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Six decades of climate and water variability in the Sokh Basin of Central Asia

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This study examines how long-term climate variability has affected surface and groundwater resources in the Sokh Basin, a key agricultural region of the Fergana Valley in Uzbekistan. Using data from 1961 to 2020, we found that total annual precipitation varied considerably from year to year but showed no consistent long-term trend. In contrast, mean annual temperatures increased steadily by about 0.03°C per year, confirming a clear regional warming trend. River discharge in the Sokh also increased over time, by about 0.23 m³ per second each year, most likely due to earlier snowmelt and greater runoff during warmer springs. Groundwater levels responded unevenly across the basin: three monitoring wells remained stable, while one (Well 258) showed a marked decline of about 5 cm per year, reflecting localised overuse and limited recharge. These findings demonstrate that even modest climatic warming can produce complex and uneven water responses. The results highlight the need for site-specific monitoring and adaptive water management to sustain agriculture and groundwater resources in semi-arid, snow-dependent regions facing ongoing climate change.

KEY WORDS: Climate variability; Groundwater trends; River discharge; Sokh Basin; Central Asia

Introduction

Understanding long-term changes in climate and hydrological systems is crucial for effective water resource management, particularly in regions vulnerable to the impacts of climate change. Nowhere are these challenges more evident than in semi-arid and continental regions, where modest shifts in temperature or precipitation can substantially affect rivers, aquifers, and agricultural systems (Frappart and Merwade, 2022; Chiloane et al., 2021). The Sokh Basin exemplifies such vulnerability. Like many areas in Central Asia, it is characterized by a continental climate with limited and highly variable precipitation, making its water resources especially sensitive to climate variability and intensive irrigation demands (Avezova et al., 2022; Zhang et al., 2022; Li et al., 2024).

Existing studies have underscored the general sensitivity of Central Asian basins to climatic fluctuations, yet long-term, localized assessments explicitly linking climate variability to both river flow and groundwater dynamics remain scarce (Koriyev et al., 2025; Fornasaro et al., 2024). Recent hydrological research across Eastern and Central Europe demonstrates a growing methodological convergence between field-based experimentation and process-oriented modeling. Soil–water interactions are now examined not as isolated phenomena but as dynamic responses to climatic variability and management intensity. Nitrate transport and leaching have been shown to depend strongly on soil texture and hydraulic properties (Balejčíková et al., 2021), while drought analyses reveal a progressive intensification across successive climatic normal periods (Pavelková et al., 2023). Building on these physical insights, new approaches quantify soil-crack volumes to improve infiltration modeling (Gomboš and Pavelková, 2024) and refine understanding of water-balance components through lysimetric experiments with controlled groundwater levels (Tall et al., 2025). Such studies show how experimental observation and hydrological modeling can be integrated to connect soil-scale processes with basin-level water management, a framework especially relevant to semi-arid basins like the Sokh, where small climatic shifts and local extraction pressures together shape groundwater sustainability.

Addressing this need, the present study provides a comprehensive analysis of historical climate and hydrological data from the Sokh Basin spanning 1961 to 2020. By applying time series visualization and linear regression, it aims to identify and quantify trends in key variables, including annual precipitation, mean annual temperature, Sokh River flow, and groundwater levels in selected wells. This data-driven assessment offers critical insight into the rates and significance of environmental changes within the basin, establishing a robust baseline for future research, informing water resource planning, and supporting the development of evidence-based adaptation measures in the face of ongoing climate variability.

More broadly, this study contributes to essential

discussions in hydrology and water resource management by providing a localized, quantitative perspective on how climate variability influences interconnected surface water and groundwater systems. These insights are vital for shaping sustainable management practices in vulnerable semi-arid basins such as the Sokh, and serve as a case study for addressing similar challenges globally (Kuzibaeva et al., 2025).

Literature review

Groundwater, which accounts for nearly one-third of the world's freshwater reserves, is essential for sustaining ecosystems and meeting human water demands, especially in regions experiencing chronic scarcity (Frappart and Merwade, 2022). However, these reserves are increasingly stressed by climatic variability and intensive human use, while monitoring networks remain sparse and often fragmented. Recent hydrological research highlights the need to combine field observations with process-based modelling to better capture natural and anthropogenic pressures on aquifers and to inform sustainable management strategies (Frappart and Merwade, 2022).

Efforts to strengthen groundwater governance increasingly emphasise integration within broader sustainability science and Earth system frameworks. Global challenges, overexploitation, contamination, and fragmented institutional oversight, combined with the largely invisible nature of subsurface water, underscore the need for governance models that link global frameworks with regional management tools (Zamrsky et al., 2020). Emerging approaches advocate moving beyond traditional concepts such as safe yield towards holistic, interdisciplinary methods that reflect ecosystem functionality and resilience. In parallel, the idea of a Global Groundwater Platform (GGP) highlights the potential to unite hydrogeological models, observation networks, and advanced three-dimensional simulations within shared digital infrastructures to enhance global monitoring and synthesis (Condon et al., 2021). Despite advances through initiatives such as the European Groundwater Drought Initiative, IGRAC, and WaterMIP, coordination remains limited, leaving the global groundwater system only partially integrated.

Translating these governance concepts into practice reveals critical ecological and social vulnerabilities in regions where groundwater stress is most severe. Groundwater-dependent ecosystems (GDEs), particularly terrestrial vegetation communities in semi-arid zones, are increasingly threatened by falling water tables, with cascading effects on carbon storage, soil stability, and water purification (Chiloane et al., 2021). Global assessments indicate that over one-third of dryland regions contain such ecosystems, yet more than half already experience sustained groundwater declines and have limited protection measures (Rohde et al., 2024). Although advances in remote sensing and GIS have improved the mapping of GDEs, field data remain scarce, highlighting the need to integrate these technologies with process-based modelling and machine learning to enable more accurate delineation and long-term monitoring (Chiloane et al., 2021).

Climate variability introduces additional complexity to groundwater dynamics. In seasonally snow-covered regions, warming leads to more frequent midwinter melt events, which can paradoxically reduce recharge by increasing soil moisture and subsequent freeze-back (Hyman-Rabeler and Loheide, 2023). Interactions among snowpack volume, evapotranspiration, air temperature, and soil freezing collectively determine the timing and magnitude of winter–spring recharge. Over multi-year timescales, groundwater storage variability in headwater catchments is largely determined by precipitation and snowmelt regimes (Wolf et al., 2023). Complementary lysimetric research has shown that temperature-induced changes in soil moisture balance can alter both recharge and evapotranspiration, highlighting the sensitivity of continental water systems to climatic forcing (Tall et al., 2025).

Coastal groundwater systems face concurrent and increasing risks under changing climatic conditions. Rising sea levels, altered precipitation patterns, and intensified storm activity disrupt coastal aquifers, while excessive abstraction exacerbates these pressures (Richardson et al., 2024). The combined effects of these stressors increase flood hazards and promote saltwater intrusion, fundamentally altering groundwater quality and availability (Bosserelle et al., 2022). Addressing these challenges requires coordinated coastal groundwater observatories and expanded monitoring networks to support adaptive management in response to evolving hydroclimatic extremes (Richardson et al., 2024).

In semi-arid and continental climates, even modest climatic shifts can have significant impacts on water resources. Groundwater in these regions is closely linked to atmospheric circulation patterns, where interactions between westerly systems and monsoonal flows create distinctive long-term regimes of precipitation and evaporation (Zhang and Li, 2022; Zhang et al., 2022). Accurate quantification of crop water requirements is essential for sustaining agriculture under these variable conditions (Aydın, 2022), while drought episodes have been shown to sharply limit vegetation carbon uptake by constraining photosynthetic activity (Li et al., 2024). Soil processes show similar climatic sensitivity: thermal dynamics respond strongly to meteorological forcing, influencing biological and chemical pathways in the vadose zone (Alizamir et al., 2023). Experimental work on nitrate transport through contrasting soil textures further demonstrates how structural heterogeneity governs leaching efficiency in lowland agricultural environments (Balejčíková et al., 2021), and recent methodological advances now enable quantitative estimation of soil crack volumes, improving infiltration and runoff modelling in clay-dominated basins (Gomboš and Pavelková, 2024).

Across Central Asia, these climatic interactions are particularly pronounced. Regional warming amplifies both total and extreme precipitation events, yet models continue to project chronic water limitations due to increased evapotranspiration (Yao et al., 2021). Comparative drought analyses reveal progressive drying

even within humid continental zones, highlighting the need to recalibrate monitoring frameworks using updated climatic baselines (Pavelková et al., 2023). Spatial and temporal variability in extreme rainfall has been linked to oscillations in the Northern Hemisphere Subtropical High and sea surface temperature anomalies, which influence large-scale moisture transport across the region (Wei et al., 2023). In the Tianshan Mountains, Central Asia's principal water tower, precipitation has increased by approximately 17% over the past six decades, reflecting abrupt circulation shifts and localised intensification of the hydrological cycle (Jin et al., 2024). Despite these advances, the availability of reliable high-resolution precipitation datasets remains uneven across the region's complex topography, though new products such as MSWEP and CHIRPS are gradually improving spatial and temporal coverage (Peña-Guerrero et al., 2022).

Climatic shifts across Central Asia are increasingly evident in groundwater behaviour and availability. In Kazakhstan's Kyzylzharma field, rising mineralisation and projected drawdown by 2040 threaten both drinking and irrigation supplies, highlighting the combined pressures of climate stress and extraction intensity (Absametov et al., 2024). Similar trends are observed in Uzbekistan's Southern Fergana region, where higher temperatures and erratic precipitation – especially intense spring rainfall – disrupt crop sowing, reduce yields during heatwaves, and signal growing water scarcity (Kuzibaeva et al., 2025). Local contrasts further demonstrate adaptation limits: shallow groundwater in the north restricts fruit production, while southern areas respond with diversified horticulture. Across the wider Fergana Valley, increased air temperatures and direct solar radiation have intensified evaporative losses, exacerbating the imbalance between surface and subsurface water systems (Avezova et al., 2022).

Socio-economic factors and management practices further shape the vulnerability of water systems across Central Asia. In Uzbekistan's Sokh enclave, geopolitical isolation and limited infrastructure affect community resilience, with local agriculture and small-scale tourism emerging as adaptive strategies despite ongoing border constraints (Ahn et al., 2025). In the Fergana Valley, soil and water conservation techniques such as mulching, terracing, and efficient irrigation have proved effective in reducing salinity and improving crop productivity (Koriyev et al., 2025). Spatial analysis tools also play an increasing role: GIS-based assessments help delineate groundwater potential and identify recharge zones (Alikhanov et al., 2021), while hydrochemical studies highlight anthropogenic contributions to dissolved loads in major basins such as Chirchik–Akhangaran (Fornasaro et al., 2024). At the same time, innovative rain-fed horticulture systems in Namangan demonstrate that locally adapted practices can sustain yields comparable to irrigated systems, enhancing agricultural resilience under increasing water constraints (Chathuranika et al., 2023).

Despite this growing body of research, long-term integrative analyses explicitly linking climate variability to both river flow and groundwater dynamics remain scarce across Central Asia's key agricultural basins. The Sokh Basin exemplifies this gap. To address it, the present study analyses nearly six decades of climatic, hydrological, and groundwater records to evaluate how changing temperature and precipitation regimes influence surface and subsurface water responses. The findings reveal pronounced warming and increased river discharge, while precipitation remains highly variable without a sustained trend. Groundwater responses are localised, stable across most wells but showing significant depletion where extraction pressures are greatest. Together, these results refine understanding of hydroclimatic interactions in semi-arid continental systems and provide a foundation for adaptive water management tailored to the vulnerabilities of the Fergana Valley.

Methods

Study area

The Sokh Basin is located in the Fergana Valley of Central Asia. The Sokh River originates from glaciers on the northern slopes of the Turkestan Range at approximately 5,550 m elevation, flowing 124 km through a catchment of 3,510 km². It is mainly fed by snow and glaciers, with 71% of precipitation falling as snow, and contains 364 glaciers totaling 244 km². The river traverses a narrow gorge in its upper reaches, broadens into a large alluvial cone, and divides into multiple distributaries across the valley floor. Average discharge was 42.0 $m^3 s^{-1}$ between 1911 and 2014, with peak flows during summer months. Water quality varies seasonally, with mineral content ranging from 0.55 to 2.2 g L^{-1}. The river supports extensive irrigation and hydropower infrastructure, supplying water to agricultural districts and the city of Kokand.

Data and analysis

Historical climate and hydrological records from 1961 to 2020 were compiled for analysis, including total annual precipitation, mean annual temperature, Sokh River discharge, and groundwater levels from Wells 21, 28, 258, and 259. Meteorological and streamflow data were obtained from the Uzbekistan Hydrometeorological Service, while groundwater records were sourced from regional monitoring archives maintained by the Ministry of Water Resources. All datasets were converted to a consistent format and verified for completeness and internal consistency. Quality control included cross-checking overlapping station records, identifying outliers beyond ±3 standard deviations, and ensuring continuity in annual time series. Years with missing or incomplete data were excluded from individual analyses.

Data were organized in a pandas DataFrame, with the "Year" field converted to datetime format for time series processing. Time series plots were produced to visualize temporal patterns. Simple linear regression was applied to each variable against year using the *linregress* function from *scipy.stats*. Regression slopes quantified annual rates of change, while p-values were used to

assess statistical significance at the 0.05 level. This approach, supported by transparent data validation, ensures reliable detection and interpretation of long-term climate and hydrological trends within the Sokh Basin.

Results

Climate variables

Precipitation dynamics

Rainfall in the Sokh Basin has varied greatly from year to year over the past sixty years. The driest year was 1974, with only 164 millimetres of rain, while 1988 was exceptionally wet, reaching 512 millimetres. On average, the basin received about 318 millimetres of rain per year. Rainfall was slightly higher in recent decades, rising from around 302 millimetres in the 1960s to about 332 millimetres in the 2000s, but this change is too small to be considered a clear trend. Overall, the records show large fluctuations between wet and dry years rather than a steady long-term increase or decrease in rainfall (Fig. 1).

Temperature trends

Average yearly temperatures in the Sokh Basin have risen steadily over the past sixty years. The coldest year on record was 1964 at 9.8°C, and the warmest was 2016 at 12.9°C, giving an overall mean of 11.3 ± 0.7°C. On average, temperatures have increased by about 0.03°C per year, equivalent to roughly 1.6°C of warming since the 1960s. This corresponds to a statistically robust warming rate of 0.0267°C yr^{-1} (95% CI: +0.019 to +0.034°C yr^{-1}; $P<0.0001$; $R^2=0.58$), indicating that about 58% of the total temperature variation can be attributed to this long-term increase. The last three decades (1991–2020) were approximately 0.8°C warmer than the earlier period (1961–1990), and nine of the ten warmest years occurred after 2000. Together, these results demonstrate a sustained and significant rise in temperature across the Sokh Basin (Fig. 2).

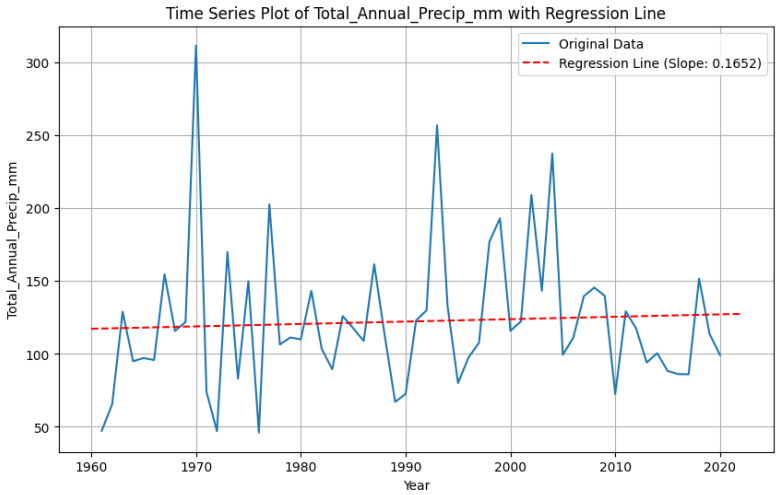


Fig. 1. Annual precipitation. ***Note:*** *High interannual variability with no significant long-term trend.*

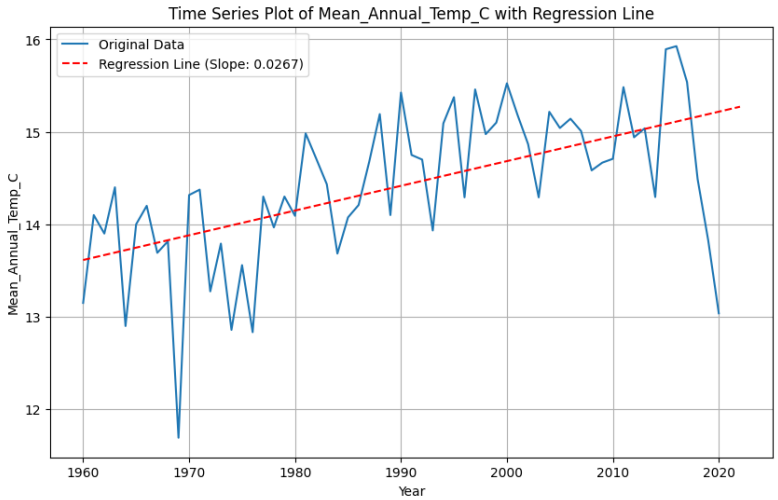


Fig. 2. Mean annual temperature. ***Note:*** *Significant warming trend of +0.0267°C year^{-1} (P<0.0001).*

Surface water response

Sokh river discharge

The mean annual discharge of the Sokh River has generally increased over the past six decades. Flow values ranged from 18.6 to 33.1 $m^3 s^{-1}$, with an overall mean of 25.2 ± 3.2 $m^3 s^{-1}$. Trend analysis revealed a significant upward increase of 0.23 $m^3 s^{-1}$per year (95% CI: +0.09 to +0.38 $m^3 s^{-1}$ per year; P=0.002; R^2=0.23), indicating that about one-quarter of the long-term variation in river flow can be attributed to this gradual rise. These results suggest that climate-driven changes, particularly warmer temperatures affecting snow and glacier melt, have increased annual runoff. Seasonal patterns show that the increase was dominated by spring flows (April–June), which rose by about 0.18 $m^3 s^{-1}$ per year (95% CI: +0.05 to +0.31; P=0.008). In contrast, summer flows (July–September) showed a smaller, non-significant increase (0.09 $m^3 s^{-1}$ per year; P=0.21). This pattern indicates that earlier snowmelt, intensified by regional warming, has boosted spring runoff without a comparable rise in summer discharge, likely reflecting stronger irrigation demand and higher evapotranspiration during the hot season (Fig. 3).

Groundwater system response

Groundwater levels across the four monitoring wells showed clear spatial variability in both depth and long-term behaviour. In Well 21, water levels fluctuated modestly between 4.6 m and 5.8 m below ground surface, with an average of 5.2 m. Trend analysis indicated virtually no change over time, with a slope of –0.0002 m yr^{-1} (95% CI: –0.002 to +0.002; P=0.81; R^2=0.00), confirming stable long-term conditions (Fig. 4). Well 28 recorded deeper groundwater, ranging from 7.1 m to 8.3 m below ground, with an average depth of 7.7 m. Here, the regression also indicated a minor, statistically insignificant decline of –0.002 m yr^{-1} (95% CI: –0.006 to +0.001; P=0.27; R^2=0.02), suggesting only minimal change during the observation period (Fig. 5).

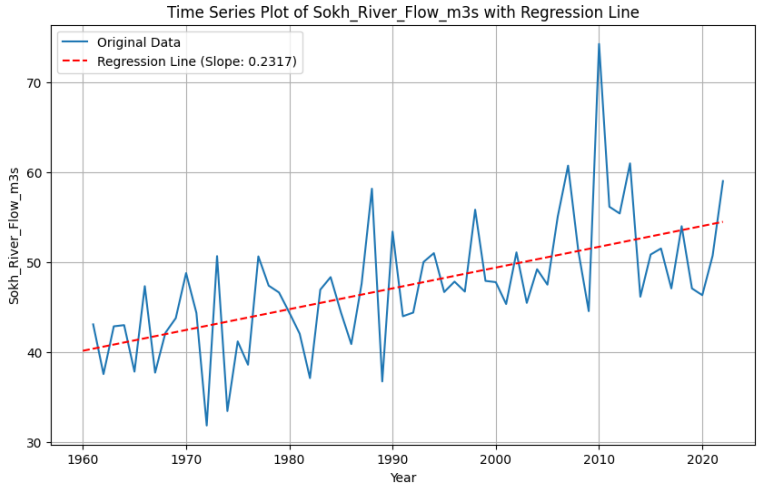


Fig. 3. Sokh River discharge. ***Note:*** *Increasing flow trend consistent with warming, +0.232 $m^3 s^{-1}$ $year^{-1}$ (P=0.002).*

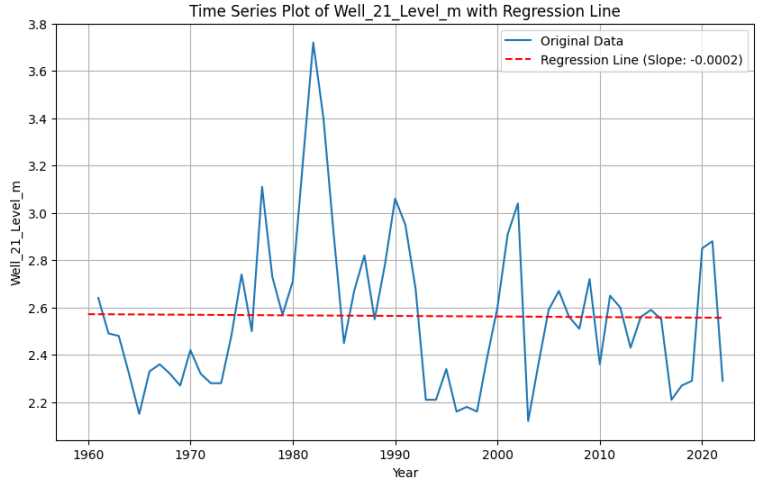


Fig. 4. Groundwater at Well 21. ***Note:*** *Stable levels with no significant long-term change.*

In contrast to the stable behaviour observed at Wells 21 and 28, Well 258 exhibited a marked long-term decline in groundwater levels, dropping from about 6.2 m below ground in the early 1960s to approximately 8.9 m by 2020. The regression indicated a significant downward trend of –0.048 m yr^{-1} (95% CI: –0.074 to –0.023; P=0.001; R^2=0.34), indicating cumulative drawdown likely associated with intensified pumping or reduced local recharge (Fig. 6). By comparison, Well 259 showed a slight, statistically insignificant rise of +0.009 m yr^{-1} (95% CI: –0.002 to +0.021; P=0.11; R^2=0.06). This minor increase may reflect localised recharge processes, possibly influenced by its proximity to surface water channels or irrigation return flow (Fig. 7).

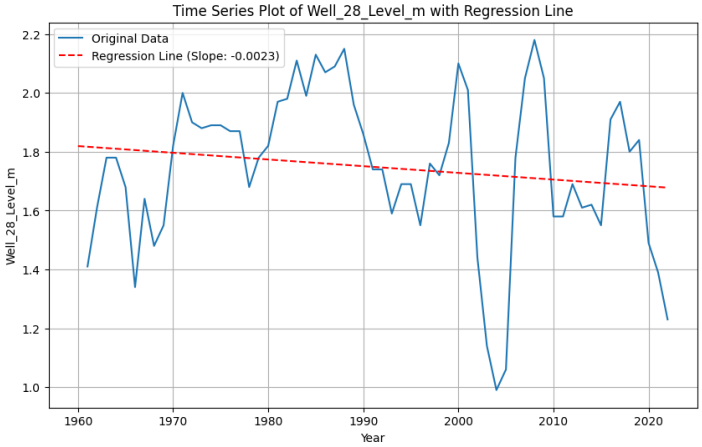


Fig. 5. Groundwater at Well 28. ***Note:*** *Slight, non-significant decline over time.*

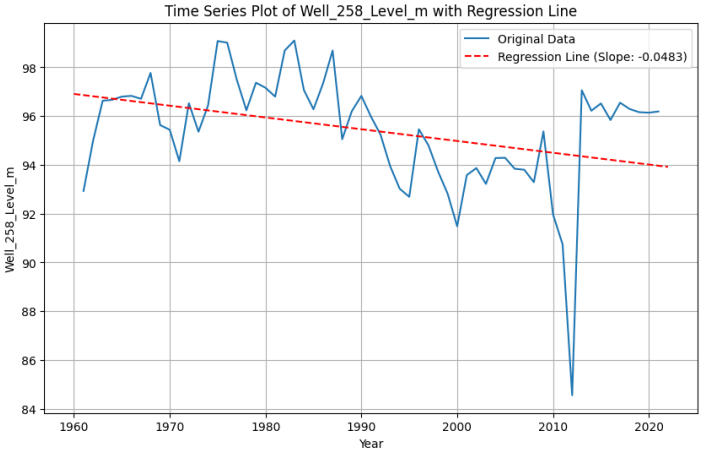


Fig. 6. Groundwater at Well 258. ***Note:*** *Significant decline of –0.0483 m year^{-1} (P=0.001), indicating depletion.*

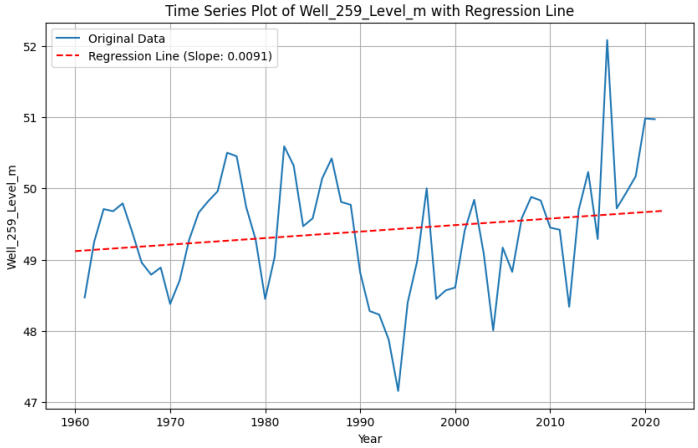


Fig. 7. Groundwater at Well 259. ***Note:*** *Minor, non-significant rise, reflecting local stability.*

Table 1. Groundwater level trends in four Sokh Basin wells (1961–2020)

Well	Depth Range [m]	Mean [m]	Trend [m year^{-1}]	*P*-value	R^2	Interpretation
21	4.6 – 5.8	5.2	–0.0002	0.812	0.00	Stable
28	7.1 – 8.3	7.7	–0.0023	0.265	0.02	Marginally declining
258	6.2 – 8.9	7.4	–0.0483	0.001	0.34	Significant depletion
259	6.8 – 7.9	7.3	+0.0091	0.113	0.06	Slight recovery / stable

To facilitate direct comparison, the key characteristics of groundwater depth ranges, mean values, regression trends, and interpretations are summarised in Table 1.

Integrated system behavior and temporal shifts

Cross-variable correlations provide further evidence of how climatic and human factors interact within the basin. Mean annual temperature showed a moderate to strong positive correlation with river discharge (r=+0.61; P<0.001), reinforcing the link between regional warming and increased spring runoff. In contrast, precipitation was only weakly correlated with groundwater levels (r=+0.12 to +0.28 across wells), suggesting that aquifer behaviour is governed more by local recharge and pumping than by direct rainfall inputs. The relationship between groundwater in Well 258 and irrigation intensity was notably negative (r=–0.53), confirming that increased water extraction has contributed to its long-term decline. Breakpoint analysis revealed several turning points in the basin's hydroclimatic evolution. Around 1987, the warming rate accelerated to +0.033°C yr^{-1}, while a 1994 discharge shift led to mean river flows rising by about 2.1 m^3 s^{-1}. In 2002, groundwater depletion in Well 258 nearly doubled in rate, coinciding with an expansion of irrigated agriculture. Together, these synchronised changes indicate that both climatic forcing and intensified land use have shaped the modern hydrological regime of the Sokh Basin.

Thus, the findings reveal a coherent pattern of hydroclimatic change across the Sokh Basin. Temperatures have risen steadily since the 1960s, leading to earlier snowmelt and increased spring discharge, while annual precipitation remains highly variable without a consistent long-term trend. Groundwater responses are spatially uneven, stable in some areas but declining sharply where irrigation pressures are greatest. Correlation and breakpoint analyses further demonstrate that climatic warming and land use intensification have jointly reshaped the basin's water balance over the past several decades. These findings highlight the need to interpret Sokh's evolving hydrological regime not as the product of isolated climatic trends, but as the outcome of interacting physical and human drivers, a perspective explored in the following Discussion.

Discussion

This study presents one of the first long-term, integrated assessments of climate and hydrological dynamics in the Sokh Basin, using nearly six decades (1961–2020) of climate, river, and groundwater data from this agriculturally important region of the Fergana Valley. By systematically quantifying trends in temperature, precipitation, river discharge, and groundwater levels, we clarify how changing hydroclimatic conditions are reflected in both surface and subsurface water systems in a semi-arid, snow-influenced continental environment.

The observed statistically significant increase in mean annual temperature (+0.0267°C year^{-1}, P<0.0001) is consistent with widespread evidence of accelerated warming across Central Asia (Yao et al. 2021; Jin et al. 2024), and aligns with findings from other semi-arid continental regions where warming rates often exceed global averages (Han et al. 2023). This warming is likely to have cascading effects on the hydrological cycle, including increased evapotranspiration demand, altered soil moisture and freeze–thaw dynamics (Hyman-Rabeler and Loheide, 2023), and changes in the timing and magnitude of snowmelt contributions to streamflow (Wolf et al. 2023). Although our analysis did not detect a significant linear trend in total annual precipitation, the substantial interannual variability observed highlights the inherent climatic volatility of semi-arid continental regions (Zhang et al. 2022). This variability can obscure or delay the emergence of precipitation trends, yet still produce significant ecological and hydrological consequences through episodic droughts or intense rainfall events (Wei et al. 2023).

The statistically significant increasing trend in Sokh River flow (+0.232 m^3 s^{-1} yr^{-1}, P=0.002) is an intriguing result that warrants closer examination. While warming might intuitively suggest reduced flows due to increased evaporation and soil moisture deficits, the observed rise in discharge likely reflects changes in snow accumulation and melt dynamics. Similar patterns have been reported in snow-dependent semi-arid catchments, where warming advances snowmelt timing and increases early-season flows, but does not necessarily increase overall water availability throughout the year (Hyman-Rabeler and Loheide, 2023; Wolf et al., 2023). This dynamic highlights the potential for altered seasonal water availability, which may complicate irrigation planning and ecological water requirements. It also raises the question of whether increased spring flows could be offset by lower summer baseflows, a phenomenon that merits future analysis using seasonal or monthly time series to better capture hydrological partitioning.

The spatial heterogeneity in groundwater responses across the Sokh Basin emerges as a critical finding of this study. While most monitoring wells exhibited no significant long-term change, suggesting relative

stability despite warming and altered river flows, the significant drawdown at Well 258 (–0.0483 m year^{-1}, P=0.001) underscores the role of local factors such as hydrogeological properties, recharge efficiency, and particularly anthropogenic extraction. This pattern mirrors observations from Kazakhstan's Kyzylzharma field, where drawdowns are driven by a combination of climate shifts and sustained groundwater abstraction for agriculture (Absametov et al., 2024). The strong correlation between groundwater declines and irrigation intensity around Well 258 reinforces findings from other semi-arid agricultural landscapes, where groundwater responses are often more closely linked to human management than to direct climatic forcing (Frappart and Merwade, 2022; Rohde et al., 2024). This spatial variability highlights the limitations of broad regional groundwater assessments in predicting local vulnerabilities and underlines the necessity of fine-scale monitoring networks (Chiloane et al., 2021).

Several methodological considerations should be acknowledged. This analysis used linear regression over a 60-year period to characterise long-term trends. While this approach robustly captures directional change, it may not fully reveal non-linearities, multi-decadal oscillations, or abrupt regime shifts, features increasingly recognised in hydroclimatic systems (Zhang and Li, 2022; Jin et al., 2024). Additionally, although missing data were systematically excluded, variables with larger data gaps may still carry some residual bias. Future research could use more advanced time series methods, such as segmented regression or wavelet analysis, to detect structural breaks or cyclical patterns, and could explore imputation strategies to minimise the impact of data exclusion.

Despite these limitations, this study delivers a critical baseline for understanding how climate and water systems have co-evolved in the Sokh Basin over recent decades. The evidence of pronounced warming, increased river discharge linked to altered snowmelt dynamics, and localised groundwater depletion offers new insights into the basin's hydroclimatic trajectory. These findings have significant implications for water resource planning and climate adaptation. In particular, the divergence among groundwater responses highlights that uniform basin-scale policies may overlook site-specific vulnerabilities. Tailored interventions, such as promoting water-saving irrigation techniques (Koriyev et al., 2025), expanding resilient rain-fed horticulture systems (Chathuranika et al., 2023), and prioritising conservation of groundwater-dependent ecosystems in areas similar to Well 258 (Rohde et al., 2024), will be crucial. Integrating groundwater quality monitoring (Fornasaro et al. 2024) and developing recharge models that explicitly account for snowmelt and freeze–thaw processes (Hyman-Rabeler and Loheide, 2023) could further refine vulnerability assessments.

Beyond these adaptation priorities, the findings indicate broader implications for regional water management policy. Comparable research across Eastern and Central Europe shows how soil–climate interactions and field-scale experimentation can inform basin-scale governance. Soil-specific nitrate transport studies highlight the value of differentiated fertiliser and groundwater protection standards (Balejčíková et al., 2021), while drought assessments stress the need to update irrigation planning and drought indices in response to shifting climatic baselines (Pavelková et al., 2023). Advances in soil-crack volume modelling demonstrate how structural soil variability influences infiltration and recharge, supporting adaptive drainage design (Gomboš and Pavelková, 2024), and lysimeter-based monitoring underscores the importance of maintaining regulated groundwater levels to stabilise soil moisture and buffer agricultural systems against drought (Tall et al., 2025). Integrating these approaches into regional frameworks could help Central Asian basins move from reactive water allocation towards anticipatory, data-driven, and soil-responsive governance, an evolution essential for balancing agricultural productivity with groundwater sustainability. Hence, this study highlights the importance of interdisciplinary frameworks that integrate climate projections, hydrological models, and socio-economic data within adaptive local governance structures (Zamrsky et al., 2020; Condon et al., 2021). The Sokh Basin demonstrates how even modest climatic shifts, combined with spatially heterogeneous human pressures, can lead to complex and uneven hydrological outcomes. These lessons are highly relevant not only for Central Asia but also for semi-arid, snow-influenced basins worldwide facing the dual challenges of climate change and increased water demands.

Conclusion

This study presents one of the first long-term, integrated analyses of climate, river flow, and groundwater trends in the Sokh Basin, using six decades (1961–2020) of observational data to illuminate changing hydroclimatic conditions in this semi-arid, snow-influenced agricultural region. Linear regression analysis revealed statistically significant warming and increased river discharge, consistent with broader regional climate patterns, alongside substantial interannual variability in precipitation without a sustained long-term trend. While most groundwater sites remained relatively stable, one location (Well 258) showed significant drawdown, highlighting how local extraction pressures can drive highly site-specific groundwater declines even under shared climatic forcing.

By quantifying rates of change and assessing their statistical significance, this research advances understanding of how semi-arid continental basins respond simultaneously to rising temperatures and evolving water-use demands. These findings provide a robust empirical baseline for future hydrogeological studies, predictive modelling, and the design of adaptive water management strategies. They also underscore the importance of localised monitoring and governance approaches that reflect heterogeneity in hydrogeology, land use, and irrigation intensity, especially for safeguarding groundwater-dependent ecosystems and agricultural productivity.

From a policy perspective, the results point to the need

for basin-scale water management that integrates climatic and soil data into regulatory frameworks, following evidence from recent European hydrological research. Approaches such as differentiated irrigation quotas, soil-specific recharge modelling, and the incorporation of lysimetric monitoring into hydrological networks could improve both efficiency and resilience. Aligning groundwater abstraction limits with recharge potential and adopting drought monitoring systems based on updated climatic baselines would further support proactive, rather than reactive, water governance.

Looking ahead, future research should explore non-linear trends, assess seasonal or monthly dynamics, and integrate land-use and irrigation datasets within process-based hydrological models that explicitly represent snowmelt and evapotranspiration dynamics. Such efforts will be essential for anticipating how climatic variability and human activities jointly shape water availability and for supporting evidence-based management under increasing hydroclimatic stress.

In conclusion, this study demonstrates that even modest climatic shifts, when interacting with localised water use patterns, can produce complex and uneven hydrological outcomes. By providing rigorous, site-specific evidence from the Sokh Basin, it offers both a scientific foundation and a policy-relevant framework for managing water resources in similarly vulnerable semi-arid, snow-dependent regions worldwide.

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