POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik

Watershed sustainability index: Concept, applications, and future directions

Havza sürdürülebilirlik indeksi: Konsept, uygulamalar ve gelecek çalışmalar üzerine bir inceleme

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To cite to this article: Kesgin E., "Watershed Sustainability Index: Concept, Applications, and Future Directions", ***Journal of Polytechnic***, *(*): *, (*).

Bu makaleye şu şekilde atıfta bulunabilirsiniz: Kesgin E., "Watershed Sustainability Index: Concept, Applications, and Future Directions", ***Politeknik Dergisi***, *(*): *, (*).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: 10.2339/politeknik.1634354

Watershed Sustainability Index: Concept, Applications, and Future Directions

Highlights

- *Watershed Sustainability Index framework integrates hydrology, environment, life, and policy.*
- *Applications show moderate watershed sustainability.*
- *Challenges include data, indicators, and stakeholder integration.*
- *Future Research should focus on spatial modeling, remote sensing, and machine learning.*
- *Policy Impact supports evidence-based decision-making in water resource management.*

Graphical Abstract

Watershed Sustainability Index assesses watershed sustainability by integrating hydrology, environment, life, and policy.

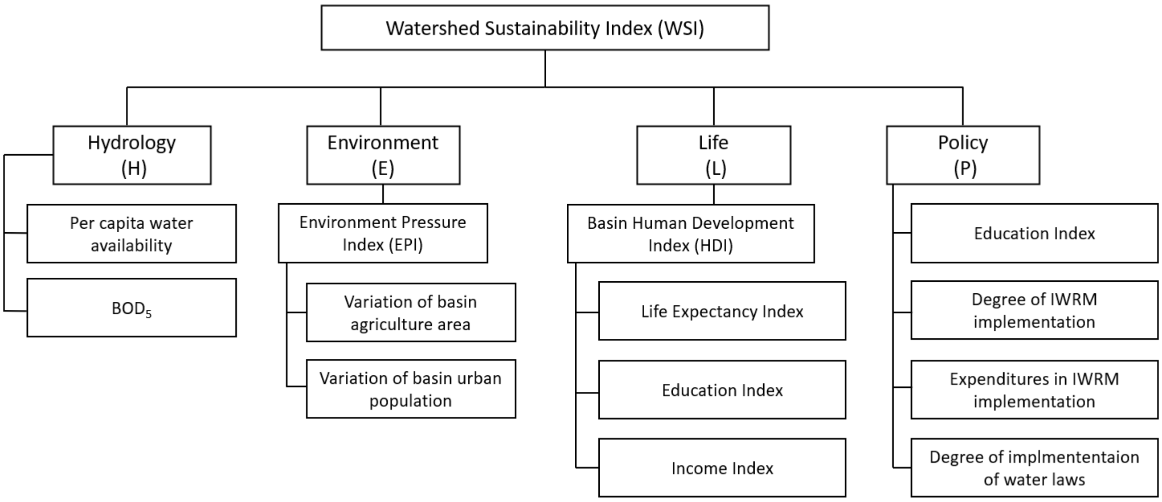

Figure. Stages of aggregation for Watershed Sustainability Index

Aim

This study provides a comprehensive overview of the Watershed Sustainability Index (WSI), its conceptual framework, applications, and future directions, highlighting its role in integrated watershed management.

Design & Methodology

The study examines the WSI's structure, including its hydrological, environmental, socio-economic, and policy components, and discusses its aggregation process using a multi-criteria approach.

Originality

It offers a detailed evaluation of the WSI's strengths and limitations, comparing it with other sustainability indices and proposing improvements for future applications.

Findings

The WSI is a valuable tool for assessing watershed sustainability, but it faces challenges such as data availability, indicator selection, and stakeholder integration.

Conclusion

Addressing these challenges through methodological refinements, emerging technologies, and stakeholder collaboration will enhance the effectiveness and applicability of the WSI in sustainable watershed management.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Watershed Sustainability Index: Concept, Applications, and Future Directions

Review Article / Derleme Makalesi

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(Geliş/Received : 07.02.2025 ; Kabul/Accepted : 14.03.2025 ; Erken Görünüm/Early View :03.04.2025)

ABSTRACT

Sustainable water resource systems are essential for meeting society's present and future needs while preserving ecological integrity. Ensuring sustainable management of a basin involves taking into account its hydrological characteristics, along with its environmental, social, and political aspects. Watershed Sustainability Index (WSI) is employed that integrates hydrology, environmental factors, biodiversity, and policy considerations. Its holistic and multidimensional approach provides insights into the complex interactions shaping watershed dynamics and supports evidence-based decision-making processes. Despite its utility, the Watershed Sustainability Index faces several challenges and limitations, including issues with data availability and quality, indicator selection and weighting, and the incorporation of diverse stakeholder perspectives. Addressing these challenges necessitates continued collaboration among researchers, practitioners, and policymakers to refine the Watershed Sustainability Index methodology and enhance its relevance and robustness. Future research should focus on refining indicator frameworks, developing spatially explicit modeling approaches, and integrating emerging technologies like remote sensing and machine learning. Efforts to enhance scalability and transferability across different scales and contexts are crucial for supporting more effective watershed management strategies. This study provides a concise overview of the Watershed Sustainability Index by considering its conceptual framework, main applications and future perspectives.

Keywords: Watershed sustainability index, hydrology, HELP, watershed management

Havza Sürdürülebilirlik İndeksi: Konsept, Uygulamalar ve Gelecek Çalışmalar Üzerine Bir İnceleme

ÖZ

Sürdürülebilir su kaynakları sistemleri, toplumun mevcut ve gelecekteki ihtiyaçlarını karşılarken ekolojik bütünlüğü korumak için önemlidir. Bir havzanın sürdürülebilir yönetimini sağlamak, hidrolojik özelliklerinin yanı sıra çevresel, sosyal ve siyasal yönlerini de dikkate almayı gerektirir. Bu durumu kapsamlı bir şekilde değerlendirmek için, hidroloji, çevresel faktörler, biyoçeşitlilik ve politika parametrelerini entegre eden Havza Sürdürülebilirlik İndeksi (HSİ) kullanılır. Ayrıca, kapsayıcı ve çok boyutlu yaklaşımı, havza dinamiklerini şekillendiren karmaşık etkileşimler hakkında yol göstermekle birlikte, kanıta dayalı karar verme süreçlerini de destekler. Diğer taraftan, Havza Sürdürülebilirlik İndeksi veri erişilebilirliği ve kalitesi, gösterge/parametre seçimi ve ağırlıklandırılması ile çeşitli paydaş görüşlerinin dahil edilmesi gibi birkaç zorluk ve kısıtlamayla karşı karşıyadır. Bu zorlukların üstesinden gelmek, indeks metodolojisini geliştirmek ve bu metodolojinin ilgili ve sağlam olmasını sağlamak için araştırmacılar, uygulayıcılar ve politika yapıcılar arasında devam eden iş birliği olması gerekmektedir. Gelecek araştırmalar, indeksi oluşturan gösterge/parametre çerçevelerini geliştirmeye, mekânsal olarak açıklayıcı modelleme yaklaşımları geliştirmeye ve uzaktan algılama ve makine öğrenimi gibi yeni teknolojileri entegre etmeye odaklanmalıdır. Farklı ölçeklerde ve bağlamlarda ölçeklenebilirlik ve transfer edilebilirlik konusunda yapılan çabalar, daha etkili havza yönetimi stratejilerini desteklemek için önemlidir. Bu çalışma, Havza Sürdürülebilirlik İndeksi'nin kavramsal çerçevesini, temel uygulamalarını ve gelecek perspektiflerini göz önünde bulundurarak genel bir bakış sunmayı hedeflemektedir.

Anahtar Kelimeler: Havza sürdürülebilirlik indeksi, hidroloji, HELP, havza yönetimi

1. INTRODUCTION

Sustainable systems are effectively structured and managed to address both current and future societal requirements, while simultaneously maintaining the ecological, hydrological, and biological equilibrium of the system [1]. Ensuring sustainability across environment, energy, infrastructure, and water resources is crucial for the long-term health of our planet and succeeding generations [2-7]. Environmental sustainability involves preserving biodiversity, curbing pollution, and addressing climate change impacts through responsible management and conservation [8,9]. Regarding energy, sustainability encompasses transitioning to renewable sources like solar and wind power, alongside enhancing energy efficiency and reducing reliance on fossil fuels [10]. Sustainable infrastructure endeavors to construct resilient systems that minimize environmental harm, improve quality of life, and support economic growth without compromising future requirements [11]. Water resource sustainability aims to guarantee fair access to clean water, tackle water scarcity, and uphold water quality via efficient usage and conservation methods [12, 13].

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Embracing sustainability principles in these domains is essential for nurturing a healthier planet and fostering a fairer and more prosperous future for all.

Moreover, watershed sustainability encompasses a wide range of areas, leading to a significant number of studies conducted. Both climate change and especially water quality studies dominate this field [14-17]. It also refers to the long-term management and conservation of watersheds in a way that ensures the health and functionality of the entire ecosystem within the watershed, including water resources, biodiversity, and human communities that depend on them [18,19]. It is also a critical concern in contemporary water resource management, necessitating comprehensive frameworks for assessment and monitoring [20-22]. The global conversation on sustainability has widened, especially concerning water resources, with a growing emphasis on enhancing performance through a variety of analyses [23-27].

Sustainability is a multifaceted concept that hinges on the interconnected dynamics of reliability, resiliency, and vulnerability [28,29]. While reliability denotes the consistent performance and availability of resources or systems, crucial for meeting present needs without compromising future capabilities, resiliency underscores the capacity of these systems to endure and rebound from disturbances, safeguarding against disruptions while promoting adaptability in the face of changing conditions [30]. Meanwhile, vulnerability illuminates potential weaknesses and susceptibilities within these systems, necessitating proactive measures to fortify their foundations against risks and uncertainties. Furthermore, while feasibility focuses on the practical implementation of specific projects or solutions, sustainability provides a holistic framework for evaluating the overall impact and effectiveness of urban water management strategies [31,32]. Ideally, feasible solutions should also align with sustainability principles to ensure that urban water systems remain resilient, equitable, and environmentally sound over the long term. Therefore, it is essential for water managers to integrate both feasibility and sustainability considerations into their decision-making processes to develop effective and enduring solutions for water management challenges.

Water is not only vital for sustaining life but also holds significant importance in bolstering ecosystems, stimulating economic progress, enhancing community welfare, and safeguarding cultural heritage [33-40]. It is underscored that achieving water sustainability involves strategically planning and efficiently managing water resources to meet societal goals, all while safeguarding ecological, environmental, and hydrological balance [41-44]. This corresponds with the definition, which underscores the capacity to supply and oversee water resources adequately in terms of both quantity and quality to fulfill present human and environmental demands while ensuring future generations can satisfy their own necessities [25]. These approaches explore methodologies that emphasize evaluating sustainability by integrating societal involvement in planning, contrasting them with approaches solely centered on water resources management. Prioritizing societal participation in planning is considered crucial for accurately gauging sustainability, especially regarding water resources. This inclusive approach allows for a more nuanced understanding of sustainable management, recognizing the importance of diverse stakeholder perspectives. By involving society in the planning process, a comprehensive evaluation of sustainability factors can be conducted, facilitating the development of more effective sustainability measurement methodologies. Incorporating societal viewpoints ultimately emphasizes how important it is to implement inclusive and holistic approaches in order to ensure sustainable management.

Concept of establishing a series of indexes to conduct the necessary analysis of water resource sustainability, presenting a more suitable definition than approaches solely centered on water resource management [45]. Sustainability metrics offer methods to quantify varying degrees of sustainability, and their definitions can vary. One method entails expressing various or weighted mixes of reliability, resilience, and vulnerability metrics for various factors influencing human welfare [44]. These metrics vary over time and in different places, aiming to assess the comparative degrees of sustainability. In order to effectively plan and manage sustainable water resource systems, it is important to first establish a shared vision that encompasses social, economic, and environmental targets for the benefit of both current and future generations [44]. Finding strategies for each party involved to contribute to the completion of this collaborative task is necessary. Establishing unified plans across all pertinent parties and engaging partners to address common issues is essential. Additionally, it's critical to implement strategies meant to restore or maintain the integrity of the environment, economic prosperity, and the natural ecosystem. Moreover, initiatives that incorporate long-term sociocultural, economic, and societal objectives ought to be prioritized and encouraged by sustainable water resource management. This entails preserving and protecting private property rights while also working toward communal projects and collaborating with private parties to achieve common goals. Recognizing the complex and constantly changing characteristics of economies, ecosystems, and institutions is also essential since they frequently exhibit diversity in variation and evolution across time and between different locations.

Tremendous focus has been placed on in recent years on gauging sustainability, with efforts such as creating evaluation instruments utilizing sustainability indicators, commonly referred to as sustainability indices [46-51]. The various indices used to assess water scarcity and water stress, highlighting the importance of considering multiple facets of water use, supply, and scarcity by [52]. The indices were basically classified according to the human water needs, water supply vulnerability, ecological water requirements, and life cycle evaluation and water footprint. According to these classifications, some indices were obtained such as the Social Water Stress Index, The Index of Local Relative Water Use and Reuse, The Watershed Sustainability Index (WSI), The Water Supply Stress Index etc. [52]. Moreover, various sustainability indices have been developed by researchers, like that the Environmental Pressure Indices [53], Water Poverty Index [54], the Environmental Sustainability Index [55], Canadian Water Sustainability Index [56], West Java Water Sustainability Index [57]. These tools are crafted to gauge sustainability levels and can aid decision-makers and stakeholders in accomplishing sustainability objectives [58].

Furthermore, it is stated that the WSI provides decision-makers with a broader perspective by being compared with other sustainability indices [37]. It is also emphasized that the WSI offers a more holistic assessment by integrating hydrological, environmental, and socio-economic components [45]. By providing a standardized way to assess sustainability, these indices can also help communicate progress to the wider community. Each index serves a specific purpose and can be used in different contexts to evaluate the sustainability of various aspects of society, economy, and the environment. By using these indices, organizations and governments can track their progress towards sustainable practices and policies.

Through the development and use of sustainability indices, researchers and policymakers aim to create a more sustainable future by identifying areas that need improvement and monitoring progress towards sustainability goals. These indices also provide a framework for assessing sustainability across different sectors and can help guide decision-making processes towards more sustainable practices [58]. Therefore, multi-criteria models offer a versatile approach to evaluating the sustainability level of integrated water resources management (IWRM) strategies [59]. Through Multi-Criteria Decision Analysis (MCDA), these models consider various factors simultaneously, such as environmental impact, social equity, economic feasibility, and institutional [60]. By weighting and aggregating these diverse criteria, MCDA also provides a comprehensive framework for decision-makers to assess the sustainability of different water management options. By utilizing these indices, stakeholders work towards a more sustainable future and communicate their achievements to the public, fostering awareness and support for sustainability initiatives.

The WSI stands out as the predominant tool utilized for evaluating the sustainability of watersheds [60, 61]. Additionally, it was explicitly applied at the basin size with the goal of combining elements of environment, livelihoods, hydrology, and economics into a single, equivalent metric [45]. In other words, the WSI is has a comprehensive perspective encompassing physical, biological, and human environments during watershed planning and management decisions [62]. It has emerged as a prominent tool for evaluating the sustainability of watersheds worldwide. While literature contains information about various indexes, there are relatively few studies specifically focusing on the research conducted using the WSI and detailing its limitations and application areas. The intention of this review is to offer a concise overview of the WSI, including its conceptual underpinnings, applications across diverse geographic contexts, and avenues for future research and development. This paper organized into 5 sections. In what follows, Sec. II reviews the characteristics of WSI as presented in [45], the applications were also discussed in Sec. III by summarizing the basin characteristics and WSI results. Thereafter, Sec. IV focuses on the challenges, weaknesses and future directions based on WSI. Finally, Sec. V summarizes the paper and gives the concluding comments.

2. WATERSHED SUSTAINABILITY INDEX

The WSI is a method to evaluate a watershed's sustainability. This index aims to provide a comprehensive assessment encompassing environmental, social, and economic factors (Fig. 1). Environmental factors include water quality, quantity, and ecosystem health, while social factors encompass community participation, local community resilience, and equal access to water resources. Economic factors focus on evaluating the economic viability and sustainability of watershed management practices. By bringing together these various factors, it also offers a holistic evaluation of a watershed's sustainability level

and guides the development of watershed management strategies.

The conceptual foundation of the WSI lies in its holistic approach to watershed assessment, integrating environmental, social, and economic dimensions of sustainability. Drawing from principles of systems thinking and sustainability science, the WSI framework emphasizes the interconnectedness of ecological processes, human activities, and socio-economic dynamics within watersheds. Key components of the WSI include environmental indicators (e.g., water quality, ecosystem health), social indicators (e.g., stakeholder engagement, community resilience), and economic indicators (e.g., cost-effectiveness, economic viability).

The WSI serves as a significant indicator that considers the state of basin Hydrology (H), Environment (E), Life (L), and Policy(P)-(HELP), encompassing the description and evaluation of pertinent socio-economic information [63]. HELP is an interdisciplinary initiative under the auspices of UNESCO, overseen by the International Hydrological Programme (IHP). It has devised a fresh strategy for integrated catchment management by establishing a framework for collaboration among experts, managers, and scientists to address water-related challenges collectively [64]. Furthermore, HELP program is introducing a fresh perspective on integrated watershed management by establishing a framework that revolves around three key indicators as Pressure, State, and Response. This model integrates cause-effect relationships, offering a more thorough comprehension of the watershed. Furthermore, in this model, Pressure represents the impact of human activities on natural resources such as the environment, soil, and water. The State reflects the current condition of these resources at a given time, while the Response evaluates the outcomes of implementing new practices and modifications within the basin [65]. The sustainability of the watershed was evaluated using the HELP program, which is a UNESCO integrated index for watershed sustainability. The WSI is computed through a two-step process. Initially, the subindices of the HELP dimensions are determined by utilizing the main indicators of each dimension, employing the following formula:

$$Subindex = \frac{Pressure + State + Response}{3} \quad (1)$$

In the subsequent phase, the WSI was determined by calculating values for all indicators within a specific range (0 – 1) as following:

$$WSI = \frac{H + E + L + P}{4} \quad (2)$$

Where the WSI is the watershed sustainability index; H, E, L, and P are indicators that they take values in the range of (0-1) such as the WSI. To simplify the users' estimation of parameter levels, both quantitative and qualitative criteria were grouped into five scale scores (0, 0.25, 0.50, 0.75, and 1.0). It is stated by [62] that the understanding of the overall index is as follows: sustainability is considered low if WSI is less than 0.1, medium if WSI falls between 0.5 and 0.8, and high if WSI exceeds 0.8.

This classification enables the utilization of spreadsheets rather than relying on equations or other intricate functions [45]. It is clearly stated that all indicators carry equal weight in the HELP program. While this situation is highly debatable, details regarding this will be addressed in the "Challenges and Limitations" section. Contrary, it's acknowledged that the weights of indicators might differ across basins and should be decided upon by stakeholders through consensus, employing uniform weights prevents bias in the outcomes [66]. The parameters, threshold levels, and corresponding scores used in the calculation of WSI sub-indices are presented in Tables 1, 2, 3, and 4. Table 1 depicts the WSI parameters in relation to each of the four indicators. The suggested parameters were chosen based on the criteria outlined by [67]. Furthermore, the parameters were divided into three tiers: Pressure, State, and Response. Employing this framework offers the advantage of integrating cause-and-effect connections [68].

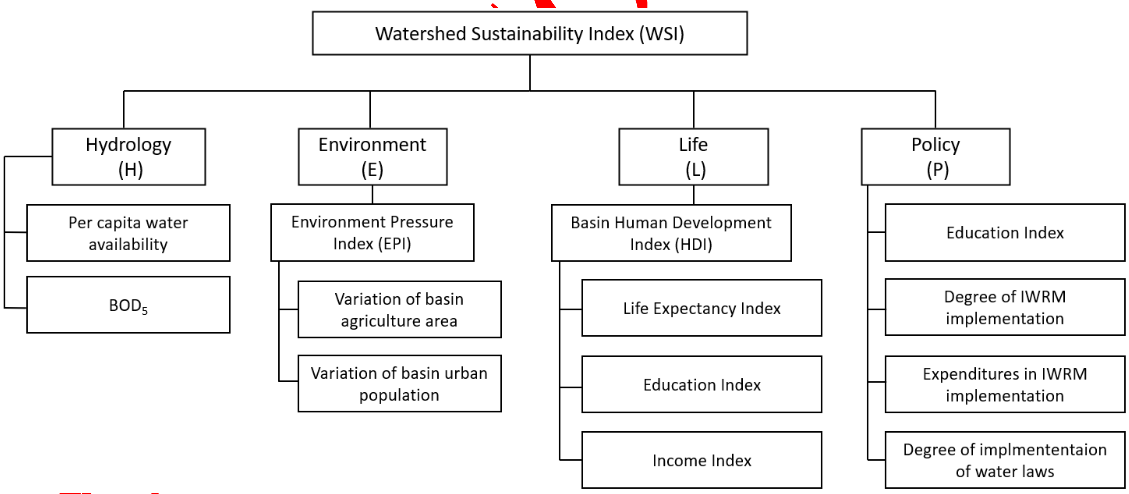

Figure 1. Stages of aggregation for the WSI [69]

2.1 Hydrology Indicator (H)

The H score indicates the average of both water quantity and quality aspects within the respective basin. Regarding the quantity, this parameter signifies the annual per capita water availability, which includes both surface and groundwater sources. It is calculated by adding the long-term average surface flowrate to the estimated available groundwater yield, and then dividing this sum by the population of the basin during the current period. According to [45], per capita water availability (W_a) was categorized into five levels, aligned with very poor, poor, medium, good, and excellent, as outlined in Table 3.

Concerning the quality, although data on biochemical oxygen demand (BOD_5, mg/l) is available in watersheds and correlates with essential water quality parameters like dissolved oxygen, turbidity, and pollutant concentration [45]. If additional factors such as nitrogen or phosphorus are considered more crucial than BOD_5 in the agricultural basin, they could be utilized as the primary indicators of water quality instead [45]. Consequently, the variation of water quality parameters during the study period compared to the long-term average is computed to assess the water quality aspect of the H.

2.2 Environmental Indicator

The E was calculated as the mean of State, Pressure, and Response as depicted in Tables 2, 3, and 4. In the case of Pressure, this is assessed using the E-Pressure Index (EPI). It is an altered version of the Antropic Pressure Index (API) given by [70]. It is also calculated as the average of the percentage change in agricultural areas within the watershed and the percentage change in the basin's population during the analyzed period. It also assumes positive, negative, or zero values, where positive values indicate heightened pressures on the vegetation that still exists in its natural phase [9]. In the case of E-State, percent of basin area under natural vegetation (Av) is calculated. Similarly, in the case of E-Response, evolution/development for watershed preservation zones in the current studied is determined.

2.3 Life Indicator (L)

The L is directly associated with human's life quality resides in the relevant basin. Moreover, the L-Pressure parameter score is obtained from the variation of Human Development Index (HDI)-Income in the basin. Changes in the average income of populations can significantly influence the overall sustainability of a basin, as it is recognized to have a profound impact on social metrics such as health and education [71]. The L-Response parameter also represents the percentage evaluation in the HDI during the studied period compared to the earlier value, providing insight into the improvement or decline in quality of life [45].

2.4 Policy Indicator (P)

The P-Pressure is the change in the HDI-Education sub-indicator in the current period. It actually shows the population educational level. It is stated by [45] that positive values of HDI-Education would be associated with the capacity and readiness of the population to engage in watershed activities, thereby placing additional strain on decision-makers. Furthermore, the P-State signifies the institutional capability of the basin in integrated water resources management (IWRM), determined by the adequacy of legal and institutional structures, alongside the level of collaborative administration during the specified period. Conversely, the P-Response parameter illustrates the changes in basin IWRM expenditures during the period studied.

Table 1. Details of the Indicators and Parameters

Indicators		**Parameters**		
		Pressure	**State**	**Response**
H	Quantity (H1)	Change in water availability (m^3/person/year)	water availability (m^3/person/year)	Water-use efficiency
	Quality (H2)	Change in BOD_5	Mean long term BOD_5	Sewage/disposal treatment
E		EPI (forest and population)	Percent of territory covered with vegetation/forest	Areas for ecological preservation
L		Change HDI expenditure	Human Development Index	Evolution in the HDI
P		Change HDI-Education	Institutional/ management	Expenditure for watershed

Table 2. Pressure parameter of WSI

Indicator	**Pressure**	**Level**	**Score**
H	Variation between the present period's water availability and the historical average (m^3 /person year) (H1)	H1<−20%	0.00
		−20%< H1<−10%	0.25
		−10%< H1<0%	0.50
		0< H1<+10%	0.75
		H1>+10%	1.00
	Variation between the present period's water quality (BOD_5) and the historical average (H2)	H2>20%	0.00
		20%> H2>10%	0.25
		0< H2<10%	0.50
		−10%< H2<0%	0.75
		H2<−10%	1.00

Table 2. (Cont.) Pressure parameter of WSI

E	Basin EPI (rural and urban) in the period	EPI>20%	0.00
		20%<EPI<10%	0.25
		10%<EPI<5%	0.50
		5%<EPI<0%	0.75
		EPI<0%	1.00
L	Change between the current period's HDI-Income (per capita) and the preceding period (L_p)	L_p <−20%	0.00
		−20%< L_p <−10%	0.25
		−10%< L_p <0%	0.50
		0< L_p <+10%	0.75
		L_p >+10%	1.00
P	Change between the present and prior periods in the HDI-Education (P_p)	P_p <−20%	0.00
		−20%< P_p <−10%	0.25
		−10%< P_p <0%	0.50
		0< P_p <+10%	0.75
		P_p >+10%	1.00

Table 3. State Parameter of WSI

Indicator	**State**	**Level**	**Score**
H	Water availability (m^3/person year)	W_a<1700	0.00
		1700< W_a <3400	0.25
		3400< W_a <5100	0.50
		5100< W_a <6800	0.75
		W_a >6800	1.00
	Long term average BOD_5 (mg/l)	BOD_5>10	0.00
		10< BOD_5<5	0.25
		5< BOD_5<3	0.50
		3< BOD_5<1	0.75
		BOD_5<1	1.00
E	Percentage of the basin area covered by natural vegetation (Av)	Av<5	0.00
		5<Av<10	0.25
		10<Av<25	0.50
		25<Av<40	0.75
		Av>40	1.00
L	Basin HDI (weighed by county population)	HDI<0.5	0.00
		0.5<HDI<0.6	0.25
		0.6<HDI<0.75	0.50
		0.75<HDI<0.9	0.75
		HDI>0.9	1.00
P	Basin institutional capacity in IWRM (legal and organizational)	Very poor	0.00
		Poor	0.25
		Medium	0.50
		Good	0.75
		Excellent	1.00

Table 4. Response Parameter of WSI

Indicator	Response	Level	Score
H	Enhancement of water utilization efficiency during the present time frame	Very poor	0.00
		Poor	0.25
		Medium	0.50
		Good	0.75
		Excellent	1.00
	Enhancing the proper treatment and disposal of sewage in the current time frame	Very poor	0.00
		Poor	0.25
		Medium	0.50
		Good	0.75
		Excellent	1.00
E	Progress in the establishment and management of conservation zones (Protected areas and BMPs) in the period studied (E_r)	$E_r < -10\%$	0.00
		$-10\% < E_r < 0\%$	0.25
		$0 < E_r < +10\%$	0.50
		$+10\% > E_r > +20\%$	0.75
		$E_r > 20\%$	1.00
L	Development in the HDI in the current period (L_r)	$L_r < -10\%$	0.00
		$-10\% < L_r < 0\%$	0.25
		$0 < L_r < +10\%$	0.50
		$+10\% > L_r > +20\%$	0.75
		$L_r > 20\%$	1.00
P	Development in the WRM costs in the current period (P_r)	$P_r < -10\%$	0.00
		$-10\% < P_r < 0\%$	0.25
		$0 < P_r < +10\%$	0.50
		$+10\% > P_r > +20\%$	0.75
		$P_r > 20\%$	1.00

3. WSI APPLICATIONS

Numerous studies have applied the WSI framework to assess watershed sustainability in diverse geographic contexts, ranging from urbanized watersheds to rural agricultural landscapes. These applications have demonstrated the utility of the WSI in identifying key sustainability challenges, evaluating the effectiveness of management interventions, and informing decision-making processes. Case studies have highlighted the importance of context-specific indicators and stakeholder engagement in WSI implementation, underscoring the need for adaptive and participatory approaches to watershed management. In this study, most of the peer-reviewed studies in the literature were presented to evaluate WSI applications.

A research investigation centered on implementing the WSI within the Elqui River basin, situated in northern Chile [72]. A period of 5 years (2001-2005) was considered to evaluate the sustainability of the basin, obtaining a global value of 0.61 for the WSI. This study was important since that the Elqui River basin has been integrated into the Chilean basin, which highlights the importance of its management and conservation. The significance of water resources was emphasized as a fundamental aspect of the sustainability framework of the Elqui River basin. Moreover, water is a vital resource that affects the sustainability of other resources as well as the general welfare of the community. Thus, it becomes imperative to manage water resources properly in order to ensure the basin's sustainability and the population's well-being. The operation of the WSI made it possible to comprehensively evaluate the sustainability of the basin, providing relevant information for decision-making and the implementation of conservation and sustainable management measures. In conclusion, the study by [72] highlights the importance of sustainable management of water resources in the Elqui River basin to guarantee its long-term sustainability.

The challenges faced by a tropical watershed, including issues like land deterioration, pollution, and water scarcity [73]. The watershed was assessed for its sustainability using the HELP indicators for the period of 2006-2011. The total WSI was 0.59, indicating that the basin had intermediate level of sustainability but still under high pressure. It is emphasized that there is an urgent need to develop integrated basin management programs in order to achieve the sustainability of this watershed. It is an integrated indicator based on basin H, E, and L. The assessment of the Batang Merao Watershed revealed the need for more comprehensive sustainability information to be gathered in order to address the challenges faced by this tropical watershed.

The research also discusses a watershed in the Hasdeo river basin, with an area of approximately 2400 km^2 [65]. This study reveals that there have been alterations in water use efficiency, BOD_5 levels, land use patterns, per capita income, human development index, education development index, and capacity in integrated water resources management in the Piperiya basin. These variations indicate the pressure, response, and state of the watershed in terms of sustainability. The improvement in certain indicators such as HDI and water use efficiency shows positive development in the watershed, while fluctuations in other indicators point towards challenges and areas that require attention for better watershed management. In brief, this study underscores the significance of monitoring and managing watersheds effectively to ensure the long-term health and well-being of the society, and economy within the region.

Moreover, the WSI was applied to the Ergene Basin located in Türkiye between 2008 and 2012 by [74]. According to his study, the overall WSI is calculated as 0.70. In the Ergene basin, the hydrology indicator was calculated as 0.54, the environmental indicator as 0.83, and the life and policy indicators as 0.67. As can be inferred from the study, the pressure indicator scores are quite good. The lowest scores occur in the state indicators. Social and political developments in the basin, improvements in water quantity and quality, and the EPI score have led to high pressure scores. State indicators, which take into account current situation information, are low due to the poor current situation. Following the basic evaluation studies, to effectively utilize the index to other basins in Türkiye and to query changes in the current situation and the examined period with more reliable data, the current situation and changes in the examined period are questioned using the weighted coefficient approach. Another study conducted by [75] focuses the WSI for the Motru River basin resulted in a value of 0.36 for a five-year period. Water availability and changes in the basin's agricultural area and urban population are key factors for assessing water quantity. Data on discharge and water quality were sourced from the Jiu River Basin Management Plan for the development of the WSI. The WSI development for the Motru River basin integrates socio-economic and natural resource aspects to facilitate integrated water resource management. The development of such indices at various administrative levels is crucial for promoting sustainable water management practices and identifying areas for improvement within river basins. By analyzing parameters related to water quantity, quality, and responses to environmental pressures, the WSI provides a comprehensive framework for evaluating and enhancing water resource sustainability in the Motru River basin.

Similarly, the WSI for the Langat River Watershed was derived from four HELP indicators using the Pressure-State-Response model [76]. With a total WSI score of 0.68, the basin demonstrates a near-optimal level of sustainability. However, the analysis highlights concern regarding hydrology quantity and quality. Limitations in obtaining localized real data for the basin pose challenges to the assessment, necessitating adjustments in projections and assumptions to improve accuracy. While there isn't a precise scale for interpreting this value, it suggests that the Langat River Basin is relatively well-situated in terms of sustainability, especially compared to basins with higher WSI values. The assessment identifies strengths in environmental, life, and policy aspects of the watershed, while noting weaknesses related to hydrology, mainly attributable to water pollution. This value serves as a practical tool for stakeholders and communities involved in managing the Langat River Basin, guiding efforts to improve its sustainability.

The sustainability of the Santiago-Guadalajara River Basin (SGRB) was investigated by [69] across multiple factors including hydrology, environment, life, and policy. This study reveals concerns, particularly in hydrology and environment, with decreasing water availability in certain areas and environmental degradation due to urbanization. They also highlight stagnant education and life expectancy improvements, along with limited policy coordination hindering sustainable water governance. Overall, the SGRB faces challenges in achieving sustainability, urging the need for integrated water resources management and targeted policy interventions. The SGRB's sustainability is rated between low and intermediate, with several sub-basins facing environmental degradation, decreasing water availability, and inadequate policy responses. The WSI score of 0.36 suggests a lower sustainability level compared to other basins globally, indicating the need for urgent measures to improve sustainability. In conclusion, they highlight the significance of implementing an integrated water resources management approach within the SGRB, emphasizing the need for collaboration among society, academia, and government. To enhance sustainability, public policies are required to address water and sanitation goals, land-use management, population decentralization, water concessions allocation, treated water reuse, and wastewater discharge regulation. Indices like the WSI play a vital role in informing and engaging citizens and policymakers on water resource issues.

In brief, however the WSI has been applied to many basins, the number of peer-reviewed studies in the literature is quite limited and there are no comprehensive researches conducted on a basin or sub-basin scale in Türkiye. These studies generally involve the application of the WSI version presented by [45] to the respective basin with minimal modifications and adaptations. Overall, the studies indicate that basins tend to have a moderate level of sustainability. Details regarding these studies are presented in Table 5.

Table 5. Summarized WSI Applications in the literature

Researchers	Basin Characteristics			WSI
	Country	Basin Name	Basin Area (km^2)	
[73]	Indonesia	Batang Merao	678.7	0.59
[72]	Chile	Elqui River	9,700.0	0.61
[75]	Romania	Motru River	1,895.0	0.36, 0.51
[65]	India	Chhattisgarh	2,400.0	0.55
[69]	Mexico	Santiago River	9,829.6	0.36
[76]	Malaysia	Langat River	2,287.0	0.68
[74]	Turkey	Ergene	1.448,8	0.70

4. RESULTS AND DISCUSSIONS

4.1. Challenges and Limitations

Despite its utility, the WSI faces several challenges and limitations that warrant consideration. These include data availability and quality, indicator selection and weighting, and the integration of diverse stakeholder perspectives. Furthermore, the applicability of the WSI in data-scarce regions and its sensitivity to temporal and spatial variability remain areas of ongoing debate and research. Overcoming these challenges necessitates continuous collaboration among researchers, practitioners, and policymakers to further refine the WSI methodology and improve its accuracy, applicability, and robustness.

One of the most significant constraints in the WSI calculations is the size of the watershed. Due to the expected greater variability in parameters and indicators in large basins, the WSI should be calculated using sub-watersheds. In this regard, it is asserted by [77] claims that in watersheds up to 2,500 km^2, watershed management at the regional and local scales is more remarkable. As a result, this is the maximum that is advised when using the WSI to evaluate the sustainability of a watershed. On the other hand, if larger watersheds are to be assessed using the WSI, they might be split up into smaller sub-basins, with the final score being determined by summing the scores of these sub-basins [45].

Moreover, the negative effects of climate change on watershed sustainability are increasing in many aspects [78-79]. In this regard, the impacts of climate change on both watershed and sub-watershed scales should be dynamically monitored, and climate change scenarios should be updated accordingly.

Some of constraints for the WSI calculation related watershed management [74]. The study remarked to data related to human population only affect the calculations of other indicators. It does not have a direct impact on the index. Also, in the evaluation of agricultural data, instead of considering factors such as crop pattern, irrigation type, and good agricultural practices, the index is calculated by the ratio of changes in agricultural areas to changes in population. Although the proportions of natural areas and protected area quantities in the basin are included in the index, the ecosystem characteristics of these areas have not been questioned. Finally, his study shows the importance of the climate change that it is not considered at any stage of evaluation within the WSI.

Another important issue is the number and adequacy of indicators used in the WSI calculations. While this may vary from basin to basin, it is generally evident that it does not encompass all sustainability parameters related to the watershed. According to [80], the following qualities deserve to be considered when taking account while choosing indicators: (1) Time-sensitive; (2) spatially or group-sensitive; (3) anticipatory or predictive; (4) reference or threshold values available; (5) impartial; (6) suitable data transformation; and (7) holistic. This issue was evaluated with considering Türkiye's special conditions by [74]. According to his study, the most significant problem encountered in practice for Türkiye is the diversity in institutional structuring. In Türkiye's institutions generating data are organized at the provincial level rather than the basin level. The technical knowledge and capabilities are insufficient. The limitations in the WSI calculation include the lack of systematic data, necessitating extrapolation, and the use of a UN Environment Programme (UNEP) questionnaire to address data gaps objectively [69].

Another problem in this scope is that the weights of the indicators are the same, and as a result of the sub-indices compensating for each other, WSI values do not come out low. The idea of complete interchangeability among the subindices is implied [81]. This means embracing the idea of trade-offs or poor sustainability, in which changes recorded by the subindices result in a decline in one dimension that is compensated by a rise in another (or dimensions). Additionally, it can be claimed that the WSI focuses awareness to prevalent difficulties with composite indices, emphasizing that the use of the index for intertemporal comparisons is substantially restricted by its presumptions of a fragile sustainability in the aggregate through a simple average [62]. Conducting a combined analysis of subindices is deemed essential. In his study, there was a reduced disparity among the HELP dimensions, primarily attributed to enhancements in the Life indicator. However, despite this improvement, the overall advancement of the WSI was modest, mainly because setbacks were noted in the Hydrology and Policy indicators. Ultimately, it is recommended that if WSI serves as a tool to facilitate effective water resource management, it becomes imperative to expedite the accessibility of official statistics crucial for its formulation [62]. This includes prioritizing the availability of georeferenced statistics pertaining to the variables of the four dimensions of the HELP model.

In brief, The WSI is a valuable tool for assessing watershed sustainability, but it faces several challenges and limitations. These include issues with data availability and quality, indicator selection and weighting, and the integration of diverse stakeholder perspectives. Furthermore, its applicability in data-scarce regions and sensitivity to temporal and spatial variability are areas of ongoing debate. Additionally, the size of the watershed poses a significant constraint, with larger basins requiring sub-watershed calculations for accuracy. Other problems include the adequacy of indicators, institutional diversity, and the lack of systematic data. The uniform weighting of indicators also leads to WSI values not accurately reflecting low sustainability. Improvements in methodology and the accessibility of official statistics are recommended to enhance the effectiveness of WSI in facilitating water resource management.

4.2. Future Directions

Contrary to the general consensus, the number of studies introducing a new approach to sustainability indexes in the literature is quite limited; however, these studies have been published in the last few years [82, 83]. In this regard, it presents a variety of well-known water-based resource indices and the authors also emphasize the importance of using the Promethee method for studying water resources, while its non-compensatory approach attempts at establishing an all-encompassing pre-order of alternatives [26]. This method allows for the consideration of various preference functions, making it suitable for both objective and subjective questions related to water sustainability. Similarly, expert-based methods were employed by [82] to calculate weights for the WSI indicators, ensuring unbiased results. Although the weights differed from the original WSI, the overall basin sustainability scores remained similar. The study revealed that the basin ranked third among developing countries, with water availability identified as a key bottleneck. Addressing this issue through appropriate water management policies could enhance basin sustainability.

There is a clear need to expand the scope of studies mentioned previously. Specifically, in Türkiye, it is crucial to determine indicator weights for different basins using expert-based approaches, both at the sub-basin and basin levels. Moreover, continuous monitoring of these values at regular intervals is essential, alongside the development of corresponding plans and programs.

A five-year period is widely used in sustainability studies for data integrity, methodological stability, and meaningful trend analysis. It balances short-term fluctuations with long-term trends. However, further research is needed on how period length affects index values. When data integrity allows, shorter periods may be preferable, and sensitivity analyses should be included.

Adaptation of WSI calculation method is necessary for basins with diverse characteristics, achieved by adjusting the quantity and quality of indicators. Notably, in basins within the Mediterranean region, tourism stands as a pivotal factor requiring inclusion within the WSI framework. Similarly, basins characterized by intensive agriculture should incorporate agriculture-related parameters such as fertilizer and irrigation.

Addressing climate change, one of today's most pressing issues, is imperative. The absence of studies considering sustainability and the significant impact of climate change on WSI calculations must be rectified. Research focusing on climate change will elucidate its influence on WSI and the resulting alterations in main indicators.

In summary, future research directions for the WSI encompass a range of areas, including the refinement of indicator frameworks, the development of spatially explicit modeling approaches, and the integration of emerging technologies such as remote sensing and machine learning. Additionally, efforts to enhance the scalability and transferability of the WSI across different scales and contexts are needed to support more effective watershed management strategies. Moreover, interdisciplinary collaborations and knowledge exchange networks can facilitate the uptake of WSI findings in policy and practice, thereby contributing to the sustainable management at different scales.

5. CONCLUSION

The WSI represents a valuable tool for assessing and promoting sustainability in watershed management. Its holistic and multidimensional approach offers insights into the complex interactions shaping watershed dynamics and supports evidence-based decision-making processes. By addressing key challenges and advancing research frontiers, the WSI holds promise for enhancing the resilience and sustainability of water resources in an increasingly uncertain and changing world.

Despite its utility, the WSI encounters numerous challenges and limitations that warrant attention. These include issues with data availability and quality, indicator selection and weighting, and the incorporation of diverse stakeholder perspectives. Furthermore, its applicability in data-scarce regions and its sensitivity to temporal and spatial variability remain areas of ongoing debate and research. Tackling these challenges necessitates ongoing cooperation among researchers, practitioners, and policymakers to improve the WSI methodology and strengthen its relevance and reliability.

One significant constraint in WSI calculations is the size of the watershed. Larger basins require sub-watershed calculations to account for greater variability in parameters and indicators. Additionally, the adequacy of indicators, institutional diversity, and the lack of systematic data present significant challenges. The uniform weighting of indicators can also lead to inaccuracies in reflecting low sustainability.

Moving forward, future research should focus on refining indicator frameworks, developing spatially explicit modeling approaches, and integrating emerging technologies like remote sensing and machine learning. Efforts to enhance scalability and transferability across different scales and contexts are crucial for supporting more effective watershed management strategies. Interdisciplinary collaborations and knowledge exchange networks can further facilitate the uptake of WSI findings in policy and practice, contributing to sustainable water resource management on local, regional, and global scales.

In conclusion, sustainable water resource systems are essential for meeting society's present and future needs while preserving ecological integrity. Watershed sustainability plays a critical role in achieving this goal by managing and conserving watersheds to ensure the health of the entire ecosystem.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Erdal KESGİN: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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