes can alter the runoff regime.

Human factors are likely to contribute to this trend. The Namangan foothills, which have long been used for intensive agriculture and grazing, have experienced extensive vegetation removal and land conversion that degrade soil structure and reduce moisture retention. Although recent initiatives such as mulching, terracing, and efficient irrigation have proven effective in local studies, their adoption remains spatially limited.[38] The continued decline in water resources despite small increases in rainfall suggests that biophysical feedbacks now outweigh local management gains. This is consistent with regional studies showing that water conservation technologies, while useful, cannot fully offset large-scale hydrothermal imbalance under continued warming.[27,37] Therefore, adaptation efforts should move beyond field-level practices to integrated watershed and land-energy management frameworks that can stabilize the hydroecological balance.

Several non-climatic drivers plausibly reinforce this decline in water resources and should be considered in any attribution. A substantial share of the foothill rivers' flow is withdrawn upstream for irrigation, so part of the measured reduction at downstream monitoring posts reflects direct abstraction and diversion rather than a change in water generation. Groundwater pumping for supplementary irrigation lowers the shallow water tables that would otherwise sustain baseflow and near-surface soil moisture. The Norin River, which retains a glacial and high-mountain snow component, exhibits less decline in water resources than the smaller, snow- and rainfed Kosonsoy and Podshaotasoy basins. This indicates that reduced seasonal snow storage and earlier melt, rather than glacier loss alone, are central to the runoff signal in the smaller catchments. Land-use change, including the expansion of horticulture onto fragile slopes, grazing pressure, and vegetation removal, further degrades soil structure and reduces water infiltration. Because these processes interact with warming, their individual contributions cannot be clearly distinguished using the present data; disentangling the effects of individual factors remains an important focus for future work.

These findings contribute to the broader understanding of land–atmosphere interactions in semi-arid systems. The Namangan foothill is an example of a self-reinforcing cycle of aridification, where rising temperatures increase evaporation, soil drying reduces vegetation and water infiltration, and the resulting higher albedo and moisture deficits further increase warming. This dynamic is more consistent with the "global aridification" hypothesis than with the "dry-gets-drier, wet-gets-wetter" model.[41] It also supports the findings of Hsu and Dirmeyer,[42] who show that rising CO_2 levels expand the transitional coupling regime in which soil moisture and evaporation interact nonlinearly, thereby intensifying the strength of the feedback. Within this framework, the Namangan foothills can be seen as active contributors rather than passive receivers of climatic forcing, where human activities and climate processes interact to accelerate hydrological transformation.

The Namangan pattern echoes findings from semi-arid mountain-front systems well beyond Central Asia. Altitude-dependent drying under warming has been documented in the Qilian Mountains of north-west China, where dryland mountain ecosystems show elevation-contingent responses to drought.[24] Comparable warming-driven reductions in mountain runoff and soil water have also been reported in parts of the semi-arid western United States, the central Chilean Andes, and the mountains in the Mediterranean and the Middle East.[24] In each case, rising evaporative demand, rather than a simple decline in precipitation, drives the shift toward drier surface conditions. Placing Namangan alongside these regions indicates that foothill aridification is a broadly shared response of continental and mountain-front drylands to warming, strengthening the wider relevance of this study while underlining the value of the century-long observational record analyzed in this study.

The findings highlight the vulnerability of foothill environments and their importance in tracking continental climate change. They reveal that local warming and drying can occur without an obvious decrease in precipitation, challenging the assumption that declining rainfall is the main cause of drought in Central Asia. For regional water management, this suggests that adaptation strategies should focus on reducing evapotranspiration, restoring vegetation cover, improving soil-water retention, and increasing irrigation efficiency. More broadly, the Namangan case study provides valuable insights into the aridification process along elevation gradients. It demonstrates that mid-elevation drylands are among the first areas to experience irreversible hydrothermal change under increased warming.

6. Limitations and future research

However, the scope of this study is limited by the temporal and spatial resolution of the available data. The lack of detailed observed soil moisture records and hydrological datasets reduces the accuracy of long-term trend analysis. Therefore, future research should combine high-resolution satellite data with field measurements of moisture and energy flux observations to better understand hydrothermal feedback. Extending this approach to other foothill systems in Central Asia would help to determine whether the Namangan pattern is a localized anomaly or part of a wider regional trend.

More specifically, the analysis was conducted using processed summaries and gauge series of two meteorological stations rather than the full raw records, which were not available for reanalysis. As a result, formal non-parametric trend tests (Mann–Kendall and Sen's slope) and confusion-matrix accuracy metrics for the soil moisture maps could not be computed; hence, the reported trends should be read as consistent directional evidence rather than as significance-tested estimates. The soil moisture classification was based on four Landsat snapshots and optical indices that are sensitive to acquisition conditions; thus, some short-term variability may be embedded in the multidecadal signal. Finally, the relative contributions of climatic warming and human water use to the runoff decline cannot be distinguished using the present data. Future work should reconstruct the complete instrumental series to permit formal trend testing, add field measurements of soil moisture and energy flux, incorporate independent microwave soil moisture products, and extend the approach to other Central Asian foothill systems to determine whether the Namangan trajectory is representative of broader regional trends.

7. Conclusion

This study examined the impact of increased global warming on the hydrothermal and ecological balance of the Namangan foothills in eastern Uzbekistan. By combining long-term meteorological, hydrological, and satellite-based soil moisture data, the study provides the first spatially detailed assessment of climate–soil–water interactions in this transitional landscape. The analysis addressed three main propositions. First, temperature and precipitation records from 1881 to 2022 revealed a clear but uneven warming trend—strongest in low- and mid-elevation zones, with only small increases in rainfall. This confirms a local warming trend that exceeds the global average. Second, soil moisture mapping derived from Landsat data (1990–2023) showed a steady increase in dry and very dry soils, indicating ongoing drying despite stable or slightly higher precipitation levels. Third, long-term discharge data (1951–2021) showed that all major rivers have experienced reduced flow, linking hydrological depletion to surface drying and reduced snowmelt inputs. Together, these findings suggest a clear sequence: climate warming → soil drying → reduced water availability.

Conceptually, this study improves our understanding of the dynamics of aridification in continental foothill systems. It shows that regional drought intensification can happen without a clear decrease in rainfall, as rising temperatures shift the system from energy-limited to water-limited conditions. This evidence not only supports the global aridification hypothesis but also highlights how foothill environments act as early indicators of hydroclimatic change. Although data limitations prevented a detailed analysis, the observed patterns provide a useful basis for future modeling of hydrothermal feedback across Central Asia's drylands. Overall, the Namangan foothills demonstrate how local landscapes can reflect and amplify the broader climate-induced aridification processes in continental regions.

Beyond its conceptual contribution, the study has practical significance for regional water and land management. Because the decline in foothill soil moisture is driven more by rising evaporative demand than by declining rainfall, adaptation measures should prioritize strategies that conserve soil moisture and reduce evaporation. These include the broader implementation of mulching, terracing, and efficient irrigation already trialed locally, together with vegetation restoration on degraded slopes and catchment-scale coordination of water allocation between upstream abstraction and downstream demand. For the research community, the Namangan case supports treating mid-

elevation foothills as priority monitoring zones and early-warning indicators of continental aridification. The main priorities for future work are to reconstruct and formally test the long instrumental series, couple satellite indices with in situ moisture and flux measurements, and compare foothill systems across Central Asia so that adaptation planning can be based on regionally consistent evidence.

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Conflict of interest

The authors declare no conflict of interest.

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Writing–review & editing: Kenjabek Rozumbetov, Eranga Wimalasiri, Upaka Rathnayake

Availability of data

All data supporting the findings of this study are included within the article.

Further disclosure

The authors have used the ChatGPT AI platform to refine the language and grammar of the manuscript. However, none of the results or discussions are generated by AI platforms.

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Appendix

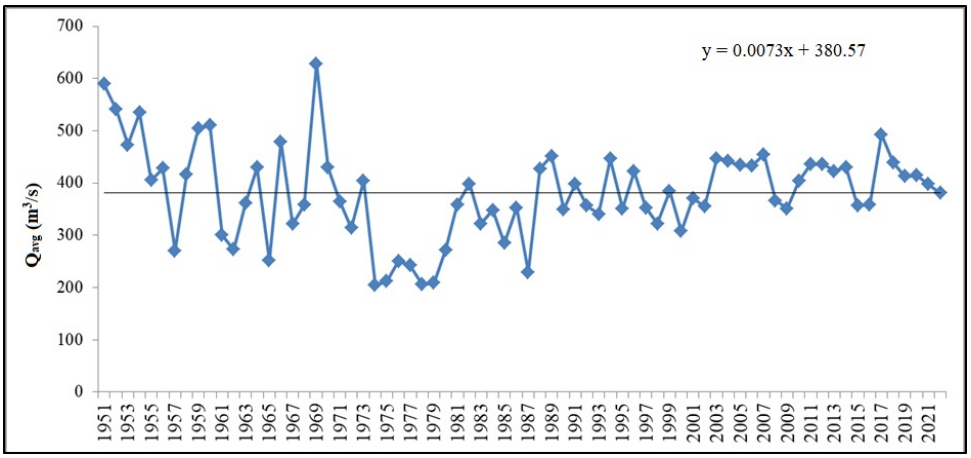

Figure A1. Chronological variation of the Norin River's average annual discharge at the Uchkurgan hydrological post (1951–2021)

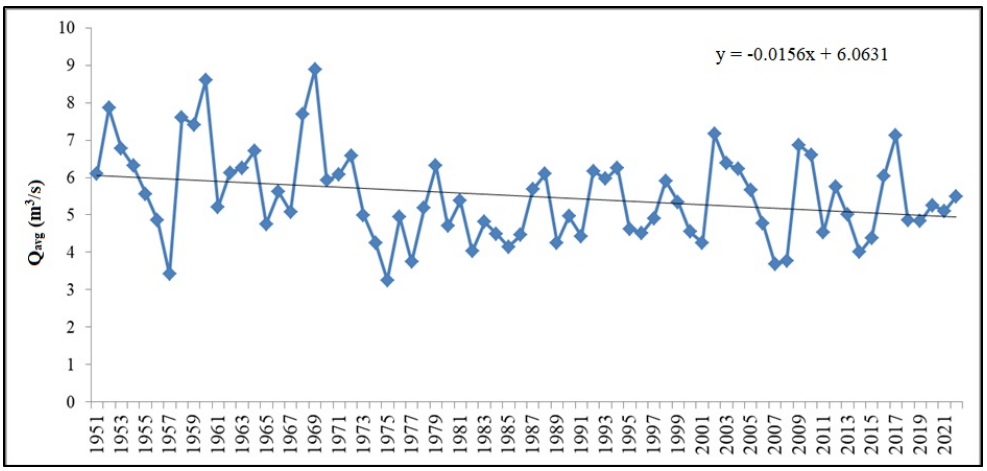

Figure A2. Chronological variation of the Podshaotasoy River's average annual discharge at the Tossu hydrological post (1951–2021)

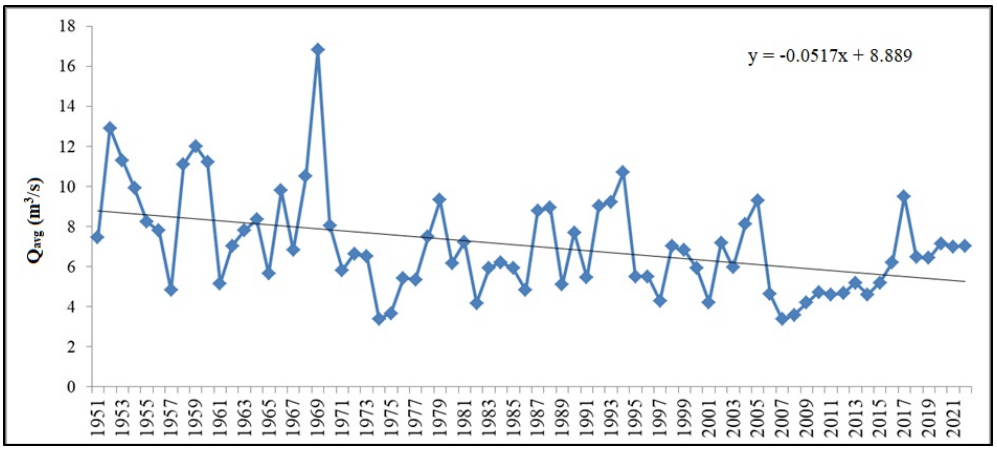

Figure A3. Chronological variation of the Kosonsoy River's average annual discharge at the Uryukti hydrological post (1951–2021)

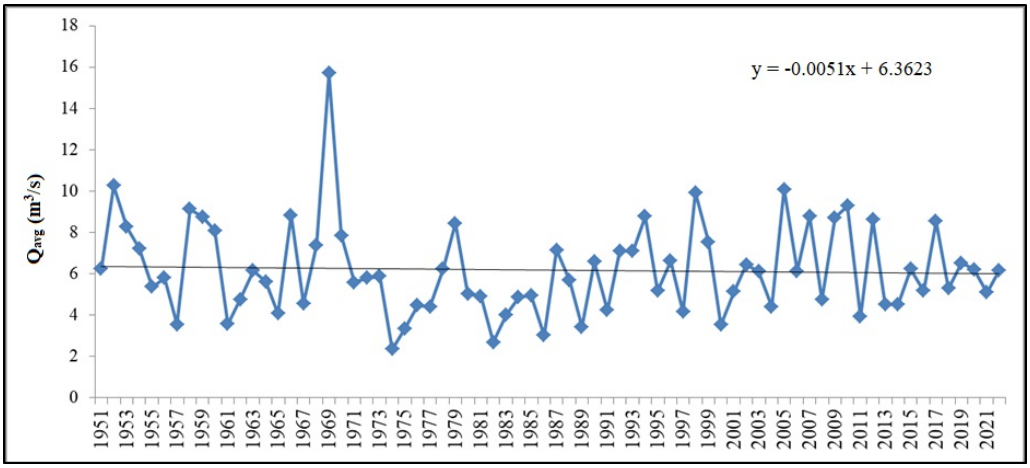

Figure A4. Chronological variation of the G'ovasoy River's average annual discharge at the G'ova hydrological post (1951–2021)

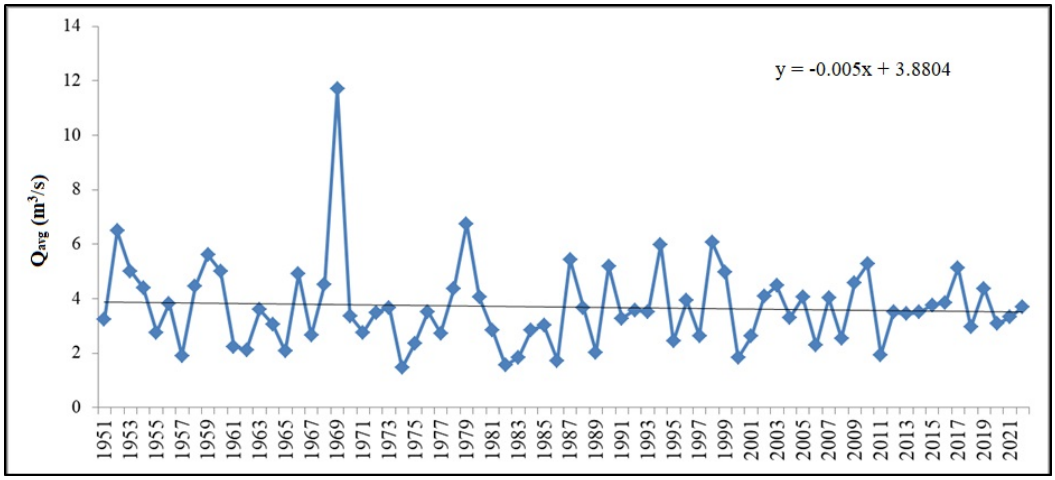

Figure A5. Chronological variation of the Chodaksay River's average annual discharge at the Julaybuloq hydrological post (1951–2021)