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Linking Hydrological Drought Progression to Water Quality Recovery Using a Multi-Stage Variable-Threshold Approach

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Research Article

Keywords: Hydrological Drought, Multi-Stage Drought Framework, Variable Threshold Method, Standardized Streamflow Index (SSI), Water Quality Recovery, Drought Propagation

Posted Date: March 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8923788/v1

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Additional Declarations: No competing interests reported.

Abstract

Hydrological drought, a critical phenomenon with cascading impacts on water resources, has traditionally been assessed through quantity-based indices, often neglecting its profound influence on water quality. This study addresses this gap by proposing and applying a novel Three-Stage Variable-Threshold (3S-VT) framework for high-resolution identification and characterization of hydrological drought events, followed by an analysis of water quality recovery dynamics. The framework dissects droughts into Development, Persistence, and Retreat stages using seasonally variable daily flow thresholds (25th percentile) in the Gorganroud River Basin, Iran. A comparative analysis is conducted against the widely used Standardized Streamflow Index (SSI) at multiple timescales (1-, 3-, 6-, and 12-month). The results reveal that the 3S-VT framework identifies fewer but longer-duration events, effectively capturing persistent, multi-seasonal droughts critical for long-term water resource stress, while the SSI is more sensitive to short-term, flash droughts. Spatially, an east-west hydro-climatic gradient is evident, with eastern high-altitude stations experiencing snowmelt-dependent, long-duration droughts, and western lowland stations facing intensifying, warm-season droughts driven by evapotranspiration. Furthermore, the study quantifies significant time lags in water quality recovery post-drought. Key parameters (e.g., TDS, EC, major ions) required an average of 52 days to return to baseline conditions after hydrological drought termination, with upstream areas showing slower recovery (up to 71 days) compared to downstream zones (~ 37 days), highlighting differential basin resilience. This research underscores the necessity of integrating multi-stage drought progression with water quality impact assessment for holistic water resource management, offering a refined tool for drought monitoring, long-term planning, and developing tailored adaptation strategies in climate-sensitive basins.

1. Introduction

Drought is a complex hydroclimatic phenomenon arising from interactions among atmospheric processes, land–surface dynamics, and human influences across multiple spatial and temporal scales (Hao et al., 2018; Guan et al., 2023). While early research primarily conceptualized drought as a precipitation deficit, subsequent work expanded the framework to include hydrological drought, characterized by sustained reductions in streamflow and groundwater availability, and agricultural drought, driven by persistent soil moisture deficits that constrain crop productivity (Wilhite & Glantz, 1985; Choukri et al., 2023; Kumar et al., 2025). More recent perspectives emphasize ecological and socio-economic impacts, recognizing drought as a cascading process that propagates through the hydrological cycle and affects both natural and human systems (Crausbay et al., 2017; Cavalcante et al., 2025). A growing body of literature has examined drought propagation and the temporal lags between meteorological forcing and hydrological response (Hao et al., 2018; Dehghani et al., 2022). However, an important dimension of this propagation—its influence on water quality—has received comparatively limited attention. During low-flow conditions, reduced dilution capacity, elevated water temperatures, and increased residence times can substantially alter river chemistry (Mosley, 2015; Kubrak et al., 2025). These processes often lead to higher salinity (e.g., EC and TDS), increased nutrient concentrations, enhanced algal growth, and shifts in dissolved oxygen and pH regimes (van Vliet et al., 2013; Mir et al., 2025). Evidence from major drought events, including the Millennium Drought in Australia, indicates that water quality recovery may lag behind hydrological recovery by months or even years (Mosley, 2015; Lintern et al., 2025). Similar patterns have been documented in European river systems, where drought conditions intensified nutrient pollution and salinization (van Vliet et al., 2013; Kohler et al., 2024). Despite this growing recognition,

most operational drought metrics remain focused on water quantity, highlighting the need for more combined assessments that explicitly consider post-drought water quality dynamics.

Reliable drought monitoring depends on well-established methods for identifying onset, duration, and severity. Threshold-based approaches have long been used to delineate hydrological drought events, typically employing fixed percentiles of streamflow (Yevjevich, 1967). Although straightforward, fixed thresholds may inadequately represent seasonal variability in hydrological regimes. Variable-threshold methods, which incorporate seasonally adjusted percentiles, provide a more realistic characterization of drought conditions (Hisdal & Tallaksen, 2003; Wu et al., 2025; Wang et al., 2025). Subsequent refinements have introduced smoothing techniques and run-theory criteria to define discrete events (van Loon, 2015). Nevertheless, conventional threshold approaches often treat drought as a binary state, offering limited insight into the internal progression of events. To address this limitation, multi-stage frameworks have been proposed to partition drought into development, persistence, and recovery phases. Ahmadi et al. (2019), for example, demonstrated that stage-based characterization can enhance understanding of drought evolution and its environmental consequences. Building on this conceptual foundation, the present study extends stage-based drought analysis by integrating an explicit evaluation of water quality recovery and conducting a systematic comparison with the widely used Standardized Streamflow Index (SSI). While SSI provides a probabilistic measure of drought severity across predefined timescales, its reliance on aggregated data may obscure intra-event dynamics that are potentially relevant for water quality response.

Understanding recovery processes is particularly important because incomplete recovery can increase ecosystem vulnerability to subsequent drought events. If a new drought occurs before hydrological and chemical conditions return to baseline, cumulative impacts may intensify ecological stress and reduce basin resilience. Although recovery has been examined in ecological contexts (Schwalm et al., 2017), the temporal relationship between hydrological termination and water quality normalization remains insufficiently quantified, especially across spatially heterogeneous river basins. Accordingly, this study addresses two interconnected gaps: (1) the limited integration of water quality recovery into hydrological drought assessments, and (2) the need for comparative evaluations of high-resolution, event-based drought diagnostics relative to standardized indices. By linking drought progression to post-event chemical response, the study seeks to provide a more comprehensive understanding of basin-scale resilience and water resource vulnerability. This research is guided by the following questions:

1. How long do key water quality variables require to return to baseline conditions following the termination of a hydrological drought?
2. How does incomplete recovery influence water quality response when successive drought events occur?
3. Does partitioning drought into distinct stages improve the characterization of event dynamics compared with conventional approaches?
4. How do drought characteristics identified by a three-stage variable-threshold framework compare with those derived from the Standardized Streamflow Index (SSI)?

To address these questions, the objectives of this study are to:

1. Develop and implement a three-stage (Development, Persistence, and Retreat) variable-threshold framework for high-resolution identification of hydrological drought events.

2. Conduct a comparative analysis between the proposed framework and SSI at multiple timescales (1-, 3-, 6-, and 12-month), evaluating agreement in event timing, duration, severity, and frequency.
3. Quantify the response and recovery times of key water quality variables, including pH, EC, TDS, and major ions, and explicitly test for temporal lags between hydrological and chemical recovery.

Applied to the Gorganroud River Basin in Iran, this integrated approach aims to advance drought monitoring by coupling detailed event diagnostics with water quality impacts while positioning a stage-based framework as a complementary tool to established probabilistic indices.

2. Study Area

The Gorganroud River Basin, the primary hydrological system of Golestan Province in northern Iran, was selected for this study due to its pronounced hydroclimatic heterogeneity and sensitivity to flow variability. Situated between the humid Caspian coastal zone and the semi-arid plains of Central Asia, the basin exhibits strong climatic and physiographic gradients that influence runoff generation and drought behavior. Elevation ranges from approximately − 28 m in the lowlands to 2800 m in the mountainous headwaters, while mean annual precipitation varies from about 200 mm in the northern sectors to over 700 mm in the southern highlands. This gradient produces diverse hydrological regimes, including rainfall-dominated lowland flows and mixed rain–snow processes in higher elevations. The basin drains an area of approximately 11,380 km², contributing nearly 828 MCM of surface water annually. Intensive agricultural activity across the region places substantial demand on water resources, increasing vulnerability to hydrological drought and amplifying the importance of understanding post-drought recovery processes for both ecosystem functioning and water supply reliability. To characterize drought dynamics under conditions that primarily reflect climatic forcing rather than flow regulation, the analysis focuses on upstream tributaries with minimal anthropogenic disturbance. Catchments located upstream of the major regulatory structures—Bustan, Golestan, and Voshmgir dams—were therefore selected to reduce the influence of reservoir operations, return flows, and localized pollution sources on observed discharge patterns. Seven hydrometric stations distributed across key headwater tributaries were used in this study: Zarin-Gol (Tamar), Haji Ghushan, Doogh (Tangrah), Ghalitapeh, Oughan (Galikesh), Chehel-Chai (Lazoureh), and Khormalou (Nodeh) (Fig. 1). This spatial configuration captures the basin's hydroclimatic variability while enabling analysis of drought characteristics and subsequent water quality recovery within relatively natural flow regimes.

3. Data Description and Preprocessing

The analysis utilizes hydrological and water-quality records obtained from the Golestan Regional Water Authority. The dataset was selected to enable event-scale drought identification and subsequent evaluation of water-quality response under varying hydrological conditions. Continuous daily streamflow records (m^3/s) from seven hydrometric stations constitute the foundation of the drought analysis. Each station provides at least 30 water years of observations, with record periods beginning between 1966 and 1971 and extending through 2017. The multi-decadal length of these records captures substantial hydroclimatic variability and multiple drought cycles, supporting Consistent statistical characterization of drought onset, persistence, and termination. Water-quality dynamics were assessed using concurrent monthly measurements collected at the same stations. The dataset includes general physicochemical indicators— pH, electrical conductivity (EC, $\mu\,\mathrm{S/cm}$), and total dissolved solids ($\mathrm{TDS},\ \mathrm{mg/L}$)—along with major cations ($\mathrm{Ca}^{2+},\ \mathrm{Mg}^{2+},\ \mathrm{Na}^{+},\ \mathrm{K}^{+}$) and

major anions (HCO_3^-, Cl^-, SO_4^{2-}). These parameters serve as key indicators of salinity, ionic composition, and overall water suitability for ecological and agricultural functions, all of which may be sensitive to prolonged low-flow conditions. The temporal alignment of streamflow and water-quality observations enables direct examination of hydrological–chemical interactions and recovery behavior following drought events. All time series underwent systematic quality control prior to analysis. Short gaps in the streamflow records (< 15 days) were infilled using regression-based relationships with nearby correlated stations, while longer gaps and periods flagged for questionable reliability were excluded to minimize uncertainty. Water-quality observations were screened for outliers and potential measurement errors using range and consistency checks before being incorporated into the analysis. The resulting dataset—characterized by long-term coverage, paired hydrological and chemical observations, and limited missing data—provides a reliable basis for evaluating drought characteristics and associated water-quality recovery within a hydroclimatically diverse river basin.

4. Methodology

To capture the intra-event dynamics of hydrological droughts and assess their subsequent effects on water quality—a critical gap in conventional drought monitoring—a three-component methodological framework was developed according to Fig. 2. This framework is structured into three consecutive, interlinked steps: (1) identification and multi-stage characterization of historical drought events; (2) comparative analysis of drought events identified by the proposed framework versus the Standardized Streamflow Index (SSI); and (3) quantification of water quality response and post-drought recovery dynamics.

Step 1: Multi-Stage Drought Event Identification and Characterization

Accurate identification of drought onset, duration, and intensity is foundational. We employ a well-established, threshold-based run theory approach combined with a three-stage drought model to capture the progression of drought events beyond a binary classification.

To account for the strong seasonality in the study area, a seasonally variable threshold $Q_{th}(d)$ is calculated for each day of the year from the long-term daily streamflow record (Hisdal & Tallaksen, 2003). The 25th percentile (Q_{25}) of the flow duration curve for each day of the year is used as the drought-initiating threshold because provides a balance between sensitivity to emerging drought conditions and avoidance of minor flow fluctuations. This percentile is computed using ± 15 day moving window centered on each day of the year to ensure a smooth temporal transition and to adequately represent low-flow conditions. For a given day of the year, the threshold is constructed from the ensemble of all daily discharge values, Q, recorded on calendar days within the window $[d-15,\ d+15]$ across all available years in the record. Mathematically, the threshold for day d is defined as:

$$Q_{th}(d) = P_{25}\left(\bigcup_{y=1}^{N}\bigcup_{i=-15}^{15}\{Q(d+i,y)\}\right) \quad (1)$$

Where:

- $Q_{th}(d)$ is the daily variable drought threshold for day of the year d.
- $P_{25}(.)$ is the operator calculating the 25th percentile of the provided data set.

- $Q(d+i, y)$ is the observed daily streamflow on the calendar day corresponding to $d+i$ in hydrological year y.
- N is the total number of years in the record.
- The inner union $\bigcup_{i=-15}^{15} \text{aggregates}$ all discharge values from the 31-day window centered on day of the year.
- The outer union $\bigcup_{y=1}^{N} \text{aggregates}$ these values across all N years.

This method generates a continuous, 365-day threshold series that reflects seasonal low-flow expectations, forming the baseline for drought event identification.

A drought event is identified when the daily streamflow Q_t falls below the seasonally variable threshold Q_{th} (t) and terminates when Q_t rises and remains above Q_{th} (t). To prevent the over-identification of minor dry spells, a pooling procedure is applied: any two consecutive periods where $Q_t < Q_{th}(t)$, separated by fewer than n days (here, $n = 10$), are merged into a single drought event (Yevjevich, 1967). For each consolidated drought event, three distinct hydrological stages are defined to characterize its progression:

1. **Development Stage (D)**: The initial period from the drought onset (first day where $Q_t < Q_{th}(t)$) until the start of the Persistence Stage.
2. **Persistence Stage (P)**: The core drought period, defined as any continuous period within the drought event where $Q_t < Q_{th}(t)$ for more than L_p consecutive days (here, $L_p = 30$). This stage represents the period of sustained peak water deficit. The selection of $L_p = 30$ days for defining the Persistence Stage follows established practices in drought event pooling, where a minimum duration of 20–30 days is commonly applied to distinguish sustained low-flow periods from transient fluctuations (Hisdal & Tallaksen, 2003). This threshold ensures that the Persistence Stage captures the core drought period—characterized by prolonged water deficit—while excluding minor dry spells that do not represent significant hydrological stress. The 30-day criterion balances sensitivity to seasonal flow variability with robustness in identifying hydrologically meaningful drought events.
3. **Retreat Stage (R)**: The final period from the end of the Persistence Stage until the drought termination (the last day where $Q_t < Q_{th}(t)$ before a sustained recovery).

For each event i, key drought characteristics are quantified:

- **Total Duration ($T_{total,i}$)**: $T_{total,i} = D_i + P_i + R_i$, measured in days.
- **Severity (S_i)**: The cumulative water deficit volume, calculated as $S_i = \sum_{t \in \, eventi}(Q_{th}(t) - Q_t)$, with units of volume (e.g., m³).
- **Peak Intensity ($I_{max,i}$)**: The maximum daily deficit, $I_{max,i} = max_{t \in \, eventi}(Q_{th}(t) - Q_t)$.

Step 2: Hydrological Drought Events (Standardized Streamflow Index)

This study utilizes the SSI, a hydrological drought metric adapted from the SPI developed by McKee et al. (1993), to quantify anomalies in river discharge. Consistent with the drought characterization framework proposed by Shukla and Wood (2008), SSI is calculated by first fitting a gamma probability distribution to long-term (minimum 30-year) monthly river discharge time series. The cumulative probabilities are then transformed using the inverse of the standard normal distribution to produce normalized SSI values. The SSI is defined as:

$$\mathrm{SSI} = \Phi^{-1}\left(G\left(Q\right)\right)$$

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Where Φ^{-1} denotes the inverse standard normal distribution, and $G\left(Q\right)$ is the cumulative probability function of the gamma distribution fitted to the discharge time series Q . This normalization facilitates the comparison of drought severity across basins and time periods. Negative SSI values reflect below-normal streamflow conditions, with drought severity classified according to standard thresholds: Mild drought (-1.0 > SSI ≥ -1.5), Moderate drought (-1.5 > SSI ≥ -2.0), and Severe drought (SSI < -2.0).

Negative SSI values indicate periods of hydrological drought, with drought duration defined as consecutive months of negative SSI and severity quantified as the cumulative magnitude of SSI during such periods. This standardized approach enables cross-basin comparisons of drought intensity and duration, critical for assessing regional hydrological imbalances. The gamma distribution is selected for its robustness in modelling skewed hydrological data, though alternative distributions (Vicente-Serrano et al., 2012) were evaluated using the Kolmogorov-Smirnov test to ensure suitability. The Gamma distribution's flexibility in capturing different shapes makes it suitable for various streamflow regimes.

Step 3: Analysis of Water Quality Response and Recovery

This step establishes a direct link between hydrological drought and its ecological and practical impacts by analyzing concomitant changes in water quality parameters. For each water quality parameter W (e.g., EC, TDS, pH, major ions), a seasonally variable baseline representing "normal" non-drought conditions is established. First, the long-term monthly median $\widetilde{W}_m$ is calculated from all data points in month mm that occur outside of identified drought periods. A 30-day central moving average is then applied to the series of monthly medians to generate a smooth, continuous baseline function $W_{baseline}\left(t\right)$. To align the daily hydrological drought stages with water quality measurements, a temporal matching procedure was implemented. With a sampling frequency of approximately four measurements per month (i.e., near-weekly resolution), each water quality observation was directly assigned to its corresponding calendar day, allowing precise identification of the concurrent drought stage (Development, Persistence, or Retreat). For recovery analysis—where drought termination and water quality response must be synchronized on a daily scale—the near-weekly observations provide sufficient temporal resolution to capture post-drought trajectories without introducing artifacts from sparse data. This approach preserves the integrity of both datasets while enabling robust quantification of water quality recovery times.The Water Quality Recovery Time (T_{rec}^{W}) for parameter W following a specific drought event is quantified. Recovery begins at the end of the event's Persistence Stage (t_{p-end}). T_{rec}^{W} is defined as the number of days from t_{p-end} until the measured water quality value W_t returns to and remains within its normal range for a sustained, consecutive period τ (here, τ = 14 days). Recovery time (T_{rec}^{W}) is referenced to the end of the Persistence Stage (t_{p-end}) rather than drought termination to capture the onset of hydrological normalization. The end of persistence marks the transition from core deficit to the Retreat Stage, when flow begins recovering toward non-drought conditions—even before consistently exceeding the threshold. This approach isolates water quality response to the initial phase of flow improvement, which is ecologically more relevant than arbitrary threshold exceedance. Drought termination occurs later, conflating recovery onset with prolonged return to threshold conditions. Referencing T_{rec}^{W} from t_{p-end} thus provides a

process-oriented metric that captures the earliest signal of water quality amelioration following hydrological relaxation. The normal range is defined as:

$$W_{baseline}(t) \mp \delta_W \tag{3}$$

where δ_W is one Median Absolute Deviation (MAD) of parameter W calculated from all non-drought data, providing a consistent measure of natural variability. Thus, recovery is confirmed when:

$$|W_t - W_{baseline}(t)| \leq \delta_W \qquad \forall\, t \in [t_{rec}, t_{rec} + \tau\ ] \tag{4}$$

where t_{rec} is the candidate start date of the stable recovery period, and $T_{rec}^{W} = t_{rec} - t_{p-end}$.

The non-parametric Kruskal-Wallis H-test is employed at a significance level of α = 0.05 to determine if the distribution of a water quality parameter during the Persistence Stage of a drought is statistically different from its distribution during the subsequent recovery period. This test is chosen for its robustness against non-normally distributed environmental data. The null hypothesis (H_0) is that the median values of the water quality parameter during the drought persistence and recovery periods are equal.

5. Results and Discussion

Hydrological drought characteristics exhibited strong spatial heterogeneity across the Gorganroud River Basin, with distinct patterns in frequency, duration, and severity between upland and lowland sub-basins. By employing a multi-stage framework based on daily flow thresholds and the Standardized Streamflow Index (SSI) concurrently, the spatio-temporal characteristics of droughts and the recovery periods of water quality parameters following drought events were investigated. The findings reveal significant complexity in the drought regime across the basin, highlighting the necessity for tailored management strategies for different sub-basins (Mishra & Singh, 2010; Van Loon, 2015).

The daily 75th percentile flow, derived from long-term time series, was established as the optimal threshold for identifying hydrological drought events. Sensitivity testing indicated that the 75th percentile provided the best balance between event detectability and avoidance of false drought classification. This variable threshold was applied uniformly across all seven hydrometric stations for each day of the year, generating 365 threshold values per station to maintain comparability in drought characteristics across the study area. Each identified drought event was dissected into three distinct phases proposed by Ahmadi et al. (2019): Growth (onset and intensification), Resistance (persistent low-flow condition), and Retreat (recovery), based on predefined criteria regarding consecutive days below the threshold.

5.1. Spatio-Temporal Analysis of Hydrological Drought Characteristics and Emerging Trends using multi-stage framework

5.1.1. Spatial Patterns of Drought Initiation and Driving Mechanisms

Multi-stage analysis of hydrological drought characteristics across the Gorganroud River Basin reveals significant spatio-temporal patterns and a clear hydro-climatic gradient. Critically, emerging trends identified in the analysis signal a rapid and non-uniform transition toward a more volatile hydro-climatic regime. The model's capability to capture real-world drought episodes is confirmed by its accurate identification and characterization of the severe basin-wide drought of 2007–2008, a well-documented extreme event in regional hydrological records. Critically, emerging trends identified in the analysis signal a rapid and non-uniform transition toward a more volatile hydro-climatic regime. Results shown in Fig. 3 confirm a severe, synchronous, and prolonged hydrological drought across all stations, capturing its large-scale climatic drivers. Additionally, the model successfully delineates a significant multi-year drought period, accurately identifying a notable respite year within the extended dry spell, thereby demonstrating its proficiency in capturing high inter-annual variability. Analysis reveals a stark east-west and elevational gradient in drought initiation. In eastern/upstream stations within higher elevations (e.g., Galikesh and Lezore), winter precipitation, particularly snowfall, is the dominant control, with 44.4% and 31.8% of droughts initiating in this season, respectively. This underscores a critical vulnerability to snowpack deficits. Conversely, at western/downstream stations (e.g., Nodeh and Haji Ghooshan), thermodynamic factors outweigh precipitation deficits, with warm seasons (summer and autumn) collectively accounting for over 60% of droughts. This seasonal shift of drought initiation highlights the increasing dominance of evapotranspirative demand and thermal stress as primary drought drivers in lower basins, necessitating a re-evaluation of traditional, precipitation-centric models. Mid-basin stations (e.g., Tamar, Tangrah) exhibit a transitional yet pronounced vulnerability to spring-onset droughts, often linked to insufficient spring rainfall and snowmelt.

5.1.2. Temporal Trends and Regime Shifts

Temporal trend analysis reveals a pronounced and a structural change in drought regimes. Based on results shown in Fig. 3, a clear transition from long-duration, moderate-intensity droughts (e.g., events 2 and 4) to short-duration, high-intensity flash droughts (e.g., events 31 to 44) is documented at stations like Tamer, representing the rise of high-intensity events. More critically, recent decades have witnessed the emergence of mega-droughts with unprecedented characteristics at Tangrah station, event 25 lasted 2484 days with a massive deficit of 1757 units, while downstream at Nodeh station, recent autumn-initiated events (e.g., 44, 45) exhibit extreme deficits (> 1000 units), signaling a collapse in basin resilience during warm seasons. The rate of intensification is non-uniform; the average drought deficit at Nodeh station has increased by approximately 300% in recent decades compared to the baseline period, a rate far exceeding that observed in upstream stations like Galikesh station (~ 150%). These non-uniform intensification rates imply spatial differences in hydrological memory, with downstream systems exhibiting greater sensitivity to deficit accumulation despite shorter drought durations.

5.1.3. Decoupling of Drought Characteristics and Management Implications

Inter-component correlation analysis reveals station-specific hydrological behaviors with major management implications, further underscoring the system's transition. A quasi-linear relationship between drought duration and cumulative deficit volume is established at stations like Tangrah, Galikesh, Lezooreh, and Nodeh stations ($r = 0.92–0.96$), making duration a reliable proxy for volumetric water loss. This strong coupling between duration and deficit volume is a direct manifestation of hydrological memory: prolonged deficits integrate over time as

storage compartments are progressively depleted, translating duration into cumulative water loss. In stark contrast, the relationship between duration and peak intensity is generally weak or non-significant (e.g., r = 0.18 at Tamar and Gholitapeh, r = 0.15 at Hajighoshan). This critical finding—the decoupling of duration and intensity—indicates that short, intense droughts can cause acute stress, while long, mild droughts deplete strategic reserves, each demanding distinct management responses and complicating prediction and preparedness frameworks. The synthesis of spatial patterns, crystallizes the basin's drought gradient and the imperative for dynamic, spatially-explicit management. Eastern/higher-altitude stations are characterized by a regime of long-duration, high-deficit droughts, primarily driven by precipitation variability. Western/downstream stations are increasingly dominated by a regime of high-intensity, shorter-duration droughts, amplified by warming. This fundamental dichotomy necessitates the development of region-specific adaptation strategies: in the east, strategies must focus on snowpack management and long-term storage; in the west, priority shifts to reducing evaporative losses and managing warm-season demand. The convergence of these trends—seasonal shift, rising intensity, mega-drought emergence, and parameter decoupling—defines a new hydrological reality for the Gorganroud Basin, underscoring the urgent need to move beyond stationary assumptions in water resources planning.

5.1.4. Analysis of Drought Event Stages: Growth, Resistance, and Retreat

The analysis of drought event across the study stations reveals distinct patterns in the phases of growth, resistance, and retreat. The drought growth phase, indicating onset and intensification, is the shortest overall, with a basin-wide average of 36 days. The Lezooreh and Tangrah stations exhibit the longest average growth phase (47 days), suggesting higher vulnerability or a slower decline in groundwater storage and baseflow. In contrast, Galikesh (29 days) and Hajighoshan (30 days) reach drought peak more rapidly. The high standard deviations at Lezooreh (110) and Nodeh (71) indicate significant inter-annual variability in growth duration, with an absolute maximum of 747 days at Lezooreh, pointing to rare, protracted drought initiation periods. The resistance phase is the most stable and longest drought stage (basin average: 310 days), aligning with the high temporal inertia of hydrological droughts. Gholitapeh station exhibits statistically anomalous behavior, with an average resistance of 708 days and an extremely high standard deviation (2126). An absolute maximum of 9699 days signifies that this area remained in persistent drought for over 26 consecutive years in some periods, likely due to specific hydrogeological features (e.g., thin aquifer or impervious bed) and a heavy reliance on sporadic precipitation. Such prolonged resistance phases, far exceeding meteorological drought duration, reflect the strong hydrological memory of the system—i.e., the ability of catchment storage (groundwater, soil moisture) to sustain deficits long after meteorological anomalies have ceased. Tangrah, with 453 days, has the second-longest average resistance phase. The retreat phase duration is similar to growth (average: 35 days), indicating a relatively rapid exit from drought conditions. Stations with the slowest recovery are Gholitapeh (48 days) and Lezooreh (38 days), potentially linked to delays in aquifer recharge. Their high standard deviations (84 and 63, respectively) further highlight variability in recovery periods. The total average drought days across all stations is 380. Gholitapeh (784 days) and Tangrah (528 days) experienced the highest cumulative drought days, whereas Hajighoshan (232 days) reported the fewest. The exceptionally high standard deviation for total days (773), particularly at Gholitapeh (2130), underscores severe inter-annual fluctuations and the necessity to account for the risk of extreme, long-term droughts in water resource management (Fig. 4).

5.1.5. Elevational Gradient and Basin-Scale Resilience Patterns

Spatially, stations in the eastern part of the basin (Galikesh, Gholitapeh, Lezooreh) generally have higher average drought days, with Gholitapeh—the easternmost and one of the highest-altitude stations—representing the most critical conditions. Central and western stations (Tamer, Hajighoshan, Nodeh) experience fewer drought days. This pattern suggests a greater susceptibility of the eastern sectors to precipitation pattern shifts. A detailed analysis reveals that a nonlinear relationship exists between altitude and drought characteristics. Mid- to high-altitude stations (Gholitapeh: 250 m, Tangrah: 330 m), despite higher precipitation, experience the most drought days. Their heavy reliance on snowmelt-driven flow renders them highly vulnerable to temperature increases and reduced snowfall, which prolong the hydrological drought period (Fig. 4). Conversely, lower-altitude stations like Hajighoshan (45 m), Tamer (132 m), and Nodeh (280 m) have fewer total drought days and significantly lower statistical variability, especially during the critical resistance phase (e.g., standard deviation of 181 at Hajighoshan vs. 2126 at Gholitapeh). This pattern indicates greater flow stability and resilience downstream, attributed to the time-lag and moderating effect of groundwater systems and baseflow. These stations benefit from delayed groundwater discharge and runoff from upstream elevations, which mitigates short-term meteorological droughts and prevents abnormally prolonged drought periods.These findings underscore the need for integrated surface and groundwater management and the imperative to protect high-altitude zones as crucial recharge sources for the more resilient lowlands. Water resource management in the Gorganrud Basin cannot be based on a uniform approach. The fundamental differences in drought behavior necessitate tailored management strategies for each sub-basin. The primary focus must be on the resistance phase and developing policies for adaptation to persistent drought, as this phase is the main determinant of water resource stress. The particular vulnerability of high-altitude stations highlights strategic priority for managing headwater resources to ensure the sustainability of the entire watershed. Overall, drought in the Gorganrud Basin is not a simple random phenomenon but follows a dynamic, multi-scale, and systematic memory-driven structure, the understanding of which is essential for modeling, forecasting, and drought risk management.

5.2. Comparative Analysis of hydrological drought monitoring using the Standardized Streamflow Index (SSI) and multi-stage framework

5.2.1. SSI-Based Characterization of Hydrological Drought

This study also employs the Standardized Streamflow Index (SSI) as a fundamental statistical tool for characterizing hydrological drought. The SSI transforms monthly streamflow data into Z-scores, enabling the probabilistic assessment of drought severity across multiple temporal scales (1-, 3-, 6-, and 12-months). A single probability distribution was fitted to the streamflow series for each station, with parameters independently calibrated per month, to ensure consistent and location-specific drought identification. Analysis of the SSI time series across seven stations (Fig. 5) reveals distinct spatio-temporal patterns of hydrological drought. A clear seasonal signature is evident, with most stations exhibiting a higher frequency of drought onset in autumn and winter, aligning with dependence on cold-season precipitation. Exceptions include Hajighoshan and Gholitapeh, where droughts concentrate in spring/summer and summer/autumn, respectively, suggesting influences from local hydro-geological factors and snowmelt regimes. Quantitatively, the number of distinct drought events varied significantly among stations, from 35 at Gholitapeh to 77 at Nodeh and Tamer,

reflecting differing hydrological volatility. A notable pattern across all basins is an apparent increase in both drought frequency and severity from the 1990s onward, with the period 2014–2017 identified as a severe, multi-year drought episode. The propagation of drought across timescales shows a common pattern: short-term SSI values (1- and 3-month) exhibit high volatility and rapid response to precipitation events, while long-term SSI (12-month) displays more persistent negative trends. This indicates that short-term rainfall provides limited recovery for groundwater systems and reservoirs reliant on cumulative, long-term recharge. Furthermore, droughts show a pronounced tendency for clustering, with consecutive events in periods such as 1997–1999 and 2014–2017, preventing full hydrological recovery and exacerbating water resource depletion. The increasing recurrence and intensity of hydrological droughts, coupled with their prolonged nature, underscore a hydrologically meaningful challenge potentially consistent with regional climatic variability, necessitating adaptive management strategies that account for both short-term variability and long-term cumulative deficits.

5.2.2. Comparative Assessment of SSI and Multi-Stage Framework

Hydrological drought detection is inherently sensitive to the timescales over which a basin stores and releases water. Because catchments integrate precipitation inputs across multiple temporal scales—from quick surface runoff to slow groundwater drainage—different analytical methods may emphasize different aspects of the same drought reality. The Standardized Streamflow Index (SSI), as a statistically-based metric, responds to deviations from monthly norms, while the multi-stage threshold framework is designed to track the continuous evolution of flow relative to seasonal expectations. A comparative assessment of hydrological drought identification was conducted using these two methods across hydrometric stations. The results reveal fundamental differences in their sensitivity, temporal resolution, and drought characterization, reflecting the underlying role of catchment memory, recharge dependency, and groundwater inertia. Quantitatively, the SSI consistently identified a greater number of drought events at all stations, with counts ranging from 35 at Gholitapeh to 77 at Tamer and Nodeh. In contrast, the multi-stage framework registered fewer events, from 18 at Galikesh to 45 at Nodeh, indicating a nearly 2:1 ratio in most cases. This disparity underscores the SSI's higher sensitivity to short-term streamflow fluctuations, leading to the identification of discrete, often short-duration events (Fig. 5). The multi-stage framework, by incorporating variable thresholds and longer-term hydrological conditions, demonstrated a tendency to merge adjacent dry periods, resulting in fewer but more persistent drought events. The seasonal patterns of drought occurrence were consistent between methods, with a predominant concentration in autumn and winter for most stations, aligning with the regional hydroclimatology. However, the methods diverged significantly in defining drought events within these patterns. For instance, at Tamer, the SSI identified frequent short-duration droughts in spring, while the multi-stage framework integrated these into longer, multi-seasonal events. This pattern was repeated across stations, such as at Tangrah and Hajighoshan, where a single prolonged multi-stage framework drought often encompassed multiple shorter SSI events (Fig. 6). A notable exception was observed at Gholitapeh, where both methods remarkably agreed on the timing and exceptional 21-season duration of a major drought event, highlighting their convergence under extreme and prolonged conditions.

5.2.3. Implications for Drought Characterization and Water Management

A critical difference lies in drought duration and severity characterization. The multi-stage framework consistently identified droughts with significantly longer average durations, often spanning multiple seasons (e.g., 15 seasons at Tangrah, 18 seasons at Galikesh). Consequently, multi-stage framework droughts are associated with higher cumulative severity, reflecting sustained water deficits more relevant for assessing long-term impacts on groundwater and aquatic ecosystems. Conversely, the SSI, with its finer temporal resolution, is more adept at detecting short-term, high-intensity droughts with rapid onset and termination, making it more suitable for early warning systems targeting sudden water shortages. The choice between SSI and multi-stage framework hinges on the specific management objective. For monitoring and early warning of short-term, flash droughts, the SSI provides greater utility. For long-term water resource planning, impact assessment of cumulative water deficits, and managing sustained drought periods, the multi-stage framework offers a more integrated and ecologically relevant perspective by focusing on persistent hydrological dry spells. The significant overlap in identifying major, severe drought events at all stations confirms that both methods are reliable for detecting substantial and persistent hydrological droughts at a seasonal scale. These findings have important implications for integrated water resource management in basins with similar hydroclimatic regimes.

5.3. Determination of Water Quality Recovery Time

5.3.1. Hydrochemical Baseline Characterization

This study investigated the recovery characteristics of key water quality parameters following hydrological droughts across monitoring stations in the Gorganrood River Basin. Post-drought processing revealed distinct spatial gradients in both baseline water quality and recovery times. A pronounced downstream deterioration in quality was observed, with Hajighoshan station identified as a hydrologically sensitive salinity hotspot. Ionic composition analysis indicates a shift from Ca-HCO3 dominance in upstream areas to Na-Cl dominance in downstream reaches. This transition suggests progressive solute enrichment driven by increased residence time, evaporative concentration, and enhanced water–rock interaction along the flow path, with potential contributions from irrigation return flows in the lower reaches. Total hardness showed extreme spatial variability, ranging from 22.0 mg/L (soft water) at Qoli Tappeh to 877.1 mg/L (very hard water) at Hajighoshan. In contrast, pH demonstrated remarkable stability across all stations, with a mean deviation from the threshold of only 0.4 units, highlighting the basin's robust natural buffering capacity. Ionic balance was maintained throughout the basin, as evidenced by the comparable sums of anions and cations at each station, despite vast differences in total solute concentrations.

5.3.2. Recovery Dynamics and Spatial Patterns

The recovery time analysis established a mean basin-wide period of 52 days for water quality parameters to return to baseline conditions post-drought. However, significant spatial heterogeneity in resilience was evident (Fig. 7). A clear longitudinal gradient emerged, with upstream stations like Tamer and Tangrah exhibiting slower recovery (mean TDS recovery: 62–65 days) compared to downstream stations such as Nodeh (mean TDS recovery: 37 days). This pattern reflects limited storage buffering and smaller effective mixing volumes in upstream reaches, where shallow soils and restricted groundwater contribution reduce the system's capacity to dilute and flush accumulated solutes following drought termination. Among parameters, pH was the most stable, with a mean recovery time of 52 days, while TDS showed slightly greater variability (54 days). Specific ions like Cl and Na exhibited prolonged recovery in certain stations, indicating their persistence within the aquatic system. Lezooreh station demonstrated comparatively rapid recovery (41–45 days), whereas Tamer

station showed the slowest (62–71 days), reflecting the influence of local hydrogeological conditions and differential self-purification mechanisms. Statistical analysis of recovery times indicates a distribution with limited skewness and few extreme recovery delays (mean TDS recovery: 54 days vs. median: 59 days basin-wide), suggesting system stability with infrequent extreme events. The balanced mean recovery times for total anions (52 days) and total cations (53 days) confirm a dynamic ionic equilibrium where anions and cations recover synchronously. This observed recovery lag—where water quality parameters require substantially more time to return to baseline conditions than streamflow itself—confirms the existence of hydrochemical memory in the Gorganroud River Basin. Even after hydrological drought termination, the chemical signature of the system retains the legacy of the deficit, emphasizing that water quality responds more slowly than discharge. This finding underscores the critical importance of post-drought water quality monitoring and suggests that recovery assessments based solely on flow thresholds may significantly underestimate the true duration of ecosystem stress. The findings underscore the need for a differentiated management approach: prioritizing drought mitigation in slow-recovery upstream areas and focusing on adaptive strategies in resilient downstream zones. Hajighoshan station, with its severely degraded baseline quality, warrants priority monitoring and continuous observation. This research delineates a complex aquatic system with varying self-purifying capacities, necessitating region-specific management strategies to preserve the basin's ecological health.

6. Conclusion

This study advances the monitoring and understanding of hydrological droughts by developing and applying combined Three-Stage Variable-Threshold (3S-VT) framework that explicitly links drought event dynamics with water quality recovery. The framework successfully characterized historical droughts in the Gorganroud River Basin into distinct Development, Persistence, and Retreat stages, providing nuanced insights beyond binary drought identification. The comparative analysis with the Standardized Streamflow Index (SSI) revealed complementary strengths: the SSI is optimal for detecting short-term, high-intensity flash droughts vital for early warning, whereas the 3S-VT framework excels in identifying persistent, cumulative deficits crucial for long-term water resource planning and ecological impact assessment. Key findings include the identification of a strong spatio-temporal gradient in drought characteristics, driven by elevation and climate. Eastern, high-altitude stations exhibited vulnerability to precipitation and snowpack variability, leading to long-duration droughts, while western, lowland stations showed a trend towards intensifying, warm-season droughts amplified by rising temperatures. This dichotomy necessitates spatially differentiated management strategies. Moreover, the analysis documented an alarming trend toward more frequent, severe, and clustered droughts since the 1990s, signaling a shift to a more volatile hydro-climatic regime. Critically, this research quantified a tangible recovery lag for water quality following hydrological drought cessation. Water quality parameters took approximately 7–8 weeks on average to stabilize, with upstream regions demonstrating slower recovery, underscoring that hydrological recovery does not equate to immediate ecological or usability recovery. This lag poses significant risks for water supply, agriculture, and ecosystem health, especially when consecutive droughts occur before full system recovery.

7. Recommendations

This study demonstrates that effective drought management in the Gorganroud River Basin requires a paradigm shift from univariate, threshold-based monitoring toward integrated, multi-scale frameworks that capture both hydrological variability and water quality dynamics. The complementary strengths of the multi-stage framework and the Standardized Streamflow Index (SSI) suggest that operational agencies should adopt a dual-monitoring approach: high-resolution frameworks for long-term planning and cumulative impact assessment, alongside standardized indices for early warning systems. The pronounced east-west and elevational gradients in drought behavior necessitate spatially-explicit adaptation strategies: in eastern headwaters, where snowpack deficits drive prolonged droughts, management should prioritize snow conservation and natural storage enhancement, while in western lowlands, where warm-season evapotranspirative demand amplifies drought intensity, interventions must focus on reducing evaporative losses and improving irrigation efficiency. The observed coupling between hydrological drought and water quality deterioration—particularly the lag in recovery of parameters such as salinity—underscores the need to integrate water quality metrics into drought declaration protocols, ensuring that assessments of water security account for both quantity and quality dimensions. The prolonged and parameter-specific recovery times documented here further highlight the importance of recovery-focused management; post-drought protocols should include targeted monitoring of key constituents until baseline conditions are reestablished, with adaptive measures to accelerate in-stream recovery. Given the increasing frequency of drought clustering and the emergence of mega-droughts, enhancing system resilience through diversified water sources, managed aquifer recharge, and ecosystem-based adaptation strategies is essential for buffering against compound stressors. Collectively, these implications point toward a new paradigm for drought management in semi-arid basins—one that embraces the non-stationary, multi-scale, and memory-driven nature of hydrological systems, and that positions water quality recovery as a central criterion for determining when drought conditions have truly abated.

Declarations

Conflict of Interest

The authors declare no conflict of interest.

Funding

This research received no specific grant from any funding agency.

Author Contribution

A.H.: Conceptualization, methodology, software, writing—original draft.N.T.: Supervision, validation, writing—review & editing.S.H.A.: Supervision, validation, writing—review & editing.M.R.N.: validation, review & editing.S.V.: validation, review & editing.

Data Availability

Data are available from the corresponding author upon reasonable request.

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Figures

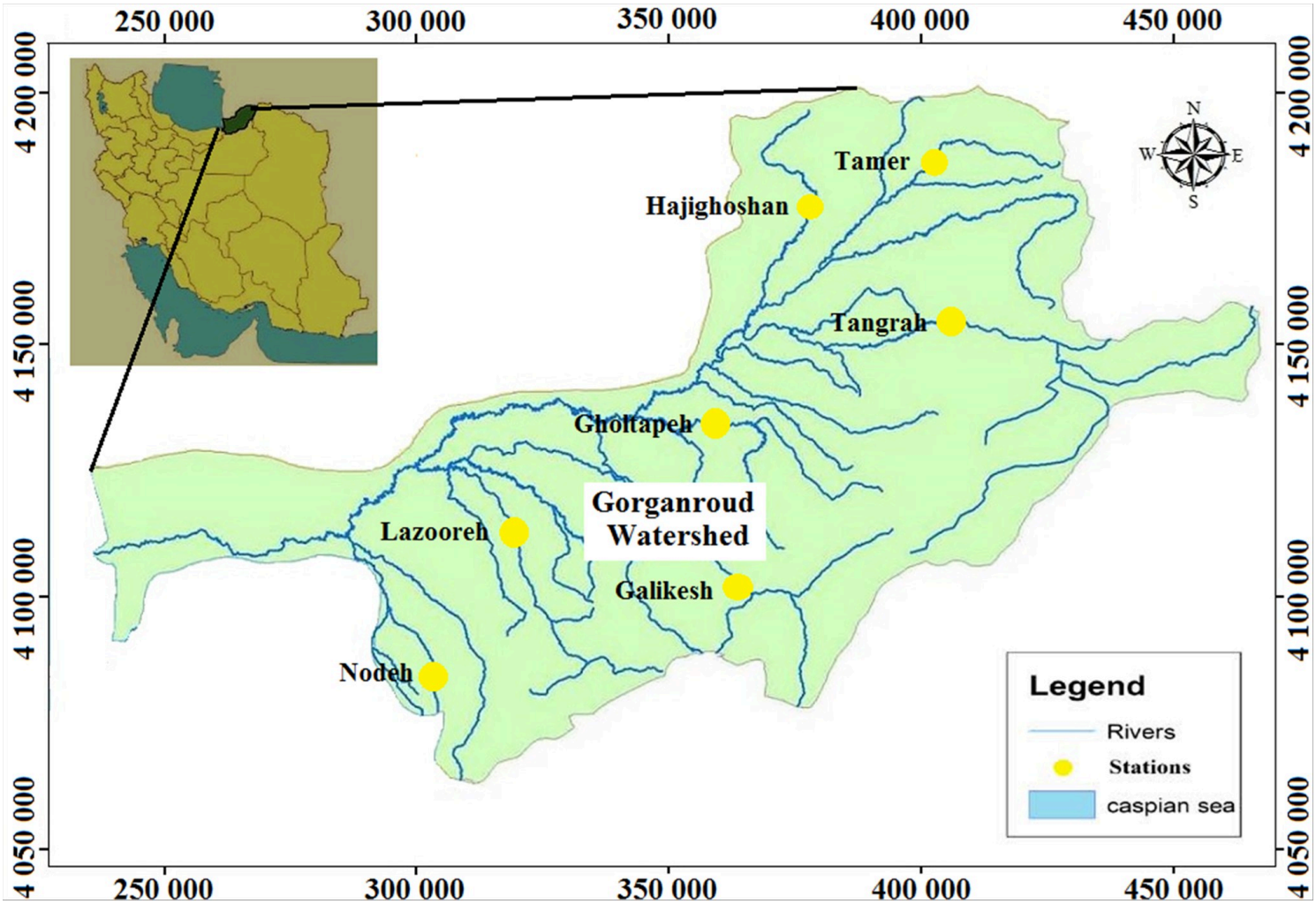


Figure 1

Detailed map of the study area within the Gorganroud River Basin, showing the locations of the seven selected hydrometric/water quality stations.

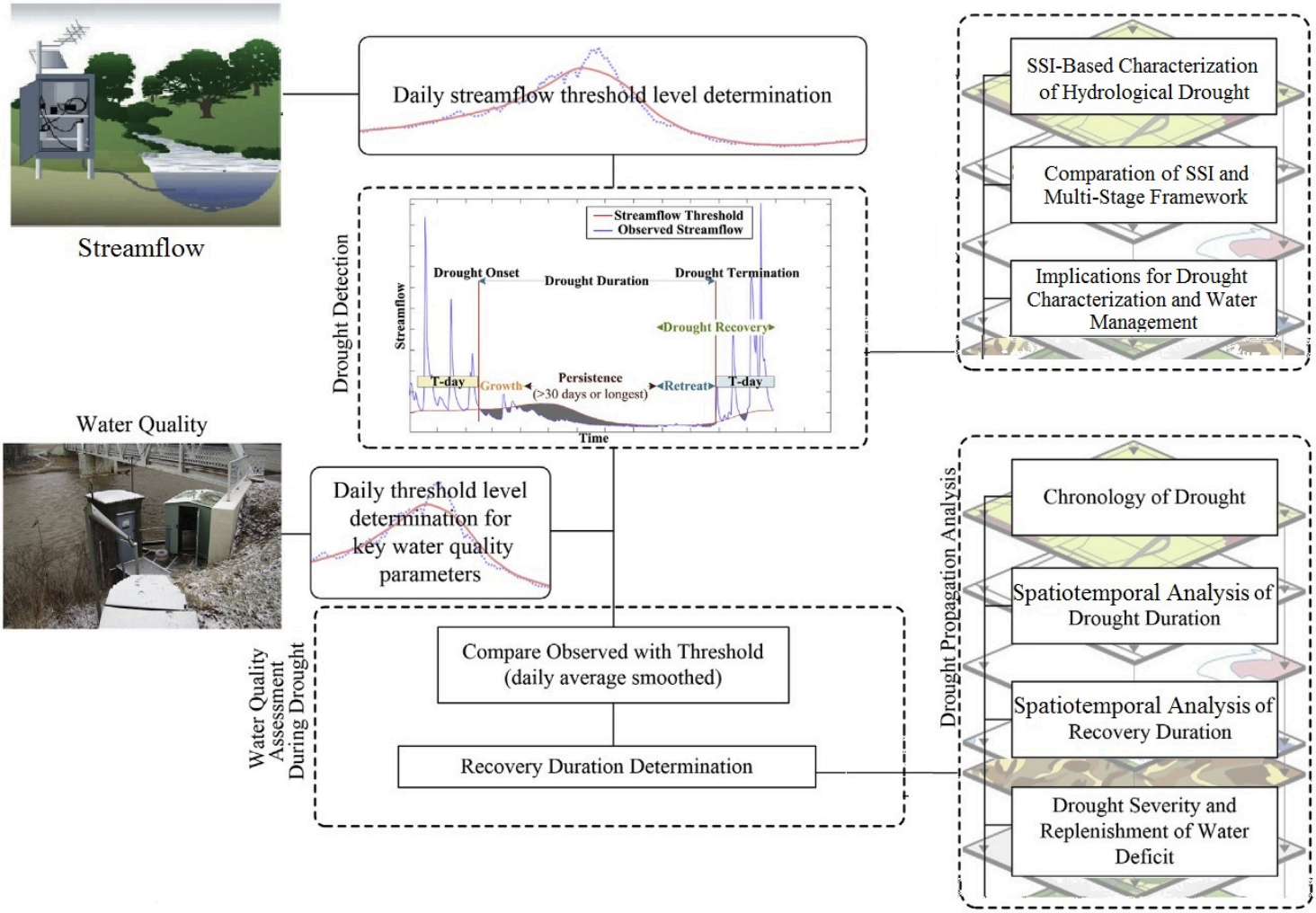


Figure 2

Flowchart of the proposed Three-Stage Variable-Threshold framework for hydrological drought identification, comparative analysis with SSI, and assessment of post-drought water quality recovery.

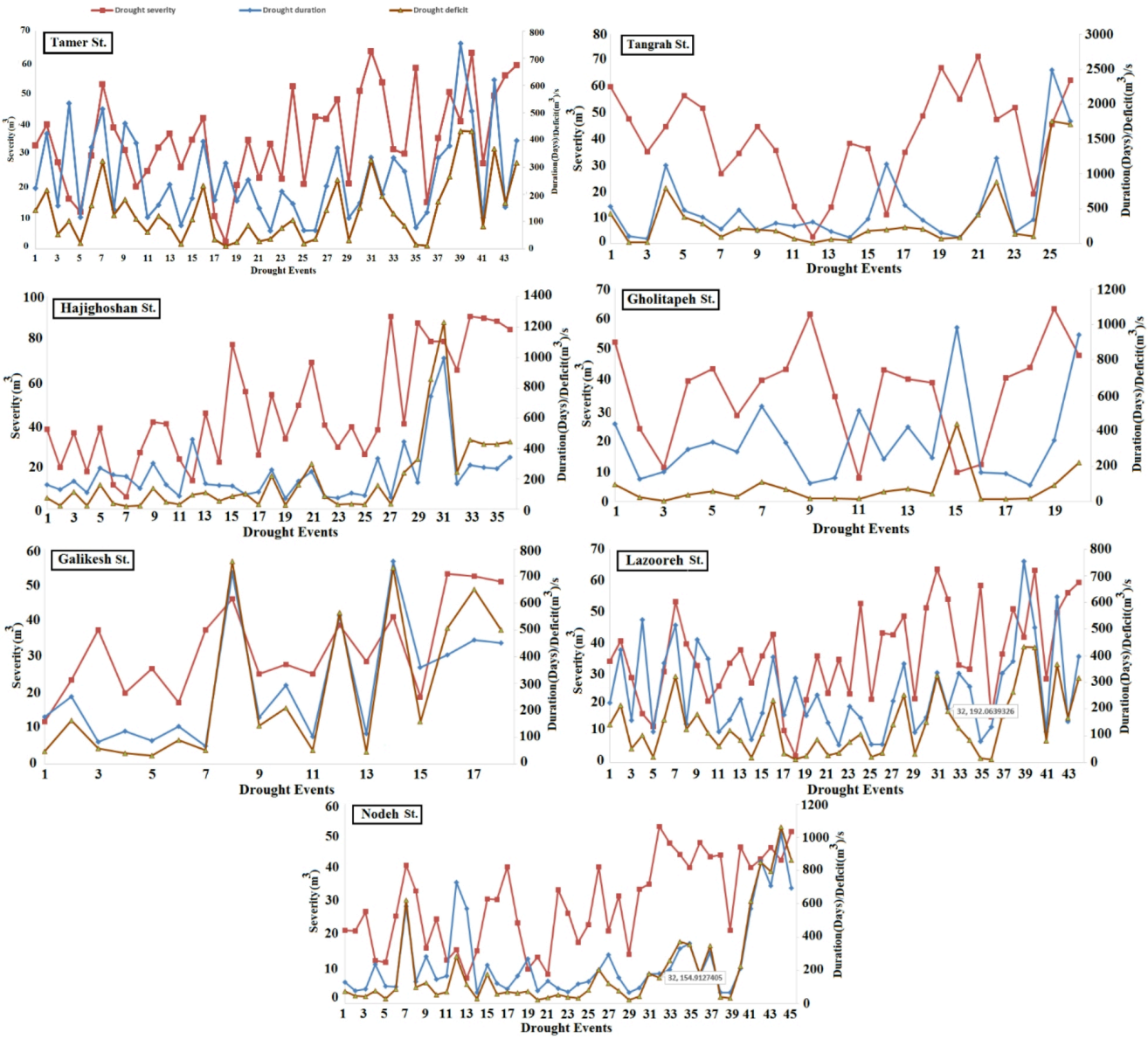


Figure 3

Comparison of Drought Severity, Duration, and Deficit at Stations during the Study Period.

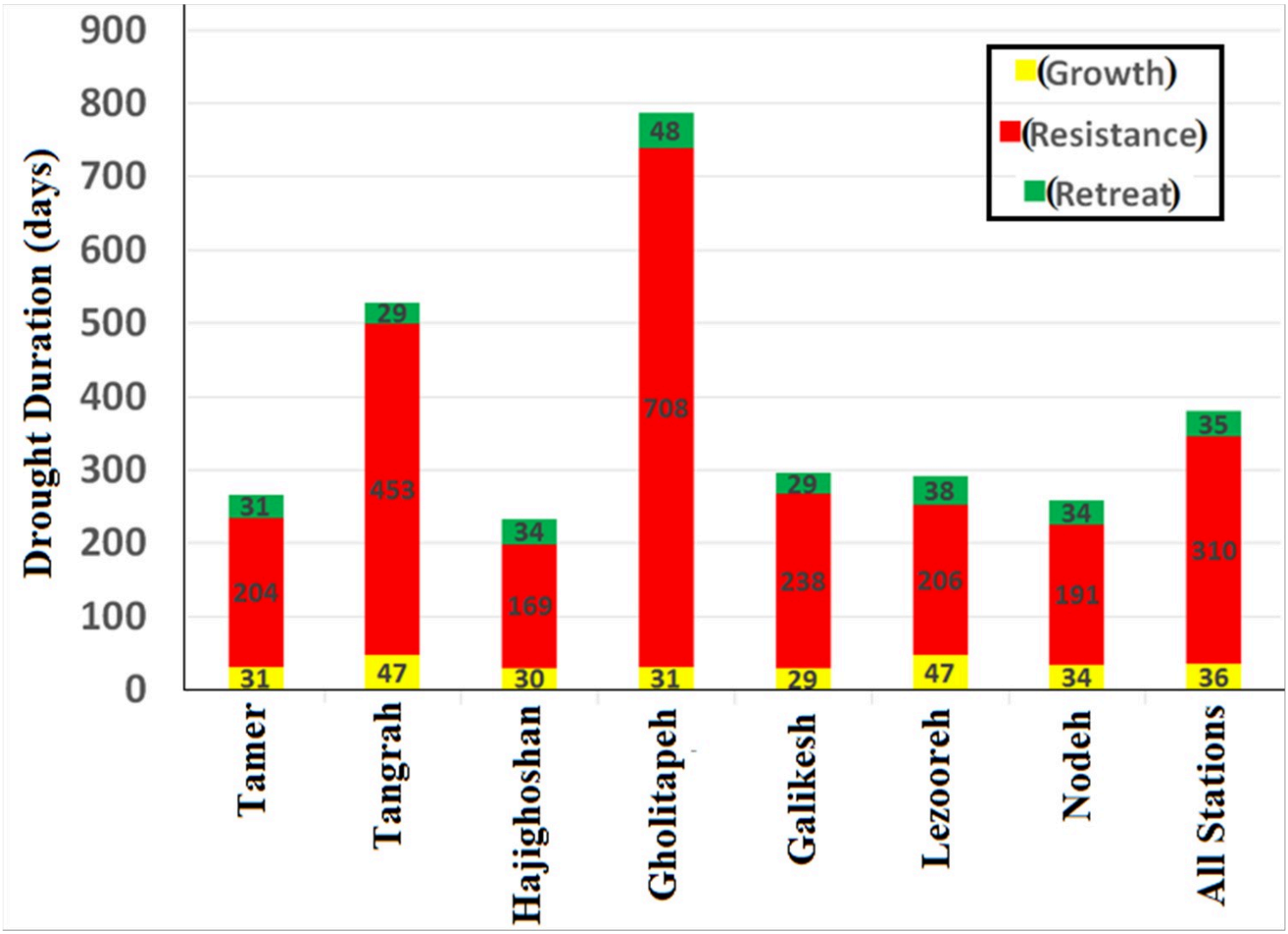


Figure 4

Comparison of Mean Drought Event Stages at the Study Stations during the Study Period.

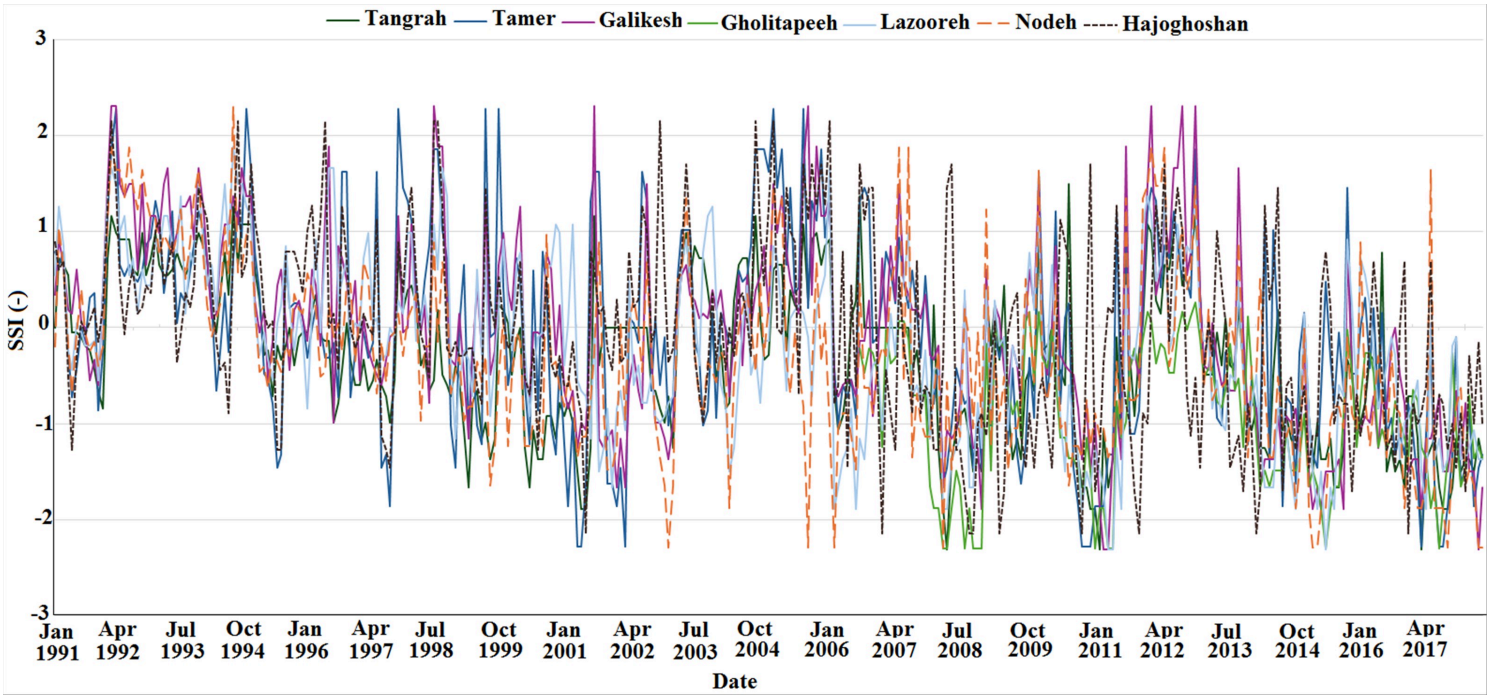


Figure 5

Time Series of the 1-Month Standardized Streamflow Index (SSI) at the Study Stations (1991–2017).



Figure 6

Comparative Plot of Hydrological Droughts from the Standardized Streamflow Index (SSI) and the Multi-Stage Framework for the Stations: Tangrah, Tamer, Hajighoshan, Gholitapeh, Galikesh, Lozooreh, and Nodeh (Top to Bottom).

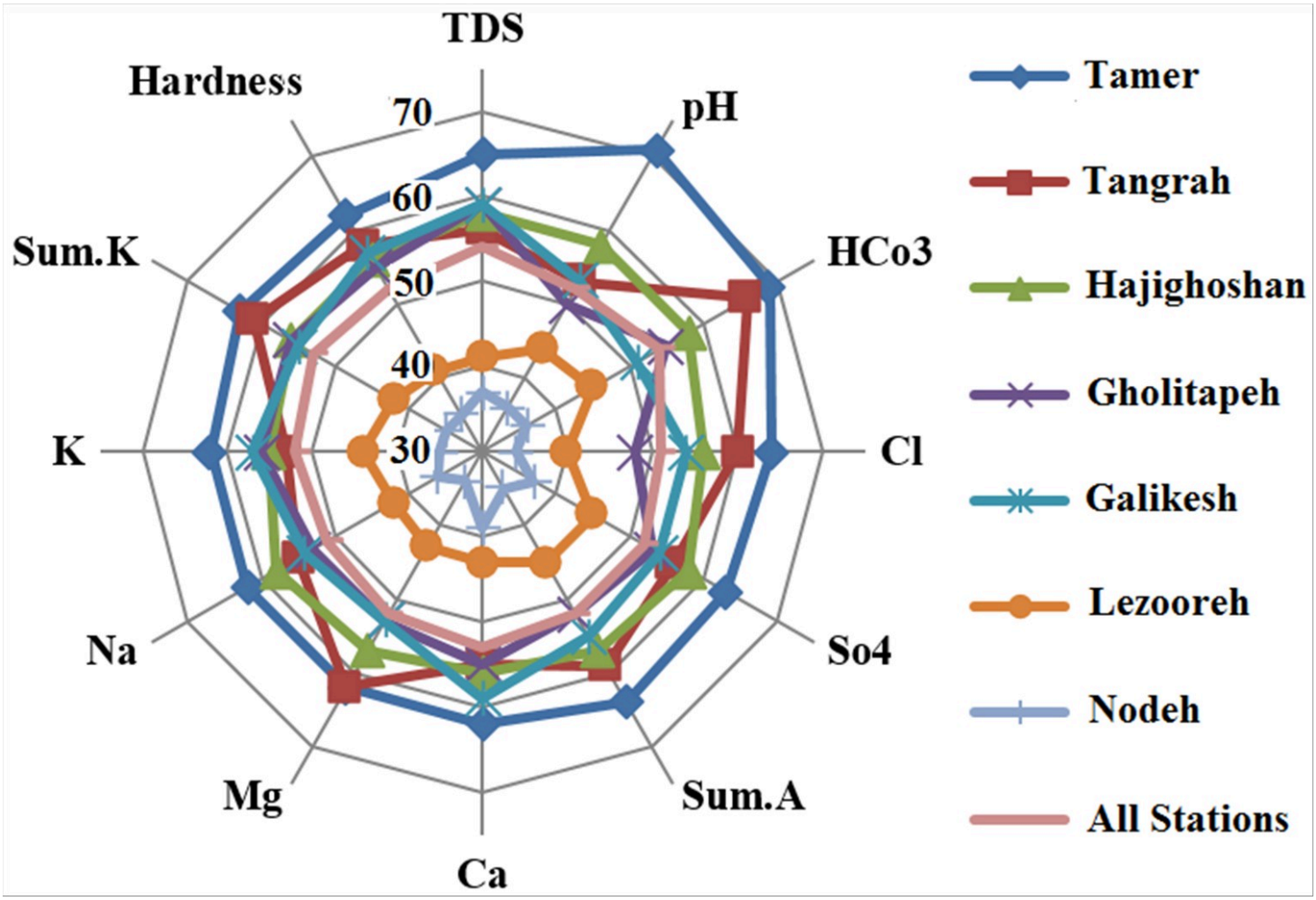


Figure 7

Mean Recovery Time (Days) for Different Water Quality Parameters at the Study Stations.