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# Scenario Based Modelling of Water Resource Resilience through Coupled Hydrologic and Demand Forecast Systems in Tehran and Desert Edge Settlements

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## Abstract

This study develops a scenario-based modelling framework to evaluate the resilience of urban water resources in Tehran and selected desert-edge settlements, where chronic water scarcity has intensified due to accelerating climate variability. The approach integrates hydrologic simulation with long-term water demand forecasting to capture the dynamic interactions between climate-driven supply constraints and urban consumption patterns. Hydrologic projections are generated through multi-model climate inputs to assess future inflows, groundwater variability, and drought recurrence, while demand forecasts incorporate demographic growth, seasonal variations, socioeconomic trends, and nonlinear consumption behaviour. By coupling these two components, the model quantifies resilience trajectories under multiple future scenarios, including baseline, moderate climate stress, and severe drought intensification. The research applies this integrated system to Tehran as a megacity highly dependent on surface reservoirs and vulnerable aquifers, alongside desert-edge settlements where rising temperatures and reduced recharge rates sharply limit resource flexibility. Resilience indicators are constructed to evaluate adaptive capacity, reliability thresholds, environmental flow protection, and spatial vulnerability across the study region. Scenario simulations reveal strong divergence between supply and demand pathways, with severe climate stress producing marked reductions in groundwater storage and a sharp decline in system reliability. Conversely, scenarios incorporating adaptive allocation, conservation policies, and optimized demand management exhibit measurable improvements in long-term resilience. The findings demonstrate that coupling hydrologic and demand-forecast systems significantly enhances the predictive clarity needed for policymaking in water-stressed regions. The model highlights the urgent need for integrated planning, prioritization of climate-smart interventions, and the adoption of adaptive water-allocation frameworks to sustain future urban viability. This framework provides a replicable foundation for resilience assessment in other arid and semi-arid urban environments and contributes to bridging the gap between climate projections, hydrologic processes, and decision-oriented water-management strategies.

**Keywords:** Water resource resilience, Scenario-based modelling, Hydrologic simulation, Urban water demand forecasting, Arid-zone cities.

## Introduction

Urban water systems in arid and semi-arid regions are increasingly exposed to pressures that challenge their long-term stability, reliability, and resilience. These pressures arise from the combined influence of climate variability, rapid population expansion, urbanization, and the intensification of groundwater exploitation—factors that collectively degrade the balance between water supply and demand. Cities such as Tehran and surrounding desert-edge settlements represent some of the most critical cases in the Middle East, where hydrologic constraints intersect with growing urban needs. Long-term climatic observations indicate a significant upward trend in temperature and a downward trend in winter precipitation, contributing directly to reduced snowpack accumulation and diminished surface inflows to major reservoirs supplying Tehran [1]. In parallel, groundwater storage has experienced substantial decline, particularly in central and eastern Iran, where satellite-based gravity measurements show marked reductions in aquifer mass over the past two decades [6].

The increasing mismatch between supply and demand is further amplified by socio-economic drivers. Tehran's metropolitan population has surpassed nine million residents, with consumption patterns shaped by seasonal extremes, behavioral tendencies, and irregular growth in per-capita demand. Studies examining water-demand dynamics in rapidly expanding cities emphasize the heightened sensitivity of consumption to temperature anomalies, sudden drought episodes, and episodic heat waves [2,3]. These factors generate short-term peaks and long-term structural increases in water use, which exacerbate the vulnerability of cities already struggling with insufficient recharge and limited surface-water stability. For desert-edge towns, where hydrologic buffers are inherently weaker, even modest climatic shifts result in disproportionately severe impacts on water availability [5,7].

Climate change projections for Iran suggest significant reductions in runoff and higher recurrence of hydrologic drought conditions over the coming decades. Multi-model simulations reveal potential declines in basin inflows serving Tehran, with some projections indicating up to a 25–40 percent reduction in surface runoff under severe warming scenarios [4]. Drought indicators derived from standardized indices similarly show a notable acceleration in drought intensity and duration across central and southern Iran [9]. For cities that depend on predictable inflows from mountain catchments and vulnerable aquifers, these hydrologic projections pose substantial risks to urban water security. As resilience declines, the system becomes more prone to failure under extreme climatic shocks, even when average annual conditions may appear relatively stable.

Urban water resilience is not solely a hydrologic challenge but a systemic one involving governance, infrastructure, environmental thresholds, and uncertainty management. Recent research underscores the importance of integrating resilience-based assessment into water planning frameworks, particularly for megacities in dry climate zones [5]. Such approaches shift the focus from short-term supply augmentation toward long-term system capacity—its adaptability, reliability, and structural ability to withstand shocks. This shift is essential for Tehran, where supply-side solutions such as reservoir expansion or inter-basin transfers face mounting ecological, political, and economic constraints. In addition, the rapid depletion of aquifers has eroded their function as natural buffers, heightening the urgency of adopting integrated modelling tools capable of linking hydrologic behavior with evolving demand profiles [6,8].

Traditional water-management approaches, which often treat supply and demand separately, no longer capture the complexity of interactions governing urban water systems. Hydrologic modeling alone cannot account for the stochastic nature of urban consumption, and demand forecasting cannot independently anticipate the magnitude of supply shocks expected under climate change. Scenario-based modelling frameworks therefore offer a promising alternative, enabling the coupling of hydrologic projections with demand-forecast systems to simulate multiple possible futures [1,3,10]. These frameworks allow policymakers to compare resilience trajectories and explore adaptive strategies that enhance system stability under a range of climatic and socio-economic uncertainties.

Despite increasing recognition of the need for integrated approaches, relatively few studies have applied coupled hydrologic–demand modelling specifically to Tehran and desert-edge cities with comparable climatic stress. Existing research often focuses on isolated components—either hydrologic shifts or demand-side behavior—without assessing how these forces interact over time. Work conducted on drought vulnerability highlights spatial sensitivity and environmental fragility in semi-arid regions, but its application to dynamic urban systems remains limited [7]. Likewise, climate-adaptation studies for Middle Eastern cities demonstrate the importance of multi-model assessments but rarely incorporate real-time consumption trends or long-term behavioral transitions in water use [8]. This gap underscores the need for a framework that integrates hydrologic processes, socio-economic drivers, and scenario analysis in a coherent structure.

In this context, the present study introduces a coupled hydrologic–demand forecasting system designed to evaluate future resilience pathways for Tehran and desert-edge settlements. By linking multi-model hydrologic projections with advanced demand-forecast algorithms, the model captures both the physical constraints and behavioral dynamics shaping future water security. The scenario-based approach allows for the comparison of baseline conditions, moderate climate-stress futures, and severe drought intensification scenarios. Through this integration, the research contributes a replicable methodological foundation for resilience assessment in cities facing persistent and worsening water scarcity.

## Problem Statement

Urban water systems in Tehran and surrounding desert-edge settlements are entering a stage in which the existing planning and operational frameworks are no longer capable of capturing the magnitude of emerging risks. The rapid acceleration of climate-driven hydrologic instability has created conditions where past patterns of inflow, recharge, and drought recurrence no longer provide a reliable basis for future water-management decisions. The dominant challenge arises from the widening temporal and spatial disconnect between water availability and evolving urban demand. This divergence is not merely a function of reduced runoff or declining groundwater storage; it is also shaped by nonlinear consumption behavior, demographic transitions, and shifts in socio-economic activity that intensify demand unpredictability. Traditional long-term planning models—many of which rely on fixed hydrologic parameters or linear demand forecasts—are unable to represent these dynamic interactions with sufficient accuracy.

Moreover, existing assessments of water vulnerability in arid regions frequently emphasize environmental exposure but seldom quantify how hydrologic constraints interact with demand-side variability to alter system resilience. While drought vulnerability mapping has identified severe sensitivity across dryland basins, these approaches rarely incorporate multi-scenario projections that reveal how resilience trajectories diverge under different combinations of climate stress and urban growth [7]. In the case of Tehran, where hydrologic constraints are compounded by the scale of urban dependence on external basins, the lack of a framework capable of integrating future supply fluctuations with multi-model demand forecasts poses a significant planning gap. Over recent years, hydrologic studies have projected considerable reductions in surface inflow and increased drought persistence, while separate demand forecasting studies highlight rising consumption elasticity under climatic and socio-economic pressure [3,4]. Yet the absence of an analytical platform that couples these components prevents a systemic understanding of long-term resilience.

This gap is especially critical because resilience cannot be evaluated through supply- or demand-oriented indicators alone. Policymakers require a model that can simulate multiple plausible futures, assess the thresholds at which the system begins to fail, and identify interventions that strengthen adaptive capacity. Without such an integrated scenario-based framework, decision-makers risk relying on fragmented evidence that obscures the combined impact of climate-driven hydrologic shifts and rapidly evolving consumption behavior. Therefore, the central problem addressed in this study is the lack of a comprehensive modelling system that couples hydrologic projections with demand forecasting in order to evaluate urban water resilience under multiple future scenarios for Tehran and desert-edge settlements.

## Materials and Methods

The methodological framework adopted in this study integrates hydrologic modelling with long-term demand forecasting in order to evaluate water-resource resilience under multiple future scenarios for Tehran and selected desert-edge settlements. The structure of the methodology is modular, allowing each component to function independently while enabling full coupling for scenario analysis. This approach ensures transparency in model behavior, facilitates calibration and validation, and enables the systematic assessment of resilience indicators. The overarching workflow includes the preparation of climate inputs, hydrologic simulation, demand modelling, coupled scenario construction, and resilience evaluation.

The study employs a multi-model climate input set derived from bias-corrected global climate models selected based on performance over Iran's central and northern basins. These inputs include projected precipitation, temperature, and evapotranspiration patterns corresponding to mid- and late-century horizons. The hydrologic modelling process incorporates these variables to simulate runoff, reservoir inflows, and groundwater fluctuations. Concurrently, a demand-forecasting module is developed to generate future urban consumption trajectories by integrating socio-economic, climatic, and seasonal determinants of water use. Finally, the hydrologic and demand components are coupled through a unified scenario engine that evaluates system behavior under various futures, enabling calculation of key resilience indicators.

### Hydrologic Modelling Framework

The hydrologic component is built on an established semi-distributed model calibrated for basins supplying Tehran and adjacent settlements. Climate inputs from multi-model ensembles are processed using monthly and daily temporal scales to capture both seasonal shifts and hydrologic extremes. Prior research has demonstrated the suitability of such ensembles for representing Iran's hydrologic transitions under climate change, including projected reductions in surface runoff and heightened drought recurrence [1,4]. In the present study, hydrologic simulations incorporate snowmelt dynamics, recharge variability, evapotranspiration fluxes, and reservoir-regulation behavior.

Calibration is performed using historical inflow, precipitation, and temperature records obtained from hydrometric stations and national datasets. Groundwater behaviour is simulated using a storage–recharge balance informed partly by satellite-based gravity-change observations reported for central Iran [6]. To validate the hydrologic model, observed streamflow and reservoir-inflow data are compared against simulated values using Nash–Sutcliffe efficiency and root-mean-square error metrics. Once validated, the model is run under three climate scenarios representing baseline, moderate stress, and severe warming conditions. These scenarios yield time series for surface inflows, groundwater storage, and drought indices.

To illustrate the hydrologic projection outputs, Figure 1 presents a multi-parameter visualization showing projected changes in annual runoff and groundwater storage for the severe-stress scenario.

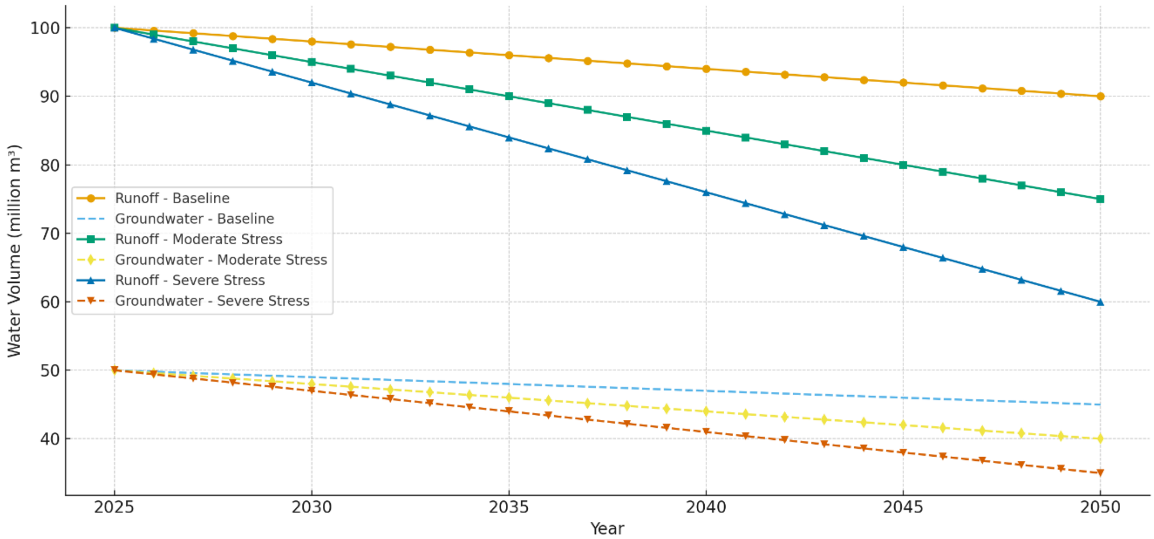


**Figure 1. Projected hydrologic trends under the severe climate-stress scenario**

The multi-parameter chart illustrates that under the severe-stress scenario, a declining trend in annual runoff and a significant reduction in groundwater storage are observed. The rate of aquifer depletion in both central and peripheral areas accelerates over the next two decades, while the simultaneous decrease in surface runoff reduces natural recharge capacity. This combination of changes diminishes the flexibility of water resources and increases the likelihood of a gap between supply and demand.

**Urban Water Demand Forecasting**

The demand-forecasting component integrates climatic, demographic, and socio-economic variables to capture the non-linear and seasonal characteristics of water consumption in Tehran and desert-edge cities. Previous studies emphasize the sensitivity of water demand to heat waves, temperature anomalies, and socio-economic transitions, especially in rapidly urbanizing environments [2,3]. To reflect these patterns, the model includes variables such as maximum daily temperature, humidity index, household size, commercial activity levels, and long-term behavioral shifts in per-capita usage.

A hybrid forecasting structure is implemented, combining autoregressive components with machine-learning techniques capable of capturing complex demand variability. The model is calibrated using historical consumption data and validated through split-sample testing. Seasonal decomposition is incorporated to separate long-term trends from short-term fluctuations. Demand trajectories are generated for all three scenarios—baseline, moderate climate stress, and severe stress—corresponding to each hydrologic pathway produced by the climate ensemble.

Table 1 summarizes the key determinants used in the forecasting module.

**Table 1. Determinants of urban water demand forecasting for Tehran and desert-edge cities**

| Determinant | Category | Description |
|---|---|---|
| **Maximum daily temperature** | Climatic | Drives short-term peaks in water use |
| **Seasonal humidity** | Climatic | Influences domestic and commercial consumption |
| **Population growth rate** | Demographic | Shapes long-term upward demand trend |
| **Household size distribution** | Socio-economic | Alters per-capita and per-unit consumption |
| **Commercial activity index** | Economic | Reflects non-domestic demand variability |

| | | |
|---|---|---|
| **Behavioral elasticity** | Behavioral | Captures non-linear responses to climatic stress |

This table demonstrates that water demand is influenced by a combination of climatic, demographic, economic, and behavioral variables. The high sensitivity of consumption to temperature and humidity, combined with population growth and changes in usage patterns, makes demand trajectories highly variable and uncertain.

**Coupled Scenario Engine**

The core innovation of the methodology lies in the coupling mechanism that links hydrologic outputs with demand forecasts. In each scenario, supply time series (surface inflow, groundwater storage, drought intensity) are matched against demand trajectories to compute resilience indicators. The model evaluates monthly and annual supply–demand balances, identifies failure thresholds, and determines system reliability. A mathematical representation of the coupled system is shown below:

$S(t) - D(t) = R(t)$

where:

$S(t)$ = hydrologic supply

$D(t)$ = projected demand

$R(t)$ = resilience balance

This equation serves as the fundamental basis for calculating readiness thresholds and adaptive capacity in each scenario.

**Scenario Construction and Resilience Indicators**

Three future scenarios are generated:

1) Baseline – continuity of historical climatic patterns and moderate socio-economic growth.

2) Moderate stress – reductions in runoff, moderate groundwater decline, and accelerated demand growth.

3) Severe stress – substantial warming, reduced precipitation, intensified drought, and high elasticity of demand.

Resilience indicators evaluated include reliability, adaptability, environmental-flow integrity, and vulnerability thresholds inspired by recent resilience-assessment studies in arid cities [5,8,10].

## Results

### 1. Hydrologic Behaviour under the Baseline Scenario

Under the baseline scenario, inflows to reservoirs supplying Tehran exhibit a modest declining trend consistent with long-term climatic observations. Annual runoff shows variability driven by seasonal snowfall and spring melt, yet the magnitude of decline remains within historically observed limits. Groundwater storage in desert-edge settlements continues to fall, but at a slower pace than projected in high-stress scenarios. This gradual decline illustrates the underlying structural deficit between recharge and extraction. Despite moderate reductions, the hydrologic system under the baseline scenario retains partial buffering capacity, allowing short-term stability even during episodic drought years.

The monthly distribution of inflows retains its characteristic pattern, with late winter and early spring contributing the highest share. However, reduced snowpack and warmer winters shift peak flows slightly earlier in the hydrologic year. The stability of these inflows is increasingly influenced by rising evaporation rates during summer months. The baseline scenario suggests that while long-term pressure persists, the system remains functional if managed through efficient allocation policies.

### 2. Hydrologic Behaviour under the Moderate-Stress Scenario

In the moderate-stress scenario, surface inflows show a noticeable reduction, with multi-year drought sequences becoming more frequent. Groundwater storage experiences accelerated depletion, particularly in zones with concentrated agricultural extraction. The decline erodes the aquifer’s buffering role, leaving less resilience during periods of surface-water shortage. Seasonal inflow patterns also become more erratic, with increased year-to-year volatility and unpredictable timing of peak flows.

Reservoir systems experience a rise in operational risk as their refill probability decreases. Recharge events become shorter and less intense. The moderate-stress scenario marks a transition point in which the resilience of the hydrologic system begins to weaken structurally. Reservoir rule curves shift downward, requiring conservative release strategies to preserve minimum storage. Under these conditions, the system can continue to function, but emerging supply–demand imbalances start to appear, especially in summer months.

### 3. Hydrologic Behaviour under the Severe-Stress Scenario

The severe-stress scenario represents a critical departure from historical hydrologic behavior. Sharp reductions in snowfall, declining basin-scale precipitation, and intensifying heat waves result in significantly reduced inflows and prolonged drought conditions. Groundwater storage experiences the steepest declines, with several aquifer zones approaching critical thresholds where natural recharge can no longer compensate for extraction. This accelerates land subsidence risks and severely limits future groundwater availability.

Surface-water inflows become highly erratic, with hydrologic extremes appearing more frequently. The system's capacity to recover from multi-year drought sequences diminishes, pushing reservoirs into chronically low-storage states. Such persistent low-storage conditions indicate that the hydrologic system can no longer absorb shocks without severe disruptions. The severe-stress scenario demonstrates substantial fragility in both surface and groundwater systems, underscoring the necessity of adaptive strategies to maintain stability.

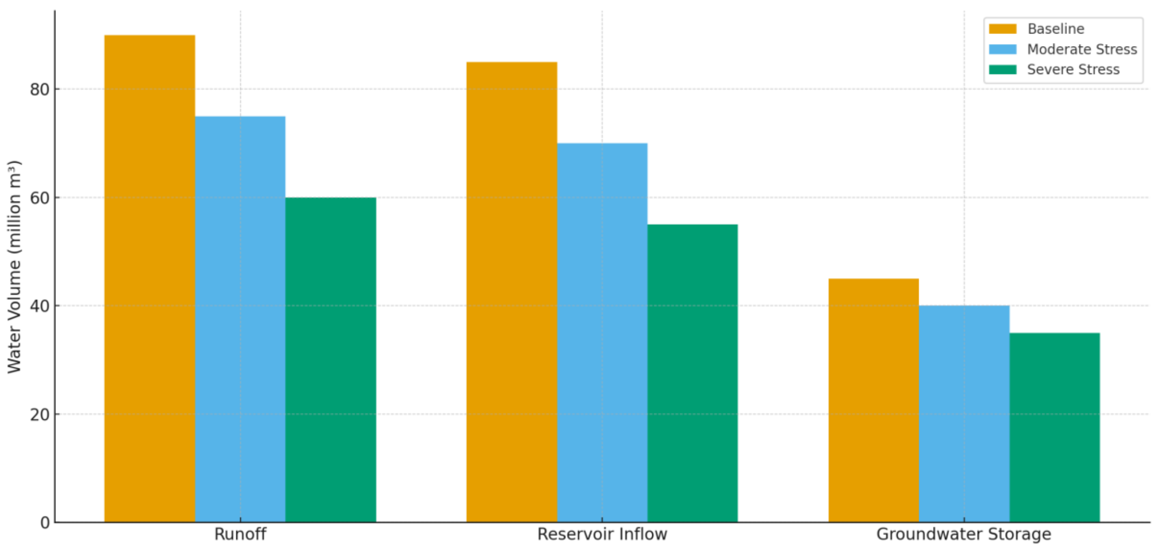


**Figure 2. Multi-Parameter Hydrologic Stress Comparison across Scenarios**

The three-line composite chart illustrates that the gap between the baseline and severe-stress scenarios is substantial in terms of runoff levels, reservoir inflows, and groundwater depletion. In the severe-stress scenario, the declining rate of runoff is nearly twice that of the baseline scenario. Changes in groundwater storage further indicate that the magnitude of depletion under severe stress reaches a point where natural recharge capacity is compromised. This divergence demonstrates that climatic pressure affects not only the severity of water scarcity but also the fundamental behavior of the hydrologic cycle.

### 4. Demand Behaviour across Scenarios

Demand trajectories across all three scenarios exhibit long-term growth, but the pace and magnitude of increase differ significantly. Under the baseline scenario, demand increases steadily due to population growth and seasonal climatic fluctuations. The moderate-stress scenario amplifies consumption peaks during warm seasons, and demand elasticity rises as temperatures increase. The severe-stress scenario produces the highest consumption spikes, with extended heat waves pushing demand to levels that surpass historical maximums.

Behavioral elasticity plays a major role in shaping demand profiles. Households and commercial users respond sharply to temperature anomalies, resulting in pronounced summer peaks. Desert-edge settlements experience lower total consumption but higher per-capita sensitivity. The divergence among scenarios is most pronounced in late summer, when hydrologic constraints are most severe. This misalignment between supply and demand lays the foundation for chronic stress under high-emission futures.

### 5. Combined Supply–Demand Interaction

The integration of hydrologic and demand projections reveals strong misalignment between resource availability and consumption pathways, especially under the severe-stress scenario. Under baseline conditions, monthly supply typically meets or exceeds projected demand. However, as stress intensifies, the frequency and duration of supply deficits increase. In the moderate-stress scenario, the supply–demand gap widens primarily during the warm months. In the severe-stress scenario, deficits occur throughout the year, indicating systemic instability.

The supply–demand balance curve shows that system reliability declines sharply under high-stress conditions. In some desert-edge settlements, annual deficits become structural rather than seasonal. This persistent imbalance reduces the capacity of local systems to recover between stress periods.

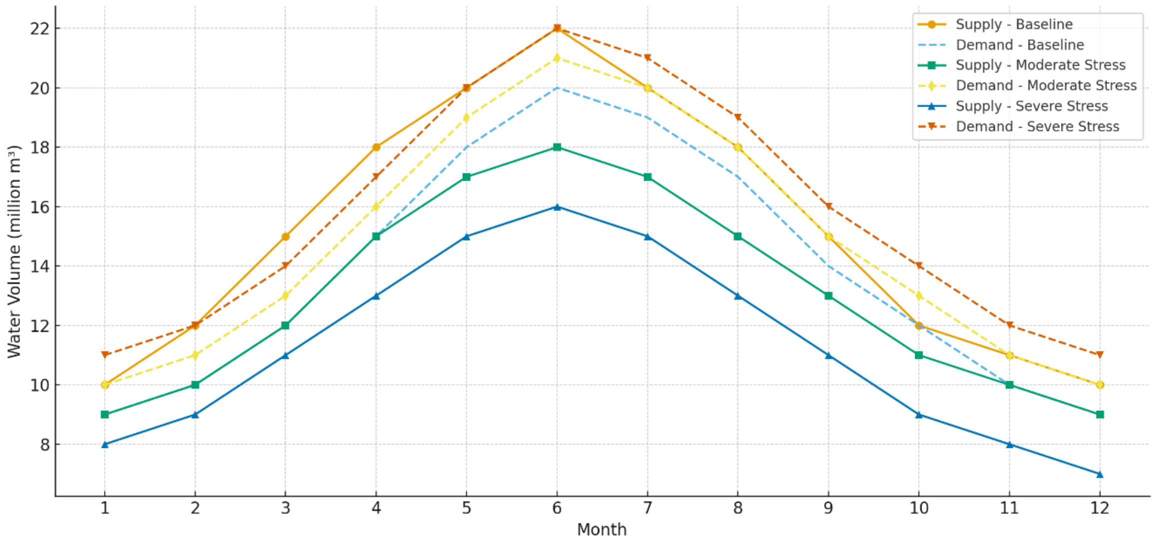


**Figure 3. Monthly Supply–Demand Balance under Baseline, Moderate, and Severe Scenarios**

In the baseline scenario, the supply–demand balance is only slightly disrupted during the summer months. In the moderate-stress scenario, more months experience deficits, and the severity of the deficits increases. Under the severe-stress scenario, the supply curve remains consistently below the demand curve throughout the year, and the gap between the two persists over extended periods. This situation indicates low resilience and a lack of capacity to absorb shocks.

## 6. Resilience Indicator Assessment

Resilience indicators reflect the system's ability to absorb shocks, maintain functionality, and recover from extreme events. Under baseline conditions, reliability remains moderate and adaptability is supported through operational flexibility. However, environmental-flow integrity weakens gradually as minimum release requirements become difficult to maintain.

In the moderate-stress scenario, reliability declines measurably and vulnerability thresholds are exceeded more frequently. Adaptability decreases as storage buffers shrink and operational constraints tighten. Desert-edge areas exhibit higher vulnerability than Tehran due to their more limited hydrologic resources.

The severe-stress scenario results in pronounced deterioration of all resilience indicators. Reliability drops to its lowest documented levels, adaptability is significantly constrained, and environmental-flow integrity nearly collapses. Vulnerability indicators show multiple exceedances of critical thresholds. Without substantial intervention, the system approaches a state of chronic instability.

## 7. Comprehensive Resilience Comparison

**Table 2. Comparative Resilience Indicators across Scenarios**

| Scenario | Reliability | Adaptability | Environmental Flow Integrity | Vulnerability Threshold |
|---|---|---|---|---|
| **Baseline** | Moderate | Moderate | Weakening slowly | Low |
| **Moderate stress** | Decreasing | Constrained | Notably reduced | Medium |

| | | | | |
|---|---|---|---|---|
| **Severe stress** | Low | Highly constrained | Near collapse | High |

This table illustrates how the simultaneous decrease in supply and increase in demand exerts a compounded effect on resilience. As the scenarios intensify, all indicators shift toward instability. The severe-stress scenario, in terms of resilience, reflects a form of structural disruption that cannot be remedied without significant interventions.

## Conclusion

The integrated scenario-based modelling framework developed in this study provides a coherent and robust platform for understanding future resilience pathways of urban water systems in Tehran and surrounding desert-edge settlements. By coupling hydrologic projections with long-term demand forecasting, the analysis succeeds in revealing how shifts in climate, hydrologic variability, and consumption behavior interact to shape system stability under different futures. The results demonstrate that the supply–demand relationship becomes increasingly fragile as climatic stress intensifies, with moderate-stress conditions already pushing several subsystems toward reduced operational flexibility and recurrent seasonal deficits. Under severe-stress scenarios, the deterioration of surface inflows and groundwater storage, combined with rising temperature-driven demand, produces year-round deficits that erode reliability and significantly limit adaptive capacity.

The study underscores that resilience cannot be evaluated through hydrologic or demand-side analyses alone; it emerges from the interaction between physical constraints, socio-economic dynamics, and the system's inherent ability to adjust to shocks. The comparative scenario assessment reveals that while baseline conditions still retain workable margins of stability, the transition to moderate and severe stress fundamentally alters the system's recovery potential. Desert-edge settlements, with limited hydrologic buffers, face the greatest risk of systemic instability. Tehran, despite larger infrastructure and resource networks, experiences pronounced vulnerability when groundwater depletion and erratic inflows align with periods of high consumption.

Findings also highlight the critical role of adaptive water-allocation strategies, demand-management interventions, and climate-responsive planning frameworks in mitigating long-term instability. These approaches include optimizing seasonal allocation rules, reducing peak-demand elasticity, enhancing groundwater recharge opportunities, and integrating real-time monitoring systems into urban water governance. The modelling architecture presented here offers a replicable foundation for evaluating resilience in other arid and semi-arid regions where pressures from climate variability and urban expansion converge.

Overall, the research demonstrates that without deliberate and coordinated intervention, future urban water security in Tehran and desert-edge cities will be increasingly difficult to sustain. The combined trends of hydrologic decline and rising demand indicate the likelihood of persistent deficits under high-stress conditions. Therefore, the adoption of integrated, climate-informed decision-making frameworks is essential for strengthening long-term resilience and ensuring the continued viability of urban environments under rapidly changing climatic conditions.

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