https://doi.org/10.5194/egusphere-2025-35
Preprint. Discussion started: 17 January 2025

Climatic, topographic, and groundwater controls on runoff response to precipitation: evidence from a large-sample data set

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Abstract. Understanding the factors that influence catchment runoff response is essential for effective water resource management. Runoff response to precipitation can vary significantly, depending on the dynamics of hillslope water storage and release, and on the transmission of hydrological signals through the channel network. Here, we use Ensemble Rainfall-Runoff Analysis (ERRA) to characterize the runoff response of 211 Iranian catchments with diverse landscapes and climates. ERRA quantifies the increase in lagged streamflow attributable to each unit of additional precipitation, while accounting for nonlinearities in catchment behavior. Peak runoff response, as quantified by ERRA across Iran, is higher in more humid climates, in steeper and smaller catchments, and in catchments with shallower water tables. The direction and approximate magnitude of these effects persist after correlations among the drivers (e.g., deeper water tables are more common in more arid regions) are accounted for. These findings highlight the importance of catchment attributes in shaping runoff behavior, particularly in arid and semi-arid regions, where climatic variability and groundwater dynamics are crucial factors in sustainable water resource management and effective flood risk mitigation.

1 Introduction

Runoff generation is influenced by the interaction of different processes which vary according to climate conditions and catchment properties (Zillgens et al., 2007). Investigating catchment hydrological responses to precipitation events can provide insights into the governing factors that control streamflow generation (von Freyberg et al., 2018).

Topography plays a significant role in rainfall-runoff responses (Beven and Kirkby, 1979; Hernandez et al., 2003; Zevenbergen and Thorne, 1987; Inaoka et al., 2020), with larger catchment areas often experiencing overland flow once the land becomes saturated, leading to a substantial increase in runoff (Inaoka et al., 2020). Although gravity influences flow along topographic and hydrological gradients, it is difficult to fully characterize dynamic runoff-generation processes using just topographic features such as slope, drainage area, and unit contour lengths (Mirus and Loague, 2013).

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The relationship between precipitation and potential evapotranspiration, as quantified by the aridity index (FAO and UNESCO, 1977), is another critical factor influencing runoff behavior. Previous studies have shown that runoff response correlates with the climatic aridity index (Saft et al., 2016; Barrientos et al., 2023; Matanó et al., 2024). The relation between runoff response and aridity may result from a less connected river drainage network, driven by lower precipitation, higher temperatures, and increased potential evapotranspiration. This effect may also be associated with reduced catchment storage levels (Eltahir and Yeh, 1999; Arora, 2002; Ragab and Prudhomme, 2002; Van De Griend et al., 2002; Rockström et al., 2010; Saft et al., 2016; Barrientos and Iroumé, 2018; Boisier et al., 2018; Barrientos et al., 2020; Barrientos et al., 2023).

A significant amount of runoff is generated by subsurface processes including groundwater flow and subsurface stormflow (Bronstert et al., 2023; Jasechko, 2016). In many landscapes, precipitation must initially replenish near-surface storage before runoff occurs. This process is common in arid regions with a strong surface water-groundwater connection and deep soil layers, highlighting the relationship between changes in rainfall-runoff behavior and catchment characteristics during dry periods (Matanó et al., 2024).

In Iran as in other arid and semi-arid environments, significant reductions in the availability of surface water resources over time and space has led to a growing dependence on groundwater, particularly in the southern, central, and eastern regions (Nabavi, 2018; Noori et al., 2021; Maghrebi et al., 2023). Over-extraction of groundwater can also affect runoff response in these regions. In environments where groundwater plays a significant role in maintaining streamflow during dry periods, a declining water table can lead to reduced groundwater discharge into rivers (Jasechko et al., 2021). As a result, surface runoff may become more erratic, and the response to rainfall events may intensify.

Here we investigate the runoff response of catchments across Iran, using Ensemble Rainfall-Runoff Analysis (ERRA: Kirchner, 2024). ERRA is based on recently developed methods for estimating impulse response functions in nonlinear, nonstationary, and heterogeneous systems (Kirchner, 2022). It is a data-driven, nonparametric, and model-independent approach for quantifying rainfall-runoff relationships across various time lags.

Although considerable progress has been made in elucidating the factors that influence runoff response, a comprehensive understanding of how topographic, climatic, and hydrological variables interact to shape runoff response remains elusive. While many studies have focused on individual drivers, the interactions between them and their combined impact on runoff response are still not fully understood. Specifically, our analysis addresses the following questions: (1) How do topographic, climatic, and groundwater variables, and their interactions, influence runoff response in catchments, and (2) How do variations in groundwater depth influence runoff response when accounting for other relevant factors such as slope, or catchment size?

In this study, we apply ERRA to analyze how runoff response is influenced by several interacting factors—including groundwater depth, aridity index, slope, and catchment area—across Iran's diverse climatic and topographic regions.

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2 Methods

2.1 Study sites

Iran has a diverse climate due to its varied topography and geography. The country's climate is primarily arid to semi-arid, with 35.5% of its land classified as hyper-arid, 29.2% as arid, and 20.1% as semi-arid. A further 5% of the country has a Mediterranean climate, while the remaining areas, located near the Caspian Sea where rainfall is more abundant, are classified as humid or hyper-humid (Ashraf et al., 2021). The average annual precipitation across Iran is about 240 mm; however, in the northern provinces near the Caspian Sea, rainfall can exceed 1,800 mm annually (World Bank, n.d.). In contrast, the central and eastern regions of Iran receive as little as 50 mm of rainfall. Potential evaporation also varies widely, from 500 mm annually in the northwest to 3,750 mm in the southern desert regions, exceeding rainfall by a factor of 75 on annual averages. The country's temperatures also vary dramatically, ranging from an average of 0°C in the north to 28°C in the south (Maghrebi et al., 2023).

2.2 Dataset

This study used daily streamflow data from 1,549 active hydrometric stations provided by the Iranian Water Resources Management Company (IWRMC). Each station is identified by a unique site code and the location of the stream gauge is given by its latitude and longitude. For each gauge, we first extracted the corresponding upstream sub-catchment using ArcGIS's watershed tools and the SRTM-DEM. Pour point snapping was used to match gauge locations to the drainage network. For 394 gages, we could not find a reasonable catchment and these gauges were discarded from our analysis, resulting in 1,155 sub-catchments with corresponding gauges and streamflow. Next, daily rainfall timeseries for each catchment were extracted from CHELSA's (Karger et al., 2017) global precipitation downscaling reanalysis, and catchments with unreasonable Q/P ratios (i.e., Q/P>0.8), were discarded from our analysis. In order to minimize the impact of dams, we excluded catchments where dams were visible on Google Earth or where dam effects were evident in the hydrographs.

To study groundwater-surface water interactions, we downloaded monthly timeseries of depth to groundwater published by Iran's Ministry of Energy for 13,538 wells covering the period 2000-2018. We calculated the temporal mean groundwater depth for each time series, then averaged these to obtain the spatial mean for each catchment. In total we have 211 catchments with rainfall-runoff data and corresponding groundwater levels. We categorized the average groundwater depth to the water table into three distinct classifications; the shallowest 25% of these catchments were classified as "shallow groundwater" (blue points in Fig. 1a), the deepest 25% were classified as "deep groundwater" (red points in Fig. 1a), and the remaining 50% were classified as "intermediate groundwater" (white points in Fig. 1a).

The aridity index (AI) is widely used as a proxy to compare climatic aridity across space and time (Arora, 2002; Nastos et al., 2013; Greve et al., 2019; Zomer et al., 2022; Barrientos et al., 2023). In this study we used the aridity index

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(AI = *P*/PET) as an indicator for climatic conditions. The mean AI value for each catchment is calculated from the Global Aridity Index Database (Trabucco and Zomer, 2018). Since AI is the ratio of precipitation to potential evapotranspiration, higher AI values indicate greater humidity.

Catchment-averaged topographic slope in this study was calculated from the 90-meter-resolution Shuttle Radar Topography Mission Digital Elevation Model (SRTM-DEM; http://srtm.csi.cgiar.org).

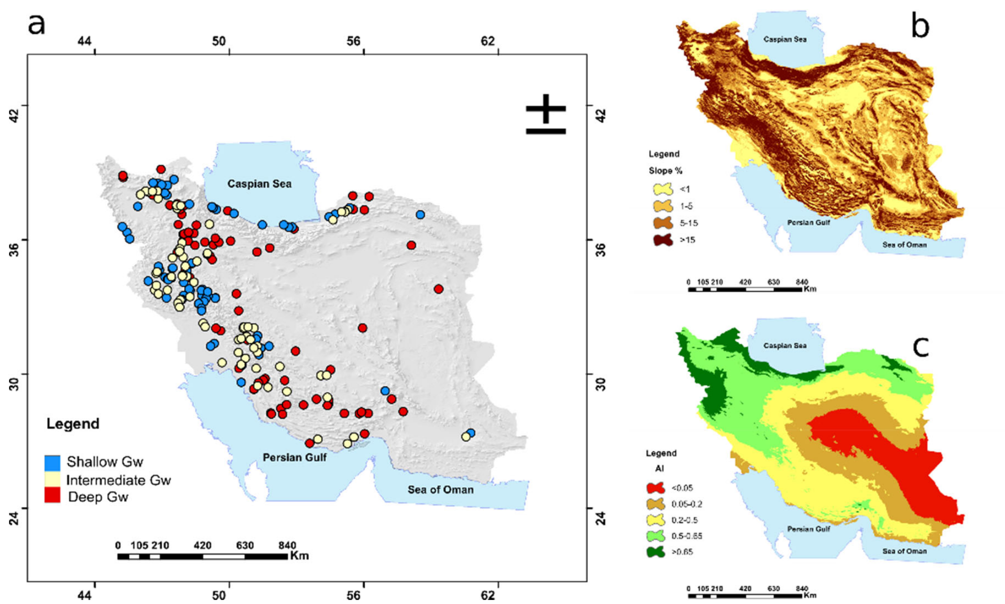

Figure 1. Locations of the study catchments, color-coded by groundwater depth and superimposed on a hillshade map of Iran (a), with maps of hillslope gradients (b) and aridity index, AI=P/PET (c). The study sites span widely differing climatic and topographic settings, with a wide range of groundwater depths.

2.3 Ensemble Rainfall-Runoff Analysis (ERRA)

Here, we examine the relationship between precipitation and streamflow using Ensemble Rainfall-Runoff Analysis (ERRA: Kirchner, 2022, 2024). ERRA is a data-driven approach that generalizes classical unit hydrograph methods to account for nonlinearity and nonstationary in hydrological response. ERRA's runoff response distributions (RRDs) measure the incremental increase in streamflow, per unit of precipitation input, over a range of lag times. With ERRA, we first estimated each catchment's nonlinear response functions (NRFs) relating daily precipitation intensity and incremental increases in streamflow at each time lag. The average of these NRFs, divided by the average precipitation intensity, yields the weighted average RRD. The weighted average RRD quantifies the catchment's average runoff response while accounting for its underlying nonlinearity, and also avoiding the overestimation bias that is inherent in applications of conventional regression-based unit hydrograph methods to nonlinear systems (see Sect. 3.4 of Kirchner, 2024). We also used ERRA's robust estimation option to reduce the influence of any outliers in our source data. With this approach, we generated runoff response distributions from our daily time series of precipitation and streamflow, and calculated the peak heights of these RRDs for all catchments. Figure 2 shows precipitation and streamflow time series for three example catchments with shallow groundwater levels and three catchments with deep groundwater levels. The corresponding RRDs for lags up to 10 days are shown in Fig. 3.

2.4 Factors affecting runoff response distributions (RRDs)

Relationships between RRD peak height and groundwater depth, aridity index, catchment slope, and catchment area were assessed using correlation and regression analyses. Spearman rank correlation coefficients (ρ) were used as robust measures of monotonic relationships between RRD peak height and the four climatic, hydrologic and topographic drivers (Fig. 4). We also accounted for the confounding effects of correlations among the different drivers using partial regression leverage plots (Fig. 5). These leverage plots measure how much the RRD peak height would change, per unit change in each of the drivers, if the other drivers were held constant; they also facilitate the identification of individual points that disproportionately affect the results (Cook and Weisberg, 1982; Hoaglin and Welsch, 1978; St. Laurent and Cook, 1992; Wei et al., 1998; Wright et al., 2019).

3 Results and discussion

3.1 Runoff response distributions (RRDs)

The impulse response of rainfall to runoff can be summarized using weighted average RRDs calculated from ERRA (Fig. 3). Runoff response distributions express how the runoff response to one unit of precipitation is distributed over time. At our 211 study catchments, runoff response typically peaks within the first day following precipitation input and then rapidly declines, lasting about 2-3 days. The results indicate that RRD peak heights are generally higher in catchments with shallow groundwater compared to those with deep groundwater, as illustrated in Fig. 2, which shows example comparisons between rainfall-runoff time series for three catchments with shallow groundwater and three with deep groundwater.

Our results show that catchments with shallower groundwater, particularly in western and northern Iran, tend to have higher average runoff peak heights. Shallow groundwater is common in Caspian Sea catchments, where many of Iran's permanent

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rivers are located, and in western regions, where high precipitation keeps groundwater close to the surface, aiding runoff. In contrast, more arid areas have deeper groundwater that is less connected to the surface, with infiltration to groundwater being limited by evaporative demand.

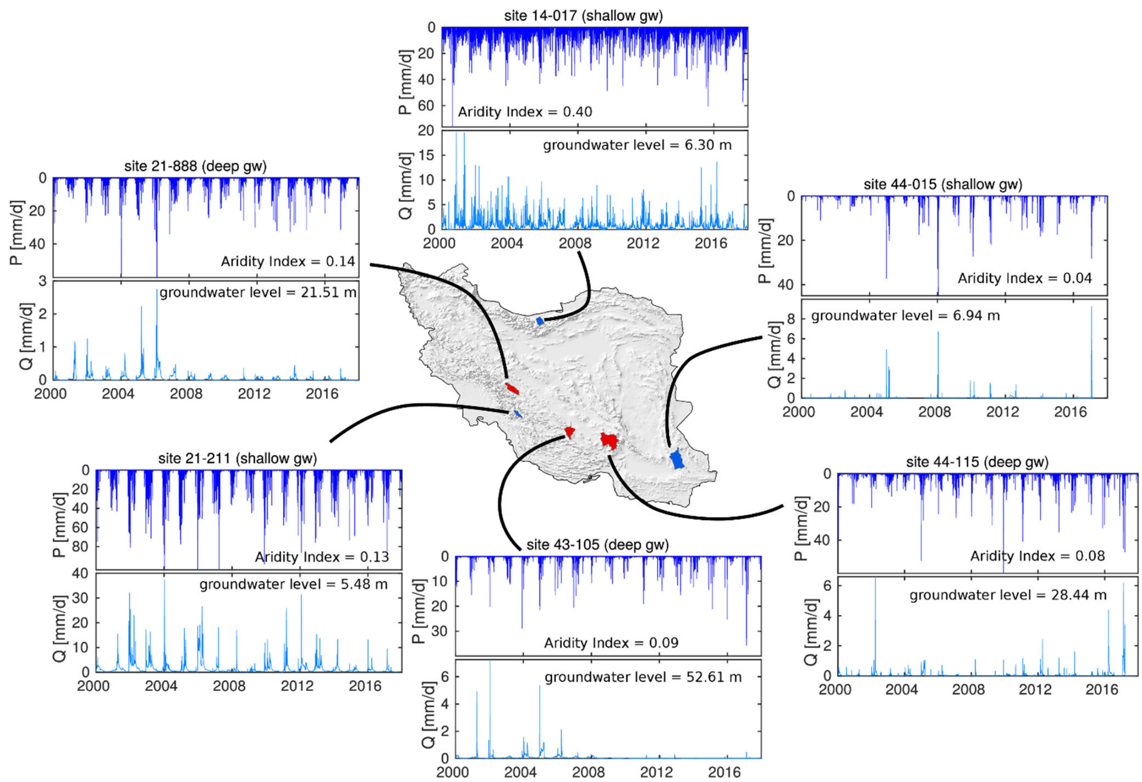

Figure 2. Time series of precipitation and stream discharge for 3 catchments with shallow groundwater (in blue on map) and 3 catchments with deep groundwater (in red on map). Note that axis scales vary so that each catchment's behavior is visible. These example time series reflect climatic differences across Iran; at the relatively humid Caspian Sea coast (site 14-017), precipitation and runoff events are frequent, whereas at the Persian Gulf & Sea of Oman catchment (site 21-211), precipitation and streamflow are strongly seasonal, with long dry periods in summer, and at the Central Plateau catchment (site 44-015), precipitation is highly episodic, yielding infrequent and brief runoff events. Catchments with deeper groundwater tend to have lower and more episodic stream flows (compare sites 21-888 and 21-211, for example). Many catchments with deeper (and declining) groundwater (e.g., 21-888 and 43-105) exhibit visually obvious decreases in streamflow, but some others (e.g., 44-115) do not.

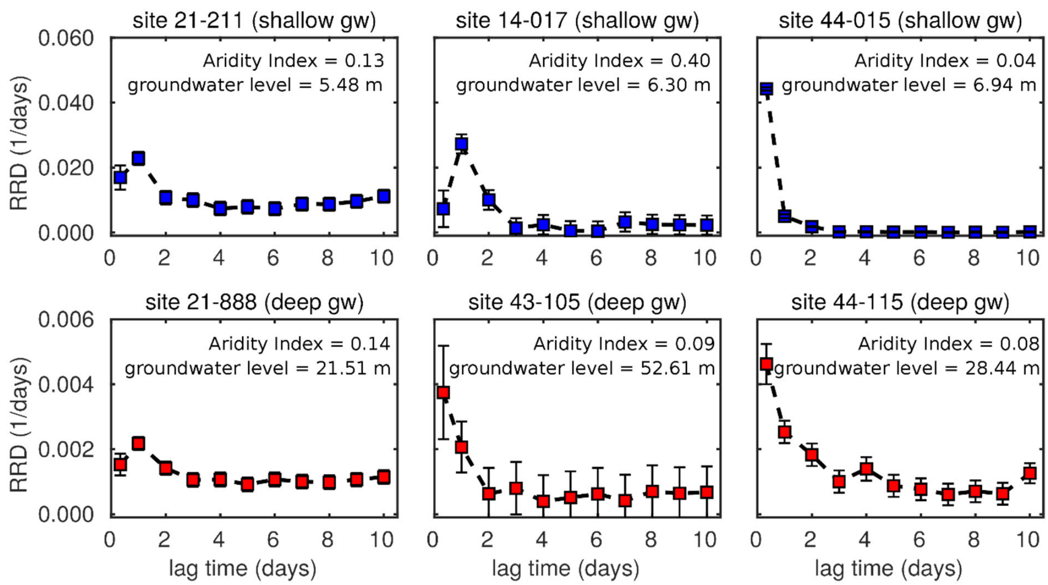

Figure 3. Weighted average runoff response distributions (RRDs) for the six example catchments shown in Fig. 2. Note the factor-of-10 difference in the axis scales for the catchments with shallow groundwater (top row) versus those with deep groundwater (bottom row). Runoff response typically peaks the same day that precipitation falls, or one day after, and decays away within the next two days. Sites with shallow groundwater (top row) exhibit much stronger runoff response than those with deep groundwater (bottom row; note different axis scale).

3.2 Factors influencing runoff peak height

Comparisons of RRD peak height and explanatory variables across catchments revealed a negative Spearman rank correlation coefficient (ρ = -0.27, $p<0.001$) between RRD peak height and groundwater depth (Fig. 4). This indicates that deeper groundwater levels are associated with smaller RRD peak heights, while catchments with shallower groundwater exhibit higher RRD peaks. In regions with shallow groundwater, limited subsurface capacity to store excess water leads to higher near-surface runoff during intense rainfall events. Rapid saturation of the surface layers can also contribute to increased overland flow (e.g., Steenhuis et al., 2005). Conversely, deeper groundwater levels enhance subsurface water retention, promoting infiltration and reducing surface runoff.

Differences in runoff behavior between areas with shallow and deep groundwater can also be attributed to subsurface flow paths. In regions with shallow water tables, translatory flow dominates, quickly displacing water stored in the soil (Hewlett and Hibbert, 1967), resulting in sharp runoff response peaks. In contrast, deeper groundwater allows for deeper infiltration of

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rainwater (Floriancic et al., 2024), bypassing intermediate layers and delaying saturation, thus leading to lower runoff response peaks and more gradual hydrological responses. However, the relatively weak correlation suggests that while groundwater depth may influence RRD peak height, it is unlikely to be the primary controlling factor in the study area.

The correlation analysis revealed a positive Spearman correlation (ρ=0.4, $p<0.001$) between RRD peak height and topographic slope, suggesting that runoff peak height is generally higher in steeper terrain. This finding is consistent with hydrological theory, as stronger topographic gradients accelerate runoff, contributing to sharper and more pronounced peaks (Inaoka et al., 2020). The observed correlation underscores the importance of topographic features in catchment hydrology and suggests that slope should be considered when assessing runoff potential in similar landscapes.

Additionally, a negative Spearman correlation (ρ=−0.27, $p<0.001$) was found between RRD peak height and catchment area, indicating that larger catchments tend to have somewhat lower peak heights. These smaller peak heights may result from dispersion of runoff peaks during transmission through the drainage network, or from the superposition of runoff peaks generated at different distances from the outlet (and thus lagged by different amounts before they reach the gauging station). Larger catchments also may encompass more varied topographic and soil characteristics, leading to a wider variety of sub-catchment runoff responses which are combined at the outlet. Nonetheless, the weak correlation suggests that catchment area alone does not dictate peak height, implying a more complex interaction among factors that influence runoff behavior.

The analysis revealed a negative correlation between the aridity index and RRD peak height (ρ=−0.18, $p<0.001$). This observation aligns with the research of Barrientos et al. (2023), who reported that runoff response is sensitive to variations in aridity. However, the weak correlation suggests that the aridity index may primarily influence other hydrological factors, such as groundwater levels, which more directly interact with runoff response. In arid regions (i.e., with low AI), groundwater wells tend to be deeper, whereas in more humid regions (with higher AI), wells are typically shallower. For instance, catchments near the Caspian Sea, with an AI > 0.65, often exhibit shallow groundwater and higher runoff peak heights. Similarly, regions in the wetter parts of Iran, with an AI between 0.5 and 0.65, also tend to show shallow groundwater and higher RRD peaks. In contrast, more arid regions exhibit deeper groundwater, with limited surface connectivity and reduced recharge due to higher evaporative demand, resulting in lower RRD peaks.

More generally, the relatively weak correlation between AI and RRD peak height suggests that AI is only one of many factors, including climatic, ecological, geographic, geological, and anthropogenic drivers, that influence runoff behavior (Van Dijk et al., 2013; Schewe et al., 2014; Barrientos et al., 2023).

Note that because the RRD quantifies the increase in streamflow per unit of precipitation, it normalizes for the differences in precipitation amounts between humid and arid catchments. Thus the higher RRD peaks in humid catchments do not simply reflect the fact that precipitation amounts tend to be higher there. Instead, the higher RRD peaks imply that humid catchments generate more streamflow per unit of precipitation, with the result that peak runoff increases more-than-proportionally to precipitation inputs.

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We used partial regression leverage plots to better understand the significance and relative influence of each driver for RRD peak height (Fig. 5). Figure 5 compares the leverage of log-transformed RRD peak height against the leverage of our four log-transformed explanatory variables (groundwater depth, aridity index, catchment area, and slope). Leverage plots show the effects of each driver, with the linear effects of the other drivers removed. The results shown in Fig. 5 are broadly similar to those shown in Fig. 4, with all variables being statistically significant drivers of RRD peak height. However, the influence of AI appears substantially stronger after the effects of the other drivers are accounted for (compare Figs. 5d and 4d). AI and topographic slope emerge as the strongest controls on RRD peak height, and catchment area is revealed to be the weakest (Fig. 5, Table 1).

These findings highlight the significant role of aridity in influencing both groundwater depth and runoff behavior. In humid regions (i.e., with high AI), where water tables are closer to the surface, limited subsurface storage capacity reduces the ability to absorb rainfall, potentially increasing near-surface runoff and accelerating hydrological response (Erdbrügger et al., 2023). Conversely, in arid regions (i.e., with low AI), groundwater tends to be deeper, and subsurface layers often retain more capacity to store rainfall. Under minimal precipitation, this leads to lower and delayed runoff peaks, as more water is absorbed into the unsaturated layers or lost through evaporation (Condon et al., 2020).

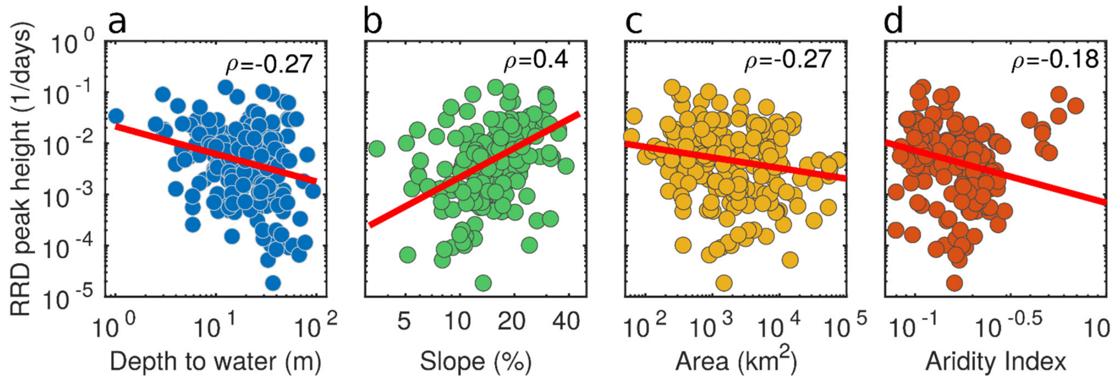

Figure 4. **Log-log scatterplots relating weighted average RRD peak height to four catchment attributes (all axes are logarithms): depth to groundwater (a), mean topographic slope (b), drainage area (c), and aridity index (d). All Spearman rank correlations (*ρ*) are statistically significant at p<0.001.**

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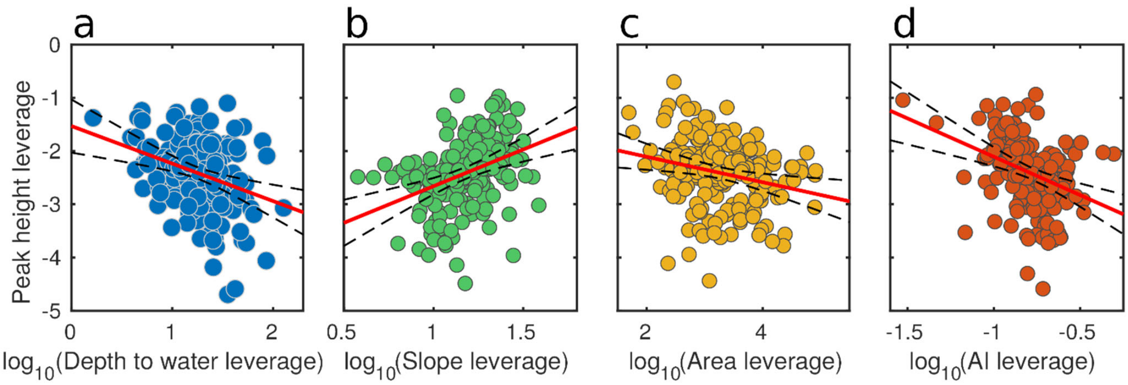

Figure 5. Leverage plots relating weighted average RRD peak height to four catchment attributes: depth to groundwater (a), mean topographic slope (b), drainage area (c), and aridity index (d) (all axes are logarithms). Leverage plots show the effects of each variable, with the linear effects of the other three variables removed. Red lines show multiple linear regression slopes (all statistically significant at $p<0.001$); dashed lines show $p=0.05$ confidence bounds.

Table 1. Partial regression results: effects of groundwater level, topography and climate on $\log_{10}$(RRD peak height)

variable	estimate	standard error	t ratio	prob>|t|	effect test sum of squares
$\log_{10}$(groundwater depth)	-0.70	0.16	-4.45	<0.0001	7.30
$\log_{10}$(AI)	-1.44	0.27	-5.29	<0.0001	10.30
$\log_{10}$(basin area)	-0.24	0.07	-3.45	0.0007	4.38
$\log_{10}$(mean slope)	1.38	0.25	-5.44	<0.0001	10.91

Conclusion

This study examines the complex relationships between topographic, climatic, and hydrological factors in shaping peak runoff response, as estimated by Ensemble Rainfall-Runoff Analysis (ERRA) for catchments across Iran. The findings reveal that topography and climate are important controls on runoff response distribution (RRD) peak height, with topographic slope and the aridity index being the most influential factors. Steeper slopes accelerate runoff, producing sharper peaks, while regions with higher AI (more humid climates) tend to have stronger runoff responses per unit of precipitation due to

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shallower groundwater tables and limited infiltration. Conversely, arid regions with lower AI (more arid climates) and deeper groundwater levels exhibit more subdued runoff responses due to greater subsurface water retention.

While groundwater depth and catchment area showed relatively weaker correlations with runoff peak height, these factors still have important effects. Shallow groundwater enhances runoff by rapidly saturating the surface, while deeper groundwater promotes infiltration. Larger catchment areas tend to reduce runoff intensity because flows generated in different parts of the catchment are not synchronized at the outlet. In conclusion, the study highlights the importance of considering multiple interacting factors when assessing runoff behavior, particularly in arid and semi-arid regions where climate and groundwater conditions play a crucial role in shaping hydrological responses. These insights may be helpful in developing effective water resource management strategies and mitigating flood risks in vulnerable regions.

Data availability. The stream flow and groundwater dataset used in our analysis is available for download at https://stu.wrm.ir. Daily rainfall time series for each catchment were obtained from the CHELSA climatology dataset (Karger et al., 2017). The aridity index dataset can be accessed from Trabucco and Zomer (2018).

Author contributions. The manuscript was written by ZE with contributions by all authors; the analysis was carried out by ZE and HJS under supervision of JWK. All authors collaboratively discussed the methodology, interpreted the results, and reviewed the manuscript.

Competing interests. The authors have declared that there are no competing interests.

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Preprint. Discussion started: 17 January 2025

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