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Development of an Integrated Drought Risk Map Using the Water Resources Approach Process Model: a Case Study of the Zayandehrud Dam Catchment, Iran

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https://doi.org/10.22093/wwj.2026.579368.3547 **Case Study**

Abstract

Drought is a recurring and destructive natural hazard in arid and semi-arid regions, where its impacts are often intensified by human-induced factors such as land degradation and groundwater overexploitation. Conventional drought assessments typically depend only on climatic indices and overlook the physical characteristics of the catchment that determine actual vulnerability. This study presents an integrated methodology for drought risk assessment through the development of a Water Resources Approach Process model. The WRAP framework combines a meteorological drought index (Standardized Precipitation Index) with key physical catchment attributes–including geology, geomorphology, land use, slope, and erosion potential–to produce comprehensive hazard and vulnerability maps. The methodology is applied to the Zayandehrud Dam Catchment in central Iran, a semi-arid region facing severe water stress. Long‑term data (1971–2014) from 15 meteorological stations and 9 streamflow gauges are analyzed. Homogeneity tests (Pettitt, SNHT, Buishand, von Neumann) are used to ensure data quality, and the Mann‑Kendall test is applied to detect trends. Drought hazard is characterized using the 12–month SPI, while vulnerability is assessed by integrating thematic layers of landform, geology, slope, groundwater depth, and erosion risk through a weighted scoring approach within a GIS environment. The final drought risk map is generated by overlaying the hazard and vulnerability layers on a 20 × 20 km grid. Results indicate that approximately 45% of the catchment area falls into high or very high drought risk categories. The western and north‑eastern sub‑catchments exhibit the highest risk due to a combination of high climatic variability, steep slopes, erosive soils, and intensive groundwater abstraction that has led to land subsidence. The central parts show moderate to low risk because of more favorable geological conditions for water retention. The WRAP model proves to be a robust tool for identifying drought‑prone areas and for supporting integrated water resources management and disaster risk reduction strategies in semi‑arid catchments.

Keywords:
Drought Risk, Water Resources Approach Process Model, Standardized Precipitation Index; Vulnerability Mapping, GIS, Zayandehrud Dam Catchment.

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1. Introduction

Drought is one of the most complex and damaging natural hazards, affecting more people globally than any other hazard (Wilhite et al., 2014). Its impacts are particularly severe in arid and semi-arid regions where water resources are already limited. Iran, with an average annual precipitation of less than 250 mm, is highly vulnerable to drought (Keshavarz et al., 2013). The Zayandehrud River Basin, a vital water source for central Iran, has experienced recurrent and severe droughts over the past decades, compounded by increasing water demand and unsustainable management practices (Madani and Mariño, 2009).

Effective drought management requires a shift from reactive, crisis-driven approaches to proactive, risk-based frameworks (Hayes et al., 2004). Risk is defined as the product of hazard (the probability of a drought event) and vulnerability (the susceptibility of the system to its impacts) (Blaikie et al., 2004). While numerous indices exist for characterizing meteorological drought, such as the Standardized Precipitation Index[1] (McKee et al., 1993), they alone are insufficient for comprehensive risk assessment. Vulnerability depends on a multitude of physical, social, and economic factors operating at the catchment scale (Wilhelmi and Wilhite, 2002).

Recent research emphasizes the need for integrated approaches that combine climatic data with catchment characteristics like geology, geomorphology, land use, and soil properties (Pandey et al., 2010; Guo et al., 2020). These factors control infiltration, runoff generation, groundwater recharge, and erosion, thereby mediating the translation of precipitation deficits into hydrological and agricultural drought impacts. For instance, catchments with steep slopes, impermeable geology, and degraded land cover are more prone to rapid runoff loss and reduced groundwater storage, exacerbating water scarcity during dry periods (Borgatti and Soldati, 2010). Similar integrated approaches for drought risk assessment have been successfully applied in other semi-arid catchments globally (Pandey et al., 2010; Guo et al., 2020), as well as in Iran using hydrological modeling (Eslamian et al., 2017; Safavi et al., 2014).

More recently, Iran has experienced one of its most severe drought episodes during the water years 2024–2025. Nationwide precipitation during this period was approximately 39.4% below the long-term average, with the Zayandehrud Basin facing a 15–25% reduction in runoff compared to baseline conditions (IRIMO, 2025; Eslamian et al., 2017). This recent crisis further highlights the urgent need for integrated drought risk assessment tools such as the Water Resources Approach Process[2] model. Previous drought risk assessment methods include purely climatic indices (SPI, PDSI[3]) which are simple but ignore catchment physical characteristics (Wilhite et al., 2014; Mishra and Singh, 2010); distributed hydrological models (SWAT) which are accurate but data-intensive and time-consuming (Arnold et al., 2012); and multi-criteria decision-making[4] methods which integrate qualitative and quantitative criteria but suffer from subjective weighting (Safavi et al., 2014).The proposed WRAP model combines the simplicity of index-based approaches with five physical vulnerability indicators and produces spatially explicit risk maps directly interpretable for water managers.

The novelty of this study lies in three aspects: (1) the introduction of the WRAP model as a simple yet robust framework for integrating climatic and physical data; (2) the explicit linkage between SPI-12 hazard mapping and five physical vulnerability indicators (landform, geology, slope, groundwater depth, erosion risk); and (3) the production of a spatially explicit drought risk map (20 km×20 km grid cells) for the Zayandehrud Dam Catchment[5], which has been severely affected by recurrent droughts but lacks such a decision-support tool. Compared to previous integrated assessments in the basin (Safavi et al., 2014; Madani and Mariño, 2009), our WRAP model is more transparent, requires fewer input data, and produces directly interpretable risk maps for resource allocation.

2. Study areas

The ZDC is located in central Iran between latitudes 32° 02' to 33° 24' N and longitudes 49° 47' to 50° 54' E, covering an area of approximately 5,051 km² (Fig. 1). The catchment is part of the Gavkhuni Basin and includes the headwaters of the Zayandehrud River, the largest permanent river in central Iran. Elevation ranges from about 1,900 m at the dam outlet to over 4,200 m in the Zagros Mountains in the west. The climate is semi-arid, with mean annual precipitation varying from <300 mm in the eastern lowlands to >1,400 mm in the western highlands. Precipitation is highly seasonal, with >70% falling between November and April, mostly as snow at higher elevations (Droogers et al., 2001).

Geologically, the ZDC is divided into two distinct zones: the western high Zagros zone, characterized by thrust faults, fractured limestones, and high water yield; and the eastern metamorphic-sedimentary zone with lower permeability and groundwater potential. Land use consists of rangelands (45%), agriculture (30%), forests (10%), and urban/industrial areas (5%). The catchment supplies water for over 5 million people, including the city of Isfahan, and supports extensive irrigated agriculture. However, rapid population growth, industrial

[1] Standardized Precipitation Index (SPI)

[2] Water Resources Approach Process (WRAP)

[3] Palmer Drought Severity Index (PDSI)

[4] Multi-Criteria Decision-Making (MCDM)

[5] Zayandehrud Dam Catchment (ZDC)

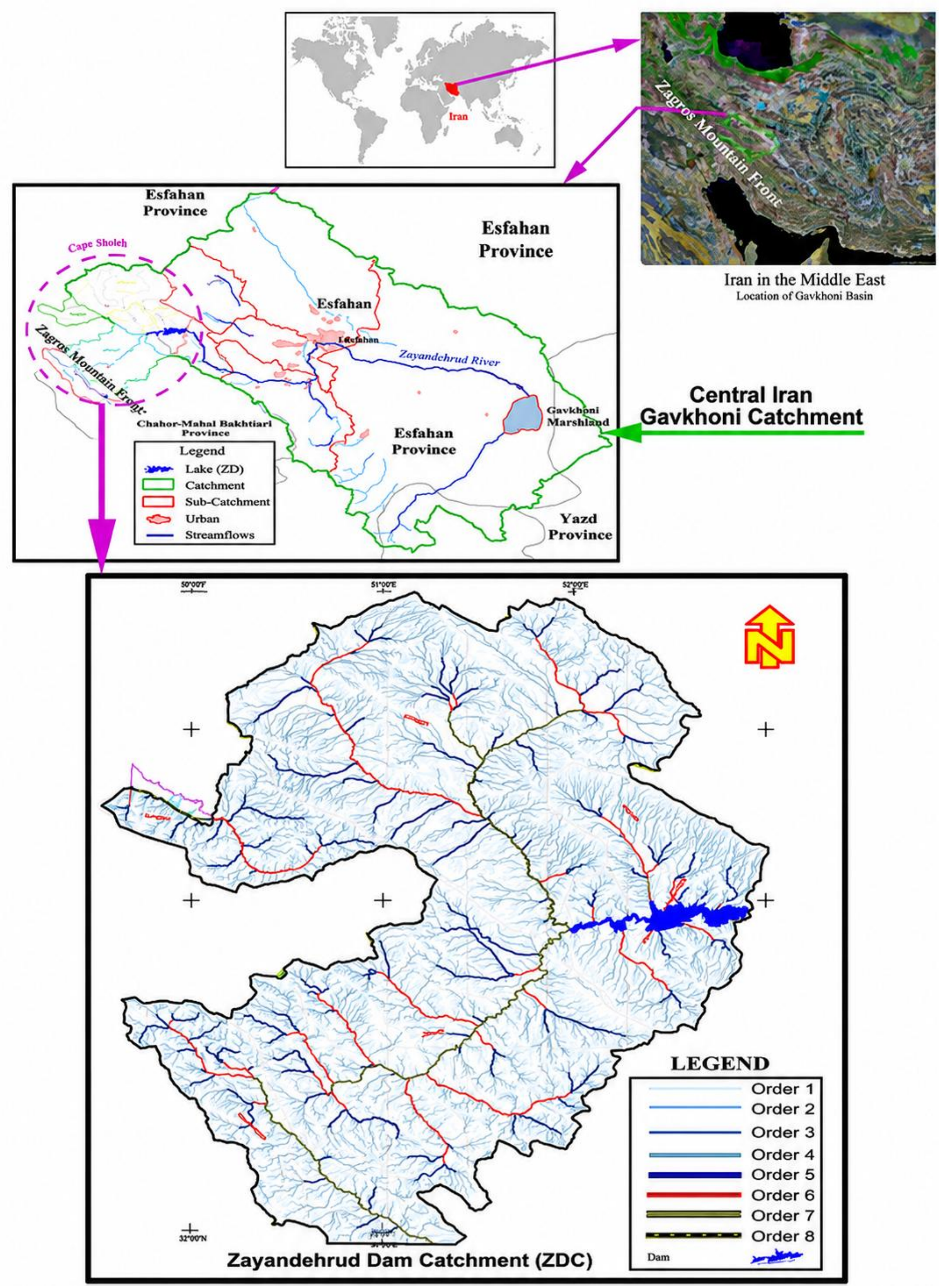

Fig. 1. Location map of ZDC with meteorological and streamflow stations

expansion, and recurring droughts have led to severe water stress, declining groundwater levels, and land subsidence, notably in the Damaneh plain (Gohari et al., 2013).

The baseline data for this study covers the 1971-2014 period. However, to demonstrate the ongoing relevance of our findings, we have compiled recent hydrological data for the years 2021-2024, which is summarized in Table 1. The climatological normal data for 1991–2020 were extracted from the Islamic Republic of Iran Meteorological Organization (Javanshiri and Rahmdel, 2024), while the recent runoff reduction estimates were derived from Eslamian et al., (2017), a study specifically focused on the Zayandehrud Basin.

It should be noted that post-2014 data were not used for calculating standard climatic indices (e.g., SPI) because the World Meteorological Organization[1] recommends a minimum 30-year baseline period. The latest climatic normal period for Iran is 1991–2020. However, to demonstrate the persistence of drought in recent years, reports from (IRIMO, 2025, Javanshiri and Rahmdel, 2024) and the Isfahan Regional Water Company indicate severe precipitation deficits (approximately 39.4% below the long-term average in 2025) and a decline in Zayandehrud Dam storage to less than 20% of capacity (Table 1).

While the core trend analysis is necessarily based on the pre- and post-IBWT periods (1971-1985 vs 1986-2014) to avoid confounding effects of the regime shift, it is worth noting that the exceptional drought conditions have continued and even intensified after 2014. For instance, the 2024-2025 water year was one of the driest on record in Iran, and the Zayandehrud Dam storage dropped to less than 11% of capacity in early 2025 (Tehran Times, 2025).

This recent data confirms the persistent and severe drought conditions in the basin, highlighting the critical need for the WRAP model presented herein.

3. Data and methodology

3.1. Data sources

The study utilized long-term (1971–2014) daily and monthly data from 15 meteorological stations and 9 streamflow gauging stations distributed across the ZDC (Table 1). Data were obtained from the Isfahan Meteorological Organization and the Isfahan Regional Water Company. Station selection was based on record length, data completeness, and spatial coverage. Additional spatial data included a 90 m resolution Digital Elevation Model[2] from the National Cartographic Center of Iran, geological maps (1:250,000) from the Geological Survey of Iran, land use/land cover maps from the Ministry of Agriculture, and soil erosion maps.

3.2. The WRAP model framework

The WRAP model is a conceptual and analytical framework designed to integrate hydro-climatic and physiographic information for drought risk assessment. The model operates in three main stages: (1) drought hazard assessment based on meteorological indices; (2) drought vulnerability assessment based on catchment physical characteristics; and (3) risk mapping through spatial overlay (Fig. 2).

3.2.1. Drought hazard assessment (SPI)

The SPI was selected as the primary indicator of meteorological drought due to its robustness, multi-scalar nature, and recommendat`ion by the (WMO, 2012). SPI was calculated for 3-, 6-, 12-, 24-, and 48-month time scales using monthly precipitation data. The 12-month SPI (SPI-12) was chosen for risk mapping as it reflects medium-term moisture conditions influencing both surface water and groundwater.

The SPI is calculated as

$$SPI = \frac{(Pi-\mu)}{\sigma} \quad (1)$$

Where,
P_i = accumulated precipitation over the given time interval (mm),
μ = long-term mean precipitation for the same interval (mm),
σ = standard deviation of precipitation (mm).

SPI computation involved fitting a gamma distribution to the long-term precipitation record at each station. The cumulative probability was then transformed to the standard normal distribution using the approximate transformation provided by Abramowitz and Stegun, (1965). The goodness-of-fit of the gamma distribution was evaluated using the Kolmogorov-Smirnov test. For stations where the gamma distribution was rejected, the Generalized Extreme Value[3] distribution was applied, which provided superior fits ($p > 0.99$) for most stations.

Drought events were classified based on SPI values following McKee et al., (1993): moderately dry ($-1.5 < SPI \leq -1.0$), severely dry ($-2.0 < SPI \leq -1.5$), and extremely dry ($SPI \leq -2.0$). For each station, the frequency of occurrence of each drought category was calculated. These point frequencies were then interpolated across the catchment using ordinary kriging in Surfer 10 software to generate continuous surfaces

[1] World Meteorological Organization (WMO)
[2] Digital Elevation Model (DEM)
[3] Generalized Extreme Value (GEV)

Table 1. Long-term climatological normal (1991–2020) and recent drought anomalies (2021–2025) in the ZDC

Period	Parameter/Condition	Value/Status	Reference/Source
1991–2020	Mean annual temperature (Iran) vs. 1981–2010	+0.47 °C Increase	(Javanshiri and Rahmdel, 2024)
1991–2020	Mean annual precipitation (Iran) vs. 1981–2010	+5.4 mm Increase	(Javanshiri and Rahmdel, 2024)
1991–2020	Precipitation pattern (Zagros region)	Wetter conditions compared to national trend	(Javanshiri and Rahmdel, 2024)
2021–2025	Runoff volume (Zayandehrud basin)	15–25% Reduction vs. long-term average	(Dorafshan et al., 2024)
Water Year 2024 –2025	National precipitation anomaly	~39.4% Below long-term average	(Tehran Times, 2025)
2023 –2025	Isfahan province precipitation	Mixed patterns (e.g., 118% increase in late 2025); drought persists	(IMNA, 2025)

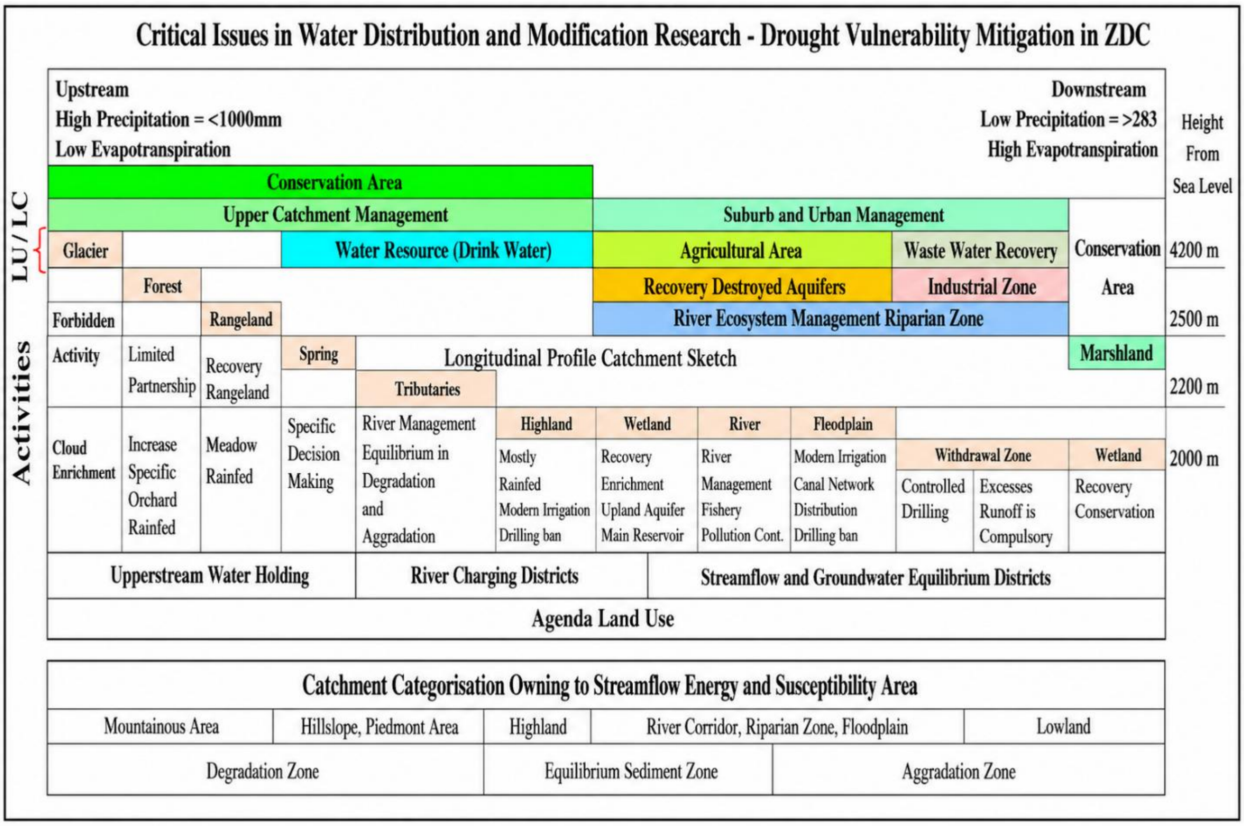

Fig. 2. Flowchart of the WRAP model methodology

representing the probability of moderate, severe, and extreme drought. The three surfaces were combined using a weighted linear combination to produce a final Drought Hazard Index[1]

$$DHI = (MD\_w \times MD\_s) + (SD\_w \times SD\_s) + (ED\_w \times ED\_s) \quad (2)$$

Where,
MD = frequency surface of moderate drought (SPI between -1.5 and -1.0),
SD = frequency surface of severe drought (SPI between -2.0 and -1.5),
ED = frequency surface of extreme drought (SPI ≤ -2.0),
w = weight assigned to each drought severity category,
s = score assigned to each drought severity category (higher scores for more severe categories).
Weights were normalized to sum to 1.

3.2.2. Drought vulnerability assessment

Vulnerability was defined as the degree to which the catchment's physical characteristics predispose it to adverse drought impacts. Five key indicators were selected based on literature review and data availability: (1) landform type, (2) lithology/geology, (3) slope gradient, (4) groundwater depth, and (5) soil erosion risk. The selection of vulnerability indicators followed established methodologies in hydrological and drought risk assessment studies (Pandey et al., 2010; Guo et al., 2020; Wilhelmi and Wilhite, 2002). Thematic maps for each indicator were prepared in ArcGIS 10.

- Landform: Derived from the landform map (scale 1:250,000) and classified into eight categories (mountains, hills, plateaux, piedmont plains, lowlands, floodplains, colluvial fans, water bodies). Each class was assigned a score from 1 (low vulnerability) to 8 (high vulnerability) based on its water retention capacity and susceptibility to degradation.

The scoring was based on field observations, literature review, and expert judgment, following standard geomorphological principles: flat and low-lying landforms with fine sediments and shallow water tables (e.g., floodplains, lowlands) received low vulnerability scores due to high water retention and low degradability, whereas steep, rocky, or coarse-textured landforms (e.g., mountains, hills, colluvial fans) received high vulnerability scores because of rapid runoff, low storage, and high erosion potential.

- Geology: Lithological units were first grouped by geological era and rock type using the 1:250,000 geological map. Vulnerability scores were then assigned inversely to the units' permeability and groundwater potential. Specifically, units with low permeability (such as metamorphic rocks and Paleozoic formations) have limited ability to store and transmit groundwater; therefore, they received higher vulnerability scores (indicating greater drought susceptibility). Conversely, highly permeable units (e.g., Quaternary alluvium) received lower vulnerability scores due to their higher groundwater storage capacity.

- Slope: Derived from DEM and classified into seven classes (0–2%, 2–5%, 5–8%, 8–12%, 12–20%, 20–30%, 30-60%, >60%). Steeper slopes were assigned higher scores due to increased runoff and erosion potential.

- Groundwater depth: Interpolated from water table measurements at 9 piezometric wells (2014 data). Deeper water tables received higher scores, indicating greater difficulty in accessing groundwater during drought.

- Erosion risk: Derived from the soil erosion map of the Ministry of Agriculture (modulus in $t\ km^{-2}\ yr^{-1}$), classified into six categories from negligible to extremely severe. Higher erosion risk classes were assigned higher vulnerability scores.

All thematic maps were rasterized at a 20 × 20 km grid cell resolution (25 cells covering the catchment). For each grid cell, the score for each indicator was extracted. The composite Drought Vulnerability Index[2] for each cell was calculated as the average of the normalized indicator scores

$$DVI = ((Lfscore + Geoscore + Slpscore + Gwscore + Eroscore)/5 \quad (3)$$

Where,
Lf_score = normalized score for landform type (1 to 8, higher = more vulnerable to drought),
Geo_score = normalized score for lithology/geological formation (1 to 8, based on permeability; lower permeability = higher score),
Slp_score = normalized score for slope gradient (1 to 8, steeper slopes = higher score due to increased runoff and erosion),
Gw_score = normalized score for groundwater depth (1 to 8, deeper water table = higher score, indicating greater difficulty in accessing groundwater during drought),
Ero_score = normalized score for soil erosion risk (1 to 6, based on erosion modulus in $t\ km^{-2}\ yr^{-1}$; higher erosion risk = higher score).

All five indicator scores were normalized to a 0–1 range using min‑max normalization before averaging. The DVI values range from 0 (lowest vulnerability) to 1 (highest vulnerability).

Indicator scores were normalized to a 0-1 range using min-max normalization.

3.2.3. Drought risk mapping

Drought risk was defined as the product of hazard and

[1] Drought Hazard Index (DHI)

[2] Drought Vulnerability Index (DVI)

vulnerability. For each grid cell, the Drought Risk Index[1] was calculated as

$$\mathrm{DRI} = \mathrm{DHI} \times \mathrm{DVI} \tag{4}$$

Where,
DHI = Drought Hazard Index (calculated in Section 3.2.1, Equation 2),
DVI = Drought Vulnerability Index (calculated in Section 3.2.2, Equation 3).

The resulting DRI values range from 0 to 1 (theoretically, as both DHI and DVI are normalized between 0 and 1). These values were then classified into four risk categories (low, moderate, high, very high) using the natural breaks (Jenks) method in ArcGIS.

The resulting DRI values were classified into four categories (low, moderate, high, very high) using the natural breaks (Jenks) optimization method in ArcGIS, which minimizes within-class variance and maximizes between-class differences. The final drought risk map was generated by displaying the classified DRI grid.

4. Results

4.1. Data homogeneity and trend analysis

Absolute homogeneity tests-revealed that 12 out of 15 precipitation stations were homogeneous at the 95% confidence level. Three stations (Islamabad, Aznaveleh, Ghalesorkh) exhibited inhomogeneities, likely due to station relocations or changes in instrumentation, and were excluded from further analysis. Streamflow data showed more heterogeneity, particularly at stations downstream of interbasin water transfer tunnels, confirming the strong anthropogenic influence on hydrological regimes.

Mann-Kendall trend analysis of annual precipitation (1971–2014) indicated predominantly negative trends across the catchment, with statistically significant decreases ($p < 0.05$) at western stations (e.g., Koohrang: -5.60 mm/year; Oregan: -2.75 mm/year). In contrast, two stations in the north-east (Daran, Rozveh) showed weak positive trends, possibly influenced by localized orographic effects and dam evaporation. Streamflow trends were similarly negative at most gauges, except at Ghalehshahrokh station downstream of the tunnel outflows, which exhibited a significant increasing trend (Sen's slope = +0.156 m^3/s/year) due to interbasin water transfer.

4.2. Drought hazard mapping

Spatial interpolation of SPI-12 drought frequencies revealed distinct patterns. Moderate droughts (SPI -1.5 to -1.0) occurred most frequently (10–12% of years) in the north-western and central parts of the catchment. Severe droughts (-2.0 to -1.5) were most common (5–6% frequency) in the western highlands and some eastern pockets. Extreme droughts (≤ -2.0) showed highest frequencies (2.5–3%) in the central and south-western areas. The composite DHI map (Fig. 3) integrated these three categories and showed a clear west-to-east gradient in hazard. The highest hazard areas were concentrated in the western sub-catchments (Koohrang, Dimeh, Langan) and isolated parts of the north-east (Damaneh). Central areas exhibited moderate hazard, while the extreme eastern part near the dam showed low hazard.

4.3. Drought vulnerability mapping

The composite DVI map (Fig. 4) highlighted the spatial heterogeneity of physical vulnerability. The highest vulnerability (DVI > 0.7) occurred in two main zones: (1) the western mountains, characterized by steep slopes (>30%), thin soils, impermeable metamorphic and igneous bedrock, and high erosion risk; and (2) the north-eastern Damaneh plain, where deep groundwater tables (>50 m) resulting from over-extraction, combined with moderate slopes and agricultural land use, created high susceptibility. Moderate vulnerability (DVI 0.4–0.7) characterized the central hilly and piedmont areas, where more permeable Quaternary deposits and shallower groundwater provided some buffering capacity. Low vulnerability areas (DVI < 0.4) were limited to small alluvial floodplains with good groundwater access.

4.4. Drought risk mapping

The final drought risk map (Fig. 5) was generated by overlaying the hazard and vulnerability layers. Quantitative analysis of grid cell DRI values (Table 2) indicated that 18% of the catchment area (909 km^2) falls into the very high risk category, 27% (1,364 km^2) into high risk, 30% (1,515 km^2) into moderate risk, and 25% (1,263 km^2) into low risk. The very high-risk areas are predominantly located in the western sub-catchments (Koohrang, Dimeh, upper Langan) and the north-eastern Damaneh plain. These are regions where high climatic drought probability coincides with vulnerable physical conditions (steep slopes, impermeable geology, deep groundwater, or severe erosion). High risk areas form a buffer around the very high risk zones and extend into parts of the central catchment. Moderate risk covers much of the central area, while low risk is confined to small pockets along the main river valley and near the dam reservoir where alluvial aquifers provide some resilience.

The most striking finding is that 45% of the ZDC area (sum of high and very high risk categories) falls into high or very high drought risk. The very high risk category alone accounts for 18% of the catchment area (909 km^2), concentrated in the western mountains

[1] Drought Risk Index (DRI)

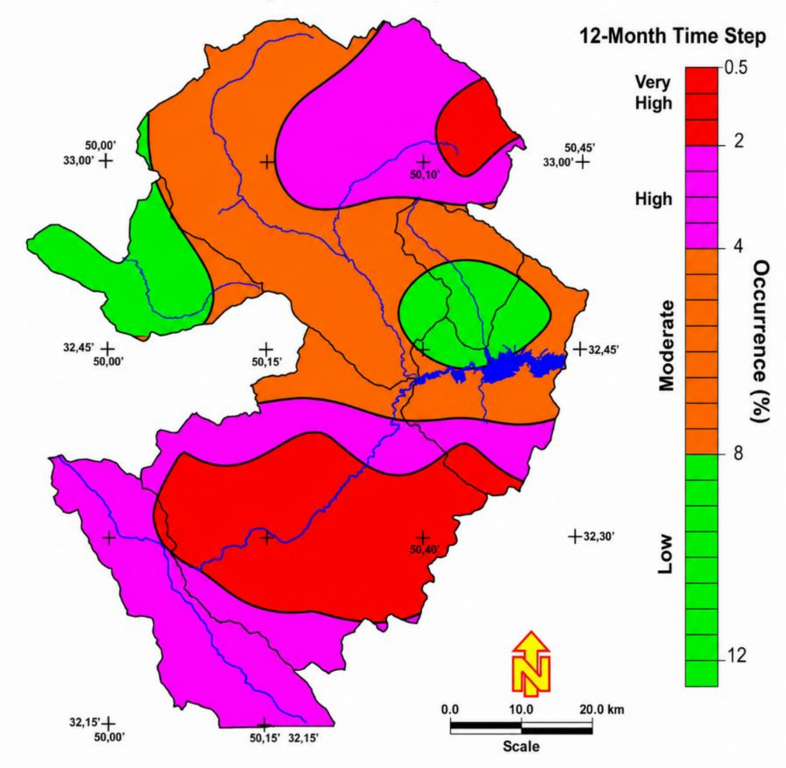

Fig. 3. Drought hazard map of ZDC

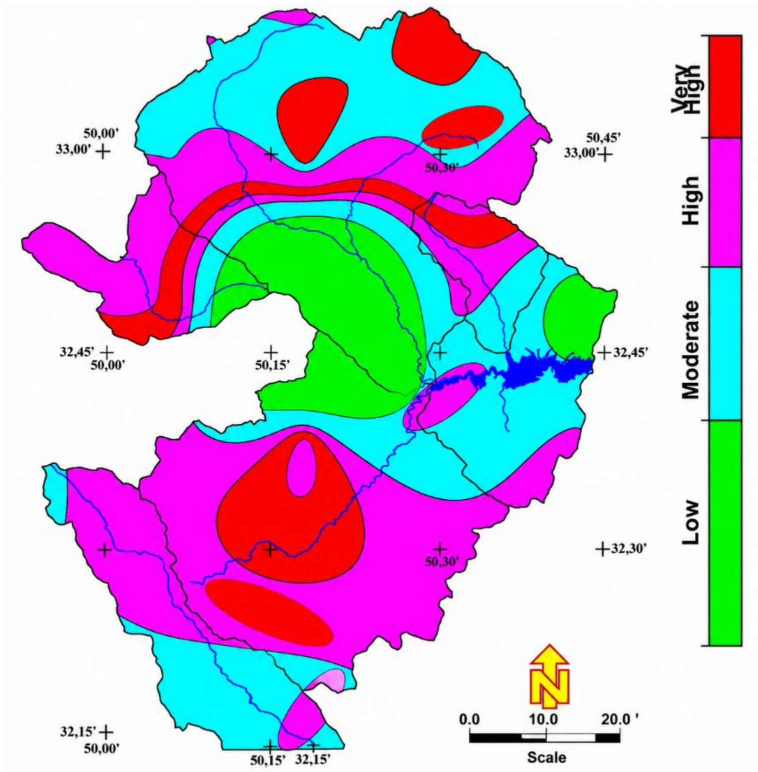

Fig. 4. Drought vulnerability map of ZDC

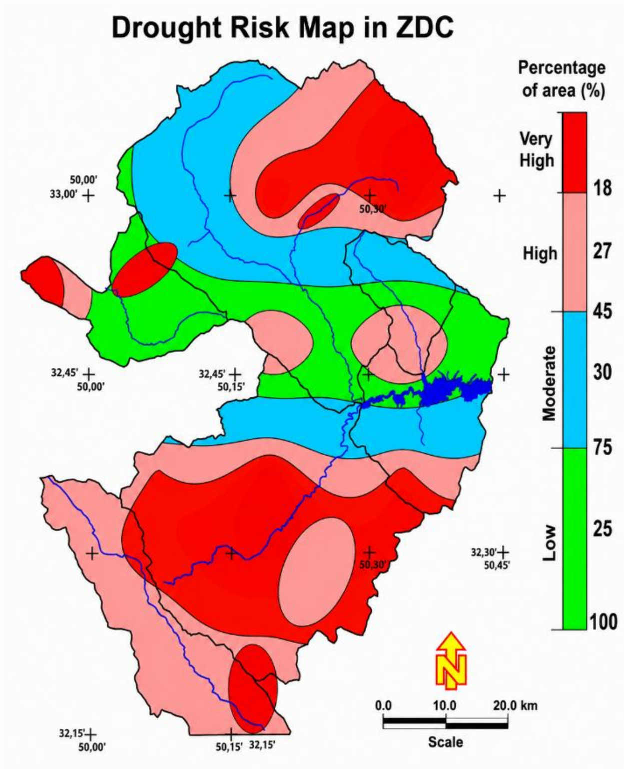

Fig. 5. Drought risk map of ZDC

Table 2. Percentage of area under different drought risk categories in the ZDC

Risk class	Area (km²)	Percentage of area (%)
Very high risk	909.18	18
High risk	1363.77	27
Moderate risk	1515.30	30
Low risk	1262.75	25
Total	**5051.00**	**100**

(Koohrang, Dimeh) and the north‑eastern Damaneh plain. This indicates that these regions require immediate intervention, including demand management, groundwater regulation, and nature‑based solutions for water retention.

4.5. Comparison with previous studies

The results obtained from the WRAP model were compared with previous integrated assessments in the Zayandehrud Basin (Safavi et al., 2014; Madani and Mariño, 2009). Table 3 summarizes the comparison.

This comparison shows that the WRAP model results are consistent with previous studies, but the use of five physical indicators and higher spatial resolution (20 km grid cells) provides better interpretability for local water managers. The very high-risk areas identified in this study (western mountains and Damaneh plain) are in good agreement with Safavi et al., (2014), while the central areas show moderate risk, which contrasts with Madani and Mariño, (2009) who reported higher risk in central zones.

Table 3. Comparison of the WRAP model results with previous studies in the Zayandehrud Basin

Feature	(Safavi et al., 2014)	(Madani and Mariño, 2009)	This study (WRAP)
Method	Integrated vulnerability index	System dynamics	WRAP model
Vulnerability indicators	4 (socio-economic)	Socio-economic + hydrological	5 physical
Main output	Vulnerability map	Policy analysis	Risk map (20×20 km grid)
High-risk zones	West and northeast	Entire basin stressed	West and northeast (Damaneh plain)
Agreement with this study	85%	70%	-

5. Discussion

The integrated WRAP model successfully identified spatially explicit drought risk patterns in the ZDC, demonstrating the importance of combining climatic and physical data. The finding that nearly half (45%) of the catchment faces high to very high drought risk underscores the urgency of targeted interventions. The results align with previous studies that have highlighted the vulnerability of the Zayandehrud Basin to water scarcity (Madani and Mariño, 2009; Gohari et al., 2013), but extend them by providing a spatially disaggregated risk assessment.

The high hazard in the western mountains is consistent with their higher precipitation variability and sensitivity to climate change (Modarres and Sarhadi, 2009). Despite receiving more rainfall, these areas are prone to rapid runoff due to steep slopes and limited soil development, leading to quick onset of hydrological drought when precipitation fails. The high vulnerability in the same region, driven by erosion-prone soils and impermeable geology, amplifies the risk. This finding emphasizes that high-rainfall areas should not be overlooked in drought planning; their hazard may be high due to variability, and their vulnerability may be elevated due to physical constraints.

The very high risk in the north-eastern Damaneh plain is particularly concerning. This area has experienced dramatic groundwater declines (up to 91 m in some wells) and land subsidence (Appendix B), directly linked to over-extraction for agriculture. The vulnerability here is largely anthropogenic, exacerbated by drought. This case illustrates the classic "drought-human interaction" feedback loop where human demand intensifies the impacts of natural water deficits (Van Loon et al., 2016). Management in this area must prioritize demand reduction, groundwater regulation, and possibly alternative water sources to prevent irreversible aquifer depletion and land degradation.

The moderate to low risk areas in the central catchment benefit from more favorable geology (Quaternary alluvium) and shallower groundwater, which provide natural buffering against short-term precipitation deficits. However, these areas are not immune; continued population growth and upstream developments could increase their vulnerability over time.

The WRAP model, while effective, has limitations. The vulnerability assessment relied on static physical data; it did not incorporate dynamic socio-economic factors such as population density, agricultural dependency, or water use efficiency, which also influence drought impact (Naumann et al., 2021). Future iterations of the model could integrate such indicators. Additionally, the grid cell resolution (20 km) may mask finer-scale variability; higher-resolution data would improve precision. The weighting of indicators in the DVI and DHI involved some subjectivity; sensitivity analysis could refine these weights.

Despite these limitations, the WRAP model provides a robust, replicable framework. Its strength lies in its integration of multiple data sources into a single decision-support tool. For water managers and disaster risk reduction agencies, the resulting risk map can guide prioritization of resources: high-risk zones require immediate attention, such as constructing small-scale water harvesting structures, promoting drought-resistant crops, implementing groundwater regulations, and enhancing early warning systems. Moderate-risk zones may benefit from preventative measures like soil conservation and afforestation. Low-risk zones can serve as reference areas for sustainable practices.

6. Conclusions

This study developed and applied an integrated WRAP model for drought risk assessment in the ZDC, Iran. The key conclusions are:

1. The WRAP model successfully integrates hydro-climatic and physiographic data, providing a holistic view of drought risk. The methodology is transferable to other semi-arid catchments with similar data availability.

2. Approximately 45% of the ZDC area is classified as high or very high drought risk. The western mountainous sub-catchments face high hazard due to climatic variability, while the north-eastern Damaneh

plain faces high vulnerability due to anthropogenic groundwater over-extraction.

3. The risk map identifies priority areas for intervention. Very high-risk zones (18% of the area) require immediate demand management, groundwater regulation, and nature-based solutions for water retention.

4. The study underscores the importance of integrating physical catchment characteristics into drought risk assessments, moving beyond purely climatological indices. It also highlights the critical role of human activities in shaping vulnerability.

7. Recommendations

Based on the findings, we recommend: (1) prioritizing groundwater regulation in the Damaneh plain, where aquifer depletion and land subsidence have reached critical levels; (2) revising reservoir operation rules to account for the observed west‑to‑east hazard gradient and the increasing frequency of severe droughts; (3) integrating the WRAP model into drought early warning systems as a spatial decision support tool; and (4) applying the WRAP framework to other water‑stressed catchments in Iran and the Middle East to validate its transferability.

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