DOI: 10.24996/ijs.2026.67.8.36

ISSN: 0067-2904

Assessment of Water Resources Carrying Capacity in Watersheds Using a Combined Simulation and Indicator-Based Approach: Case Study: Maharlo Catchment, Iran

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Received: 5/8/2025 Accepted: 12/10 /2025 Published: 30/8 /2026

Abstract

Water Resources Carrying Capacity [WRCC] originates from the broader ecological notion of carrying capacity within natural resource management. This study refines and applies the WRCC concept by integrating simulation modeling, indicator-based evaluation, and a pressure–support framework to deliver a comprehensive assessment of water sustainability. A novel evaluation framework was proposed to address shortcomings in existing methods, particularly the limited consideration of environmental health and the substitutability of assessment indicators. This integrated approach was applied to the Maharlo catchment in southern Iran from 2003 to 2023. For a more nuanced understanding, the study period was segmented into three phases: 2003–2009, 2010–2017, and 2018–2023, with evaluations performed on annual and multi-year scales. Results indicate that water usage remained within the carrying capacity only during the first phase. The second and third phases witnessed increasing water resource stress. According to standardized evaluation criteria, WRCC and environmental health declined by one level in the latter periods, reaching their lowest levels by the final phase. The pressure–support analysis further illustrates a consistent rise in stress levels on water resources, coupled with a diminishing capacity for support. These outcomes suggest that regional development policies have prioritized rapid economic expansion over environmental constraints. Given the strong consistency between the model outputs and observed field conditions, the proposed framework can serve as a practical tool for evaluating water management policies in other similar watershed contexts.

Keywords: Environmental sustainability; Environmental health; Pressure–support framework; Carrying capacity; Maharlo watershed; Iran.

تقييم قدرة موارد المياه على التحمل في أحواض الأنهار باستخدام منهجية مدمجة تجمع بين المحاكاة والتقييم القائم على المؤشرات دراسة حالة: حوض ماهارلو، إيران

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الخلاصة

نشأ مفهوم قدرة موارد المياه على التحمل [WRCC] من الفكرة الأوسع لقدرة التحمل في إدارة الموارد الطبيعية. تطبق هذه الدراسة هذا المفهوم وتطوره من خلال دمج نمذجة المحاكاة، والتقييم القائم على المؤشرات، وإطار الضغط–الدعم لتقييم قدرة التحمل لموارد المياه. تم تطوير إطار تقييم جديد لتجاوز القيود في الطرق الحالية، مثل عدم الاعتبار الكافي للصحة البيئية والتداخل في استخدام مؤشرات التقييم. يُطبق هذا المنهج المتكامل لتقييم قدرة تحمل موارد المياه في حوض ماهارلو في جنوب إيران خلال الفترة من 2003 إلى 2023. لتوفير رؤى أعمق، قُسمت فترة التقييم إلى ثلاث مراحل: 2003–2009، 2010–2017، و2018–2023، وأُجريت التحليلات على أساس سنوي ومتعدد السنوات. تُظهر النتائج أن استخدام المياه في المنطقة ظل ضمن قدرة التحمل فقط خلال المرحلة الأولى. في المرحلتين الأخيرتين، شهد الحوض زيادة في الضغط على موارد المياه. وفقًا لمعايير التقييم المعتمدة، انخفض كل من قدرة تحمل موارد المياه والصحة البيئية بمستوى واحد في الفترتين الثانية والثالثة، ليصل إلى أدنى حالة مسجلة في المرحلة الأخيرة. يكشف تحليل الضغط–الدعم عن زيادة مستمرة في الضغط على موارد المياه وانخفاض مكافئ في قدرتها على الدعم عبر جميع الفترات. تشير هذه النتائج إلى أن السياسات الإقليمية فضلت التنمية الاقتصادية السريعة دون الأخذ في الاعتبار القيود البيئية. وبالنظر إلى التوافق القوي بين نتائج التقييم والملاحظات الواقعية، يمكن تطبيق هذا الإطار لتقييم سياسات المياه في سياقات أحواض أنهار مشابهة.

1. Introduction

Water is fundamental to human survival and socio-economic development [1,2]. As a vital natural resource, water sustains ecosystems and underpins the progress of civilization [3,4]. However, its scarcity poses significant threats to food security, energy stability, and economic development, making water a strategic resource [5,6]. Addressing challenges such as water shortages and spatial imbalances in availability has become essential for achieving global sustainability. Therefore, aligning water resource management with socio-economic development objectives is an urgent priority [7,8].

The concept of carrying capacity provides a scientific basis for evaluating the sustainable limits of natural systems in supporting both human and ecological functions [9,10,11]. Recent research has focused on definitions, methodological development, and practical applications [12,13]. Specifically, studies on Agricultural WRCC [AWRCC] have employed predictive approaches such as system dynamics [3; 7; 10] and mathematical modeling [13,14] to support sustainable planning. Stem dynamics models are popular but sensitive to subjective parameterization, resulting in unreliable results [15,16]. In contrast, mathematical models offer a more robust and objective alternative.
Mathematical modeling methods can be categorized into two groups:
First: direct WRCC prediction based on historical data [17,18,19] and second projection of evaluation indicators followed by implementation within assessment frameworks [20,21,22]. Applications of WRCC assessment span various spatial scales, including urban [23, 24], regional [25, 26], and basin-level studies [2,3]. Nevertheless, integrated approaches that combine simulation and indicator-based evaluation remain scarce in the global literature. This research addresses this gap.

The Maharlo watershed in Fars Province, central Iran, represents a critical case of ecological fragility and resource depletion. Since the early 2010s, agricultural expansion, inter-basin water transfers, and recurrent droughts have intensified water stress, leading to heavy reliance on groundwater and functional loss of surface water resources.

To address these challenges, this study introduces an integrated Water Resources Carrying Capacity (WRCC) assessment framework that combines simulation modeling, indicator-based analysis, and pressure–support evaluation. Unlike traditional methods, the proposed approach incorporates environmental health, avoids arbitrary indicator substitution, and better reflects local ecological realities. Through annual and multi-period analyses, it captures dynamic changes in water conditions.

This is the first comprehensive WRCC evaluation applied at the watershed scale in Iran, offering both a scientific basis for sustainable development in Maharlo and a replicable framework for other water-stressed basins.

2. Study Area

The Maharlo watershed (≈4,270 km²) lies in southwestern Iran within the Zagros Mountains, between 29°01′–29°58′ N and 53°12′–53°28′ E (Figure X). Its central feature, Maharlo Lake (Pink Lake), is located east of the Shiraz Plain at 1,461 m elevation, covering about 600 km² with a maximum depth of ~3 m. The hypersaline lake, though devoid of fish, serves as a seasonal habitat for migratory birds, reptiles, and amphibians, with Artemia supporting large flamingo populations during autumn migration.
Hydrologically, the basin relies on surface and groundwater resources, but permanent rivers are absent. Instead, inflows come mainly from ephemeral streams, particularly the Khoshk River, which deliver variable runoff during wet seasons. These inputs are insufficient to balance high evaporation in the hot, arid climate, resulting in extensive salt flat formation on the lakebed.

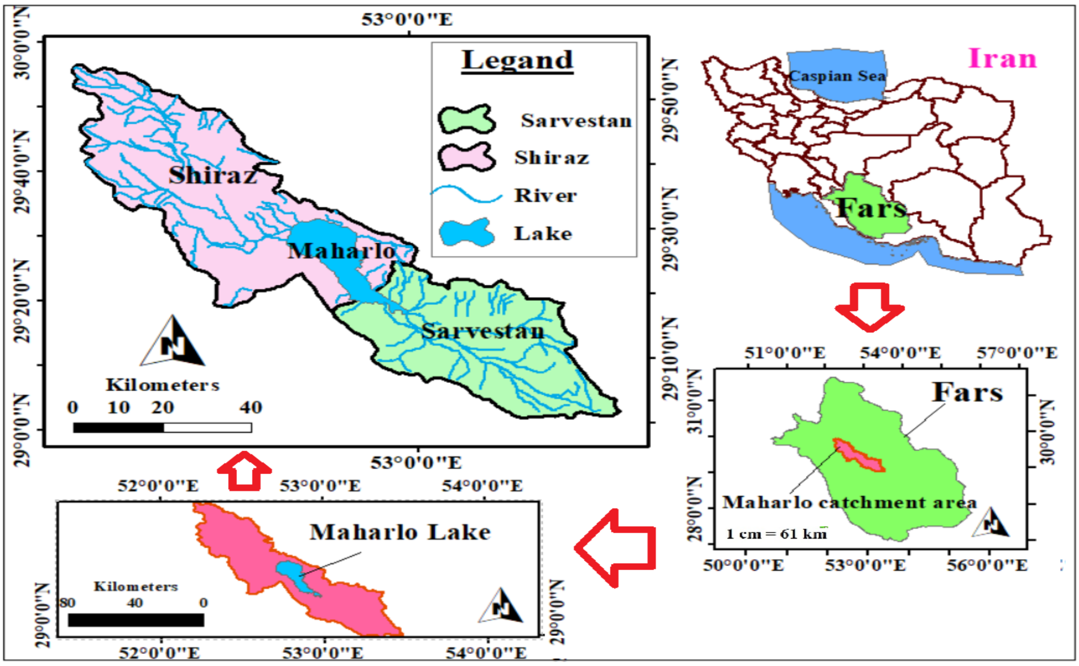

Figure 1: Location of the study area

3. Methodology

This study employed an integrated approach that combines simulation modeling with an indicator. A brief indicator-based assessment was employed to evaluate the Water Resources Carrying Capacity (WRCC) of the Maharlo watershed. The methodology consists of five key stages:

Stage 1: Watershed System Characterization and Data Collection in the Agricultural Sector. Key hydrological and agricultural data were gathered and processed using the Soil and Water Assessment Tool [SWAT] model. In addition, estimates were made for water demands across various sector; including agriculture, domestic, industrial, and service sectors as well as inter-basin water transfers. This stage laid the groundwork for subsequent simulation and indicator-based analysis.

Stage 2: Indicator Selection and Assessment Using the Pressure–Support–Status [PSS] Framework

In this stage, a set of indicators essential for WRCC evaluation was selected and computed within the reassurance–status [PSS] framework. The indicators were grouped into three subsystems—pressure, support, and status, and appropriate weights were assigned to each. Composite indices were then calculated at subsystem and system-wide levels to derive the overall WRCC index. The PSS framework was applied over [2003–2023], enabling a structured and multi-faceted, approach, Table 1 and Figure 2.

Stage 3: Environmental Sustainability and System Balance Evaluation

A three-tiered evaluation process was adopted to emphasize environmental sustainability as a prerequisite for water resource assessment:
Habitat Suitability Index [HSI] was employed to assess environmental sustainability.

The Water Environmental Carrying Capacity Index [WECCI] was calculated to evaluate the system's ecological load capacity.

The ratio was analyzed to determine the
The rationale behind the PS ratio is that even if environmental indicators show acceptable values, an imbalance between pressure and support subsystems may jeopardize future sustainability. Therefore, the third step serves as a critical diagnostic tool for identifying latent risks in the system.
Threshold values for the three indices were defined as follows:

- HSI [environmental threshold]: 0.32 [standardized]
- WECCI [WRCC threshold]: 0.40
- PS Index [PI threshold]: 1.00

The system was deemed "only when all three thresholds are satisfied. Any deviation indicates an "overloaded" or unsustainable condition.

Table 1: Water indicators

Category	No	indicator	Unit	Indicator explanation
Pressure	1	Population density	Persons/km2	Population/Land area
	2	Income per unit area	Rial/km2	Income /Land area
	3	Calories per unit area	-	Calories /Land area
Supportive force	4	Evaporation	mm	Actual water consumption of the agricultural sector
	5	River runoff per unit of land area	mm/km2	River runoff/ Land area
	6	Precipitation	mm	Reflects the annual precipitation
	7	Groundwater recharge	mm	Reflects the annual groundwater recharge
Health state	8	Per capita water resources	m3/ Persons	Total water resources/ Population
	9	Inflow	m3/s	round river basin

[19,11]

Stage 4: System State Evaluation and Scenario Analysis

The overall state of the watershed system during the study period was assessed by applying the above thresholds and evaluating various pressure–support scenarios. Environmental health status was primarily determined using a key "Status" indicator annual inflow to the Maharlo watershed. Based on hydrological analysis, the sustainable inflow threshold for Maharlo Lake was estimated at 1,271 million cubic meters per year, corresponding to a standardized value of 0.32. Environmental health was categorized into six levels [Table 2], while WRCC levels were classified into five grades following [7] [Table 3].

Table 2: Standards for assessing the carrying capacity of water resources

indicator	Grades	Standards	levels	indicator	Grades	Standards	levels
HSI	I	[0.8 - 1]	Healthy	WECCI	I	[0.8 - 1]	Excellent carrying
	II	[0.64 - 0.8]	Sub-healthy		II	[0.6 – 0.8]	Good carrying
	Ш	[0.48 - 0.64]	Normal		Ш	[0.4 – 0.6]	General
	IV	[0.32 - 0.48]	Critical		IV	[0.2 – 0.4]	Poor carrying
	V	[0.16 - 0.32]	Poor		V	[0 – 0.2]	Very poor carrying
	VI	[0 - 0.16]	Extremely poor				

[28]

Stage 5: Pressure–Support Interaction Analysis:

The final stage explored the dynamic relationship between pressure and support subsystems through the Pressure–Support Index [PI]. Four distinct development states of water resources were identified [Table 4]:

State A – High Pressure / High Support: Reflects intensive development with high utilization and resilience. While this state can be favorable, ongoing enhancements to support mechanisms are essential to prevent overload.

State B – High Pressure / Low Support: Indicates unsustainable development driven by economic activities without adequate environmental protection. Although it may yield short-term gains, it is unsuitable for long-term resilience.

State C – Low Pressure / Low Support: Characterizes underdeveloped and weakly supported systems with low WRCC. Interventions should focus on strengthening support capacity to transition toward more sustainable states.

State D – Low Pressure / High Support: Signifies underutilized potential. While indicative of conservation, prolonged stagnation may hinder socio-economic development and lead to inefficient resource use.

Table 3: Types of system states in different pressure-support connection modes

Quadrant	A	B	C	D
Coupling state	High-High	High-Low	Low-Low	Low-High
Type	Advanced	Unsustainable	Weak	Potential

[28]

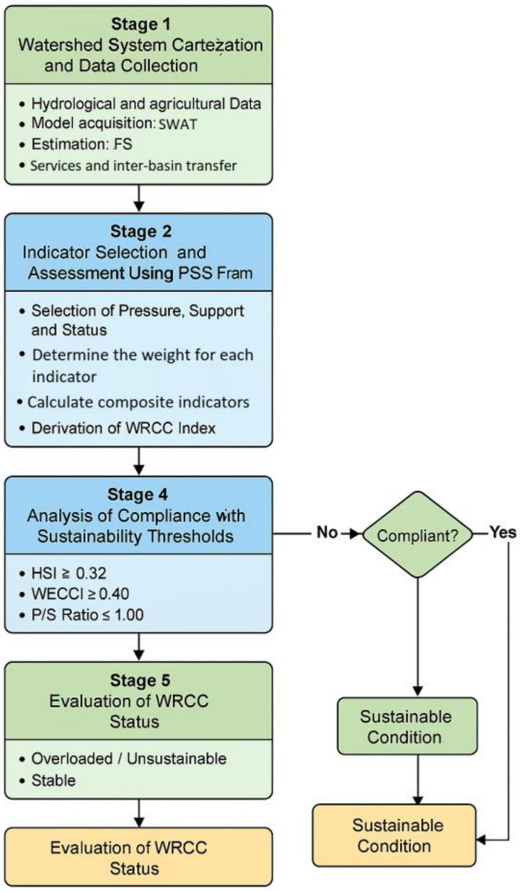

Figure 3: Method of Analysis

4. Results and Discussion

Step 1: Assessment of Basin Status

The current status of the Maharlo watershed was evaluated with a primary focus on the agricultural sector, utilizing outputs from the calibrated Soil and Water Assessment Tool (SWAT) model. The model developed by [1] was adopted, with calibration and validation results detailed in Tables 4 and 5.

Key hydrological and agricultural parameters—including actual agricultural water consumption [evapotranspiration], crop yield, cultivated area, groundwater recharge, and runoff per unit area—were quantified for 2003–2023 using SWAT simulation outputs.

To eliminate the effects of inflation, income values were adjusted using the Consumer Price Index (CPI) based on the Laspeyres formula. This formula calculates price changes by comparing the cost of a fixed basket of goods and services in the current year to their cost in a base year. Furthermore, data obtained from the 2022 Agricultural Calendar enable a comprehensive evaluation of agricultural productivity and food energy output across the basin.

Table 4: Results of calibration and validation of discharge at existing stations in the Maharlo watershed

Station name	Period	Calibration Period				Validation Period			
		p-factor	d-factor	R2	NS	p-factor	d-factor	R2	NS
SHIRAZ	2000-2022	0.04	0.2	0.83	0.65	0.33	0.55	0.81	0.61
KOHANJAN	2000-2022	0.06	0.65	0.81	0.63	0.52	0.64	0.62	0.42
SARDAN	2000-2022	0.07	0.75	0.84	0.73	0.57	0.44	0.52	0.71
GHALAT	2000-2022	0.06	0.45	0.90	0.75	0.66	0.61	0.86	0.69

Table 5: Values of R2 and NS indices of evapotranspiration and crop yield in the Maharlo watershed

Crops		wheat	pistachio	fig	Pomegranate	almond	Barley	Potato
Evapotranspiration	R^2	0.83	0.91	0.98	0.96	0.7	0.47	0.92
	NS	0.82	0.91	0.98	0.36	0.69	0.62	0.92
Yield	R^2	0.71	0.	0.92	0.50	0.68	0.79	0.63
	NS	0.68	0.61	0.92	0.53	0.29	0.70	0.45

Step 2: Evaluation of Pressure, Support, and Status Indicators

Pressure Indicators

The pressure subsystem comprises four key indicators: population density, income per unit area, caloric production per unit area, and actual agricultural water consumption [measured as evapotranspiration]. These indicators were calculated annually throughout the study period. The results exhibit fluctuating patterns; however, a clear increasing trend was observed from 2003 to 2023. This upward trajectory indicates an intensifying pressure on regional water resources driven by socio-economic development and agricultural expansion.

Support Indicators

The support subsystem includes indicators such as runoff per unit area, precipitation, groundwater recharge, and per capita water availability. Annual analyses of these indicators reveal a general decline over the two-decade period. This decline reflects the diminishing natural capacity of the watershed to meet the growing water demands, suggesting a weakening in the region's ability to manage its water resources sustainably."

The status of the water system was assessed based on the inflow volume of the Khorramrud River, a critical source that sustains Maharlo Lake. As the sole indicator of status, Khorramrud's inflow reflects the broader health of the watershed. Results demonstrate a persistent decrease in inflow over time, further exacerbating the degradation of environmental health and signaling potential long-term ecological instability in the Maharlo basin.

The support subsystem comprises key indicators, including runoff per unit area, precipitation, groundwater recharge, and per capita water availability, all of which are calculated annually [Figure 4]. Although these indicators exhibited interannual variability, the overall trend across the 2003–2023 period shows a clear and consistent decline. This downward trajectory indicates a progressive weakening in the watershed's capacity to sustain, replenish, and regulate its water resources. The persistent reduction in these support factors highlights the increasing environmental stress and declining resilience of the Maharlo watershed in the face of rising demand and climatic fluctuations.

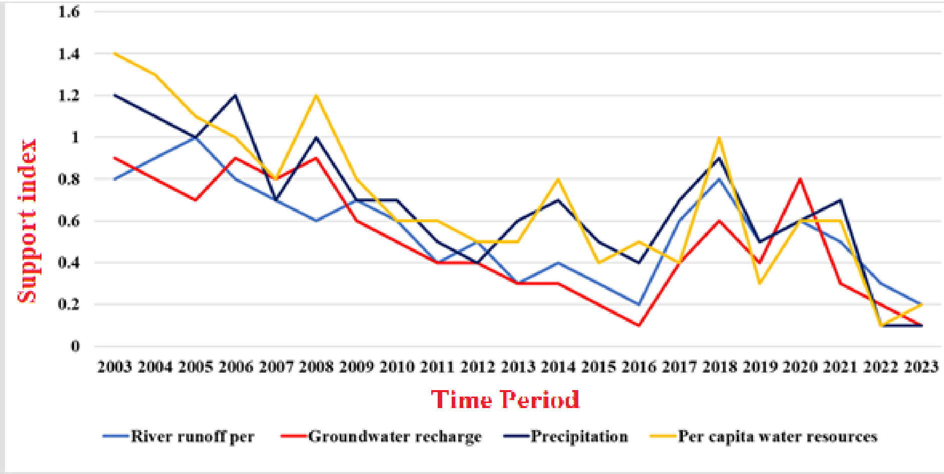

Figure 4: Support index values in the period 2003 to 2023

In comprehensive multi-criteria assessments, due to the diversity and differing dimensions of indicators, standardization and normalization are essential and unavoidable. Standardizing the evaluation indicators ensures consistency, reliability, transparency in computational methods, and comparability of results [7]. In this study, the following mathematical equations were used to standardize the evaluation indicators:

Equation (1)

$$X_1 = \frac{X_I - X_{min}}{X_{max} - X_{min}}$$

1. Negative Indicators

Equation (2)

$$X_1 = \frac{X_{max} - X_I}{X_{max} - X_{min}}$$

Where:
Xi: Standardized value of the indicator
X_I : Actual (observed) value of the indicator
X_{max}: Maximum value of the indicator in the study period
X_{min}: Minimum value of the indicator in the study period

For weighting the indicators, various methods are available. One of the widely used and well-regarded methods due to its objectivity and accuracy is the entropy weighting [27]. In this method, the greater the variability of an indicator among evaluation units, the more informative it is considered, and accordingly, it is assigned a higher weight [11, 15]. In this study, entropy weighting was used to determine the weights of evaluation indicators.

After standardization and weight assignment, composite indicators for each subsystem (Pressure – Support – State) were calculated using the following equations [15,28]:

2. Composite Pressure Index (PI):

Equation (3)

$$PI = \sum_i^n p_i \,.\, W_i \qquad i = 1.2. \ldots .n$$

3. Composite Support Index (SI):

Equation (4)

$$SI = \sum_i^n S_i \,.\, W_i \qquad i = 1.2. \ldots .n$$

4. Pressure–Support Ratio (PS):

Equation (5) $$PS = \frac{PI}{SI}$$

5. Water Environmental Carrying Capacity Index (WECCI):

Equation (6) $$WECCI = (1 - PI) \times W_{PI} + SI \times W_{SI} + HSI \times W_{HSI}$$

Where:
PI: Composite index of socio-economic pressure
p_i: Individual socio-economic pressure indicator
SI: Composite index of water resource support
Si: Individual water resource support indicator
W_i: Weight of the corresponding indicator
PS: Pressure–Support ratio
WECCI: Comprehensive Water Environmental Carrying Capacity Index
W_{PI}: Weight of the socio-economic pressure index
W_{SI}: Weight of the water resource support index
HSI: Composite index of environmental health status
W_{HSI}: Weight of the environmental health status index

Note: The weights of the three main components (socio-economic pressure, water resource support, and environmental health status) were assumed to be equal in this study. The assigned weights for the pressure indicators are illustrated in Figure 8, while the weights corresponding to the support indicators are shown in Figure 5 and 6.

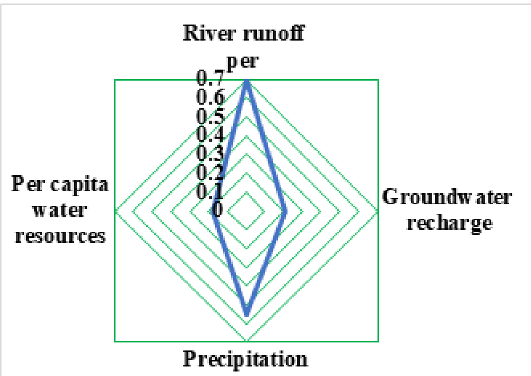

Figure 5 : Weight of support indicators

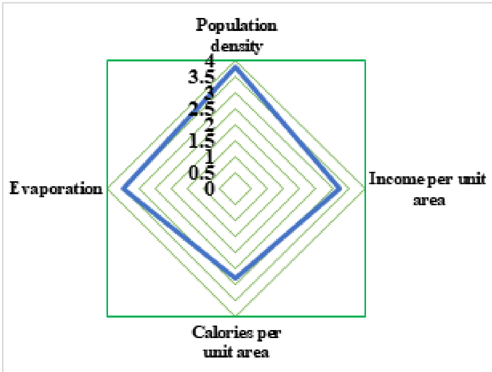

Figure 6 : Weight and pressure indicators

Step 3: Index Aggregation and Comprehensive Evaluation
Following standardization and entropy-based weighting, the indicators within each subsystem—pressure, support, and status—were aggregated to derive composite indices for each category. These aggregated indices provide a structured representation of the dynamics within the watershed's water resource system. Furthermore, a comprehensive Water Resources Carrying Capacity [WRCC] index was calculated to capture the overall sustainability status of the Maharlo watershed.

The temporal evolution of these indices over the entire study period [2003–2023] is depicted in Figure 7, offering insight into long-term trends in water resource pressures, support capacity, and environmental status.

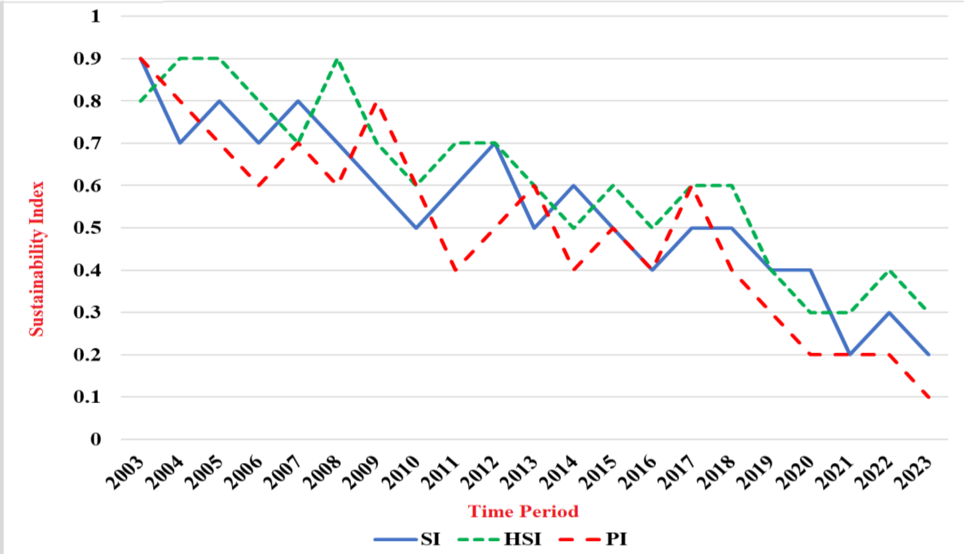

Figure 7: Changes in cumulative pressure, support, and status indicators over the period 2003 to 2023

Pressure–Support Index and Periodic Trends

In this study, the pressure–support index [PS] was used to quantify the ratio of pressure exerted on water resources relative to their carrying capacity. The average changes in the PS index across the three defined study periods are illustrated in Figure 8. In parallel, average values for the cumulative pressure, support, and overall water resources carrying capacity [WRCC] indices were computed for each period, with the results presented in Figure 9.

The analysis reveals an upward trend in the PS ratio over time, alongside a significant decline in WRCC and environmental health across the three periods. These patterns indicate mounting pressure on the watershed's capacity to support water availability and ecosystem functions sustainably.

Key Parameter Trends:

Precipitation and Inflow:

Precipitation is one of the most influential factors affecting water resource sustainability during the study period. This reduction, in turn, contributed to diminished inflow volumes to Maharlo Lake, further undermining the region's environmental health and support capacity.

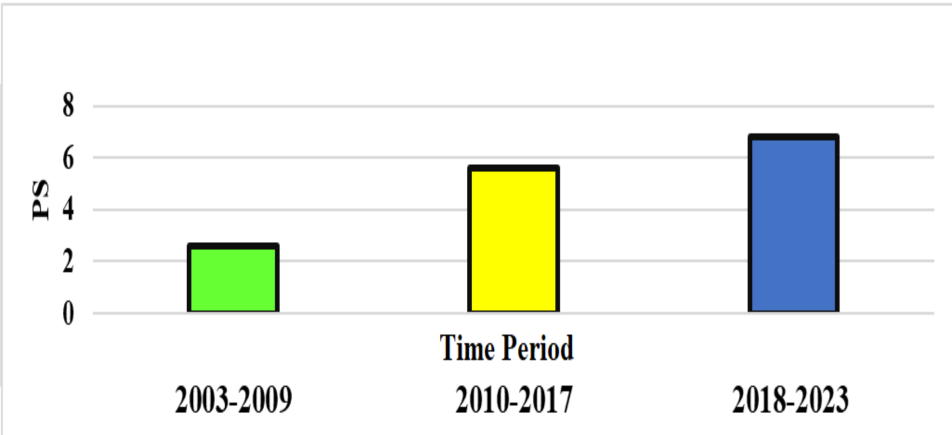

Figure 8: Average changes in the degree of pressure-support index in the three periods studied

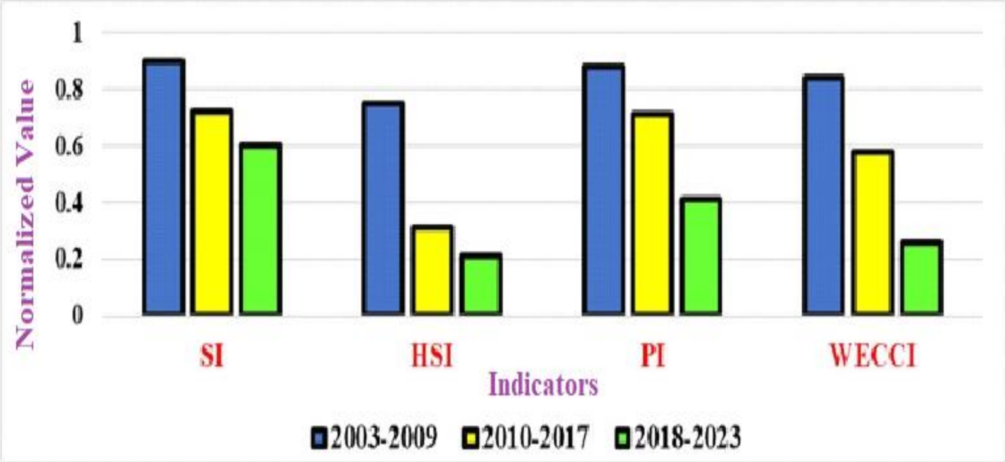

Figure 9: Average changes in cumulative pressure, support, and status indices and comprehensive water resource carrying capacity index in three time periods

Step 4:Final Evaluation of Water Resources Carrying Capacity

The final determination of water resources carrying capacity [WRCC] was conducted based on the multi-criteria decision-making process illustrated in Figure 10. The evaluation process followed a hierarchical structure, with three successive indicators used as decision gates: the Environmental Health Index [EHI], the Comprehensive Water Environmental Carrying Capacity Index [WECCI], and the Pressure–Support Index [PS]. The outcomes for each study period are summarized below:

First Period [2003–2009]:

The Environmental Health Index [EHI] was 0.75, significantly exceeding the threshold value of 0.32. This allowed progression to the second evaluation level, where the WECCI was calculated at 0.84, also above the critical limit of 0.4. The third stage involved assessing the Pressure–Support Index, which yielded a value of 0.90, remaining below the threshold of 1.0. Therefore, during this period, the water resources system was classified, indicating sustainable conditions.

Second Period [2010–2017]:

The EHI decreased sharply to 0.31, falling just below the permissible threshold. Given that the environmental health prerequisite was not satisfied, the system was directly categorized as being in an “Overload” state, regardless of subsequent indices.

Third Period [2018–2023]:

The EHI continued to decline, reaching 0.21, further confirming the system's degradation. As in the second period, this low EHI value immediately signaled an “Overload” state, WRCC.

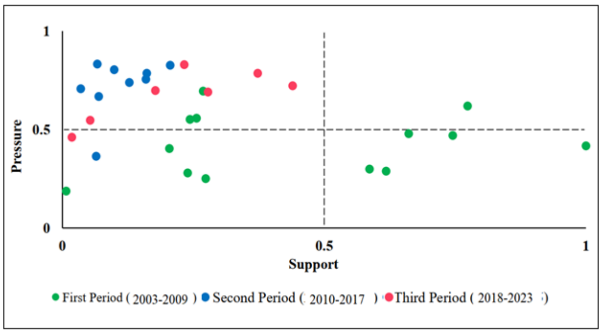

Figure 10: Pressure-Support Index Values in the period [2003-2023]

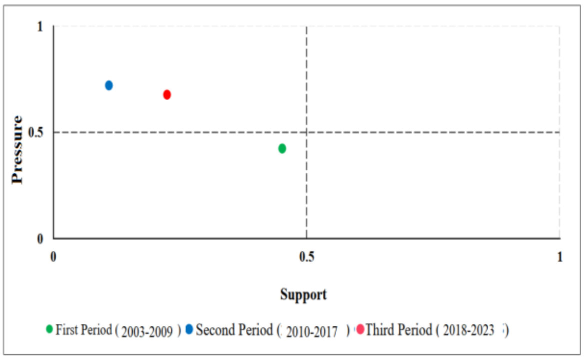

Figure 11: Average pressure-support index in the three periods studied

Step 5: Pressure–Support Ratio Analysis Across Study Periods

The pressure–support (PS) ratio across the three study periods highlights significant shifts in the balance between water demand and support capacity.

First Period:

PS values showed interannual variability, yet conditions largely corresponded to State "C," with occasional transitions toward State "D." This indicates low overall pressure but insufficient utilization of water resources. Management priorities in this stage should focus on enhancing the support subsystem (infrastructure, recharge, and allocation efficiency) to progress toward sustainable conditions (State "A").

Second Period:

The system shifted predominantly to State "B," reflecting unsustainable water use and ecological degradation. This transition signaled mounting stress in the watershed's capacity to meet demand. Ideally, adaptive strategies were needed to alleviate water stress; however, the persistence of State "B" suggests ineffective or counterproductive interventions that intensified resource pressure.

Third Period:

The watershed remained in State "B," but in a more critical condition than before. Declining support indicators combined with sustained or increasing demand signal a deepening imbalance that threatens the long-term sustainability of the Maharlo watershed.

The temporal evolution of water resources carrying capacity and environmental health is illustrated in Figure 12.

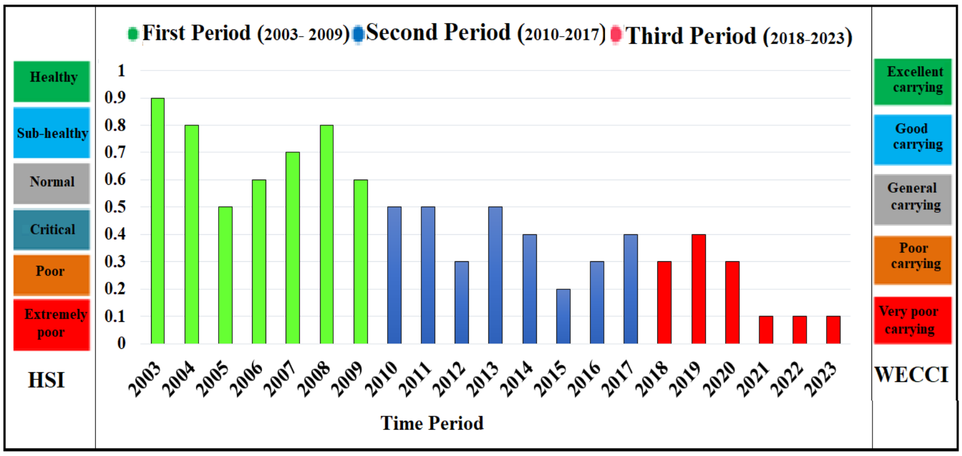

Figure 15: Changes in the comprehensive index of water resources carrying capacity over the period [2003-2023

This study shares several commonalities with prior research that emphasizes the critical role of assessing water resources carrying capacity [WRCC] in sustainable water management, consistent with findings by [8, 9]. Similar to earlier investigations by [20, 21], it employs simulation modeling and indicator-based evaluation to analyze water resource sustainability. Climate change in the region has caused a decrease in relative humidity and high temperatures and an increase in evaporation, which is consistent with the studies of [30,29]. Population growth, arid climate, and agricultural and industrial development have increased pressure on water resources, which is consistent with the results of [31].

Conclusion:

However, this research distinguishes itself by integrating the SWAT hydrological model with an indicator– [PSS] framework. This combined methodology enables a more comprehensive and dynamic evaluation of the water resources system by incorporating natural hydrological processes and human-induced pressures. Unlike many previous studies that rely solely on either modeling or indicator assessments, this integrated approach offers a holistic understanding of the complex interactions affecting water resource sustainability.
Furthermore, the study introduces environmental health thresholds and the pressure-support ratio as key criteria for evaluating long-term sustainability, addressing gaps often overlooked in prior research. While earlier studies frequently focus on urban or broader regional scales, this work concentrates on the Maharlo watershed—a vulnerable and ecologically sensitive basin. This localized focus permits a detailed temporal and spatial analysis of water resource conditions under varying environmental and anthropogenic influences.In summary, this study advances the field by combining established methodologies with novel sustainability criteria, providing valuable insights for effective water resource management policies, particularly in semi-arid and vulnerable watershed regions.

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