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A review of groundwater stress indices for a quantitative assessment of the resource

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ABSTRACT
Groundwater represents about 30% of the global fresh water and is the primary source of drinking water for 3 billion people. In the context of climate change, reliance on this resource is increasing, but the altered precipitation patterns, and consequently aquifer recharge, increase groundwater supply vulnerability. In this framework, monitoring and quantifying groundwater stress is an urgent need. This review aims to provide a critical overview of the approaches proposed in the literature to assess the sustainability of groundwater exploitation from a quantitative perspective. Three main approaches are identified: those based on water flux balances, which define overexploitation as an excess of consumption with respect to the available renewable resource; those based on the evaluation of stored volumes, which identify groundwater stress as a progressive depletion; and hybrid approaches, which combine the previous two while incorporating economic, social and regulatory constraints. The analysis highlights a substantial lack of standardization in the definition of core variables (e.g., recharge) and a limited comparability among the results of stress indices, inhibiting their application in the regulatory framework. By identifying these limitations, this review aims to promote the development of more transparent interdisciplinary indicators capable of informing groundwater management in a context of growing stress and uncertainty.

KEYWORDS groundwater; groundwater indices; groundwater drought; sustainable groundwater use

1. Introduction

Fresh water accounts for about 2.5% of global water resources. Out of this fraction, 68.7% is found in glaciers and ice caps, 30.1% in groundwater and 1.2% in surface water [1]. Groundwater therefore represents the largest available storage of fresh water on the planet. Up to 3 billion people rely on groundwater as their primary drinking supply, and 60–70% of groundwater withdrawals are used for irrigation [2]. India, the USA, and China are ranked among the countries with highest rate of withdrawal [3], whereas groundwater-dependent ecosystems are located predominantly in central Asia, Sahel, Southern Africa, and Australia [4]. In the 27 EU member states, groundwater alone provides 65% of drinking water and 25% of irrigation water [5]. Therefore, this resource supports domestic consumption, irrigated agriculture, and industrial production in many areas of the world, particularly in semi-arid regions and more generally where surface water resources are overexploited or subject to high seasonal variability [6,7].

Over the past several decades, water demand has constantly increased in all sectors, mainly associated with population expansion, and a growing reliance on groundwater as the primary supply is observed, particularly for agriculture. Moreover, impacts on groundwater are foreseen to be connected to direct and indirect effects of climate change on the water cycle and water withdrawals [2]: climate change causes a lowering of the piezometric levels because of snow retention reduction, changes in precipitation regimes and spatial distribution of vegetation species. In the agricultural sector, with higher temperatures the irrigation requirements of crops are expected to rise due to the increase in potential evapotranspiration [8,9]. At the same time, warmer temperatures will likely promote the expansion of agricultural lands to higher altitudes and, in general, to areas traditionally characterized by less intense water demand [10]. Finally, from another perspective, over-abstraction in water-stressed areas might also affect the qualitative state of groundwater by enhancing saltwater intrusion in coastal aquifers or mobilizing polluted waters [5].

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The already observed increasing dependence of water supply systems on groundwater has evidenced the urgent need for reliable metrics suitable to assess the sustainability of its exploitation. Over the past two decades, several indices aimed at synthetically representing the anthropic pressures on the resource in the specific hydrogeological context have proliferated. The proposed indicators vary significantly in terms of conceptual approach, required data, complexity, and scale, and therefore are only partly comparable.

The required data ranges from direct measurements of groundwater levels to estimations of hydrological variables (e.g., effective precipitation, environmental flows supported by groundwater), to groundwater abstraction or loss censuses and artificially infiltrated volumes, to estimates from satellite data (e.g., the NASA Gravity Recovery And Climate Experiment - GRACE - missions) or numerical hydrogeological models.

The usual approach is based on the "withdrawal-to-availability" ratio, which relies on the conceptually simple comparison of the water demand to the renewable resource [11,12]. Most of them are based on a groundwater flow balance that compares inputs (natural, and eventually anthropogenic, such as losses from water pipe networks or irrigation losses) and outputs (e.g., artificial extraction and environmental flow), in various combinations. Other indicators rely on sophisticated technologies able to estimate the long-term trends in groundwater storage from satellite gravimetry anomalies [13]. Moreover, some indices explicitly take into account the forecast of future demand, and the technical, economic, legislative, and environmental constraints on groundwater abstractions [14,15]. Since these indices are in most cases intended to offer support to aquifer classification and prioritization, water management policy definition, and decision making more generally, often outside the scientific community [16–18], the diversity of available approaches—and consequently results—may generate confusion and lead to incomparable results.

This review aims to provide a critical synthesis of groundwater stress indices proposed in the literature, with particular attention to their conceptual foundations, input requirements, robustness, and scalability. The indicators are categorized into three broad families: flux-based indices, which define the water stress based on a balance of abstractions and renewable inflow; storage-based indices, which identify water stress by quantifying long-term trends in the water volume stored in the aquifer, through in-field groundwater monitoring data, groundwater models, or gravimetric methods, or a combination of these; and hybrid indices, which combine the previous two approaches with economic, legislative, and social aspects or more generally with elements of the broader context of sustainability. For each group, we present the indices proposed in the literature, examine the key assumptions underlying them, and identify the major strengths and limitations, with particular attention to current research gaps with respect to harmonization and policy relevance. Particular attention is also given to how different indicators incorporate environmental flow requirements, handle the notion of "exploitable" groundwater, and distinguish between abstraction of renewable and nonrenewable resources.

2. Indices of water scarcity

Although the focus of this review is primarily on groundwater, it is useful to provide an introductory overview on the broader context of water stress indicators, which usually aggregate surface and groundwater resources into a single metric of availability or pressure. The concept of water scarcity dates back to the 1990s, but its first translation into an indicator is attributed to Falkenmark [19]. The ***Falkenmark index*** measures scarcity as the available water resources per capita, usually at the national scale. Values lower than 1300 m^3/year per person indicate a water deficit, meaning that the area does not have enough water resources to guarantee food production for its population [20]. Despite its relevance in the early stages of the development of water stress indicators, this index is often considered inadequate for practical applications, since it does not consider the hydrological context and spatial-temporal variability, the infrastructure constraints, or the water allocation priorities [11].

Later, the scientific community converged toward an approach based on the "withdrawal-to-availability" ratio—that is, the quantification of water stress comparing water demand (i.e., abstractions) and its availability (i.e., the renewable water resource) over a given reference period, often 1 year. An example is the commonly used ***Water Scarcity Index*** (***WSI***) [21]:

$$WSI = \frac{(W - D)}{RFWR} \tag{1}$$

where W, D and RFWR respectively represent the total water withdrawals for human needs (W), the water produced through desalination (D) and the renewable freshwater resources (RFWR) available in the study area. Conventionally, WSI values higher than 0.4 suggest that the area is characterized by water stress.

The structure of the WSI has been slightly modified at the European scale: as a part of the reporting obligations in the framework of the Water Information System for Europe (WISE)—the official data and reporting platform established by the Water Framework Directive [22]—all member states are required to submit standardized water resource assessments, including the calculation of the ***Water Exploitation Index Plus*** (***WEI+***), which compares water consumption to the renewable available fresh water:

$$WEI+ = \frac{C}{RFWR} \tag{2}$$

where C represents the net consumption—that is, the amount of water withdrawn, exploited by the civil, agricultural, and industrial sectors, that is not returned to the natural system, thus evidencing, compared to WSI, that part of the withdrawn resource is returned to the original water bodies. WEI$+$ is computed for a reference study area and a desired time interval. In general, values of WEI$+$ higher than 0.2 suggest water stress conditions, while values higher than 0.4 point out severe water stress.

More recently, the EU Agenda 2030 [23] also introduced, as part of Sustainable Development Goal (SDG) number 6, the ***Indicator 6.4.2—Level of water stress***, which shows a structure similar to WEI$+$, being defined as the ratio of total withdrawals (W) to total renewable resources (RFRW) adjusted for the amount of water necessary to preserve the dependent ecosystems, known as the environmental flow (E):

$$Indicator\ 6.4.2 = \frac{W}{RFRW - E} \tag{3}$$

This indicator stresses that only a fraction of the renewable resource is available for human consumption.

The estimation of the RFWR is usually obtained from global or regional climate models. For instance, in Italy the Institute for Environmental Protection and Research (ISPRA) calculates RFWR as the balance among precipitation, evapotranspiration, external intake from adjacent territories, and change in water storage [24].

The three abovementioned indicators are conceptually straightforward, but show two main limitations: on the one hand, they do not distinguish between surface water and groundwater, which reduces their contribution in identifying those situations in which groundwater may be under particular stress and represents the critical point of water supplies; on the other hand, they are typically implemented effectively at a national or regional scale, but may lack the resolution necessary to inform basin-level or local management strategies. However, these indicators play a key role in promoting discussions on water scarcity and in supporting the identification, at a large scale, of particularly critical areas, where groundwater-specific assessments can be more useful.

3. Indices of groundwater stress

Surface and groundwater resources are usually interconnected from a hydrological point of view, but their response times and management requirements differ significantly: groundwater systems typically exhibit a delayed response to stress, greater inertia to change, and higher spatial heterogeneity, particularly in terms of recharge rates, flow velocities, and storage properties [16]. Moreover, unlike surface systems, where withdrawals are often constrained by evident scarcity (e.g., low discharge in a river or low level in a lake) or infrastructure limitations (e.g., low level in an artificial basin), groundwater can often be exploited beyond sustainability without immediate evidence of unsustainable use, thus leading to overuse which is then recoverable on a longer time frame [13]. For these reasons, when the freshwater sources are primarily aquifer systems, groundwater-specific stress indicators are preferred to general indices lumping together all freshwater resources.

As a general rule, groundwater stress indices aim to quantify the degree to which the withdrawals exceed the renewable supply or deplete the storage in an unsustainable manner, following the "withdrawal-to-availability" ratio approach that characterizes WSI, WEI$+$, and Indicator 6.4.2. A variety of groundwater-specific indices have been developed in the last few years; some are specifically designed to support forecasting models, even very simple ones, and allow for future estimates in water availability and demand; others are defined with more generic aims to quantify the current state of groundwater stress.

From a technical point of view, two types of approaches used for the definition of these indices can be distinguished: some indices compute a water balance between the input into the groundwater system, e.g., recharge (R), and the outputs, such as human withdrawals (Q) and groundwater contribution to the environmental flow (E); other indices estimate a volume of stocked groundwater and evaluate how abstractions affect it. Table 1 provides a description of the variables used in the indices that will be presented. A graphical summary of the variables is presented in Figure 1.

The groundwater stress indices proposed in the literature can be grouped into the following classes, having similar conceptual foundations and operational aims:

a. Flux-based indices, which evaluate the relationship between recharge and abstraction utilizing the hydrological balance;
b. Storage-based indices, which are based on measured or estimated changes in stored groundwater volume;
c. Hybrid indices, which integrate hydrological fluxes and stored volumes with additional environmental or socio-economic aspects.

Indices based on water flux balance or stored volumes rely on hydrogeological modeling and description of the physical processes, while hybrid indices may also integrate socio-economic, ecological, and governance-related aspects. The following paragraphs provide a synthetic description of the indices classified in these three categories. Table 2 provides an overview of their classification, formulas, and conceptualization in graphical form.

3.1. Flux-based indices

This category of indices relies on the hydrological balance and represents an intuitive approach to quantify

Table 1. Variables used in the presented groundwater stress indices.

Symbol	Variable	Dimension	Description
Q	Withdrawals	L^3T^{-1}	Human withdrawals from aquifer systems, via pumping wells, artesian wells, or natural springs, for civil, agricultural, or industrial applications.
R	Groundwater recharge	L^3T^{-1}	Total recharge (from precipitation, surface water bodies, leaks from potable water supply system or irrigation network, managed aquifer recharge (MAR), flux incoming from adjacent aquifers).
R_{NAT}	Natural recharge	L^3T^{-1}	Natural recharge (from precipitation, surface water bodies, flux incoming from adjacent aquifers); it does not consider the human contribution to recharge R.
R_{IRR}	Recharge from irrigation	L^3T^{-1}	Recharge due to infiltration of water whenever irrigation operations exceed the physiological needs of the vegetation/crops. It does not consider the contributions of runoff and evaporation.
R_{SYS}	Recharge from losses in distribution/collection systems	L^3T^{-1}	Losses in the water distribution system and sewage collection networks.
L	Leaks	L^3T^{-1}	Anthropic unintentional recharge, given by the sum of R_{IRR} and R_{SYS}.
MAR	Managed aquifer recharge	L^3T^{-1}	Anthropic intentional recharge (e.g., using infiltration basins).
C	Consumption	L^3T^{-1}	The amount of water withdrawn, exploited by the civil, agricultural, and industrial sector and that is not returned to the groundwater system. e.g., the water is embedded into the goods or is released into the atmosphere or surface water bodies after the multiple processes it undergoes.
E	GW contribution to the environmental flow	L^3T^{-1}	Contribution of groundwater bodies to the preservation of the environmental flows (e.g., river baseflow) and to the support of groundwater-dependent ecosystems (e.g., forests).
GW_R	Renewable groundwater storage	L^3	The porous volume saturated by the infiltrated water coming from annual recharge. It corresponds to the highest threshold of water volume that humans can withdraw without exceeding recharge.
GW_{NR}	Nonrenewable groundwater storage	L^3	Groundwater volume cumulated over a long time period. At the human time scale it appears nonrenewable.
$\Delta GWSA$	Groundwater storage anomaly	L^1T^{-1}	Trend in the anomaly of groundwater stock, evaluated by means of gravimetric satellite measurements (GRACE).
GW_{EX}	Exploitable groundwater storage	L^3T^{-1} (L^3)	Amount of groundwater that can be exploited from the aquifer system. The definition of the threshold depends on technical, economic, legislative, and environmental conditions. It can be expressed as an annual volume to be consistent with GW_R.

The table summarizes their symbol, name, dimension and, finally, their description.

groundwater stress. Their structure is based on the “withdrawal-to-availability” ratio, with numerous variations regarding how “withdrawals” and “availability” are defined.

The “withdrawals” (the numerator) are defined, depending on the indicator, considering either the properly called withdrawal (i.e., total abstracted water, Q); or the net consumption (i.e., the fraction of withdrawn water exploited in human activities that is not returned to the natural systems, C); or the net withdrawal (i.e., the abstracted water net of leaks, Q–L). Leaks may in turn be defined including both losses in the water distribution system and sewage collection networks (R_{SYS}) and excess irrigation (R_{IRR}), or only one of them, depending on the authors.

Similarly, “availability” is variously defined as the natural recharge alone (R_{NAT}); or as the total recharge (R), i.e., including both natural recharge (R_{NAT}), leaks (L) and artificial recharge of the aquifer system (MAR); or as the total recharge net of environmental flows (R–E).

It is therefore evident that the combinations of withdrawals and availability can be many, driven by different conceptual approaches to the definition of groundwater stress, and can lead to quantitative results that differ significantly. Moreover, it is worth evidencing that the reliability of the estimates of the different components can vary significantly, since some of them are directly or indirectly measured (e.g., total withdrawals can be estimated using databases of water abstraction licenses and datasets combined with statistics) and others are estimated through hydrological models (e.g., the environmental flows).

An overview of a selection of flux-based indices proposed in the literature is provided in the first part of Table 2. The ***Withdrawal To Renewable water* (*WTR*) *index*** is the most diffuse one, and can be considered a

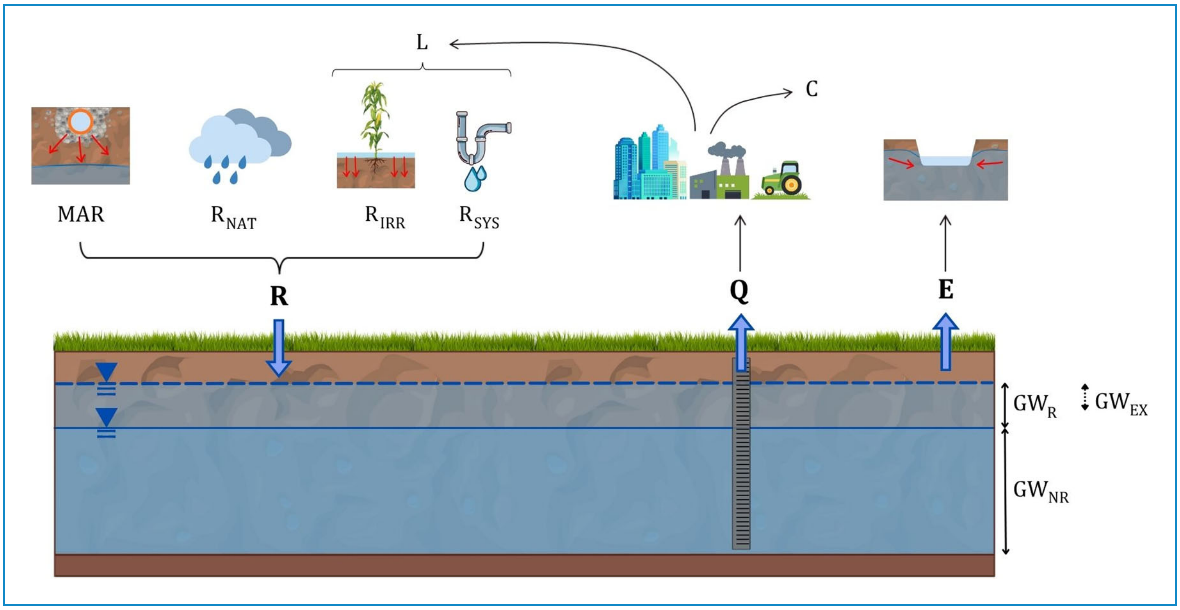


Figure 1. Graphical summary of the variables used in the groundwater stress indices presented in this review. Note that the recharge is represented both as an incoming flux (R) and as the equivalent renewable groundwater storage (GW_R) saturated by the annual recharge. The latter adds up to the long-term nonrenewable groundwater storage (GW_{NR}), represented in a darker shade of blue. The exploitable groundwater (GW_{EX}) is represented, conventionally, as a fraction of the GW_R to comply with sustainable extraction. The other variables are: withdrawals (Q); groundwater contribution to the environmental flow (E); consumption (C); managed aquifer recharge (MAR); natural recharge (R_{NAT}); leaks (L); recharge from irrigation (R_{IRR}); recharge from losses in distribution/collection systems (R_{SYS}).

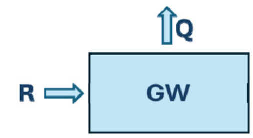
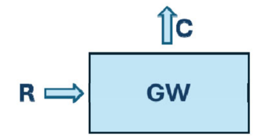
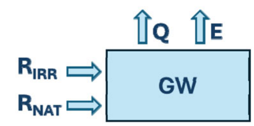
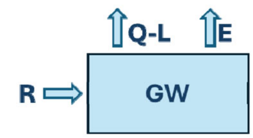
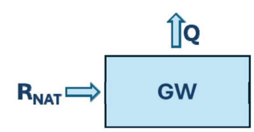
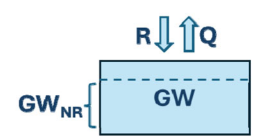
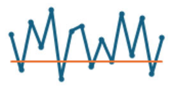
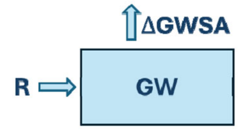
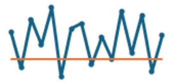
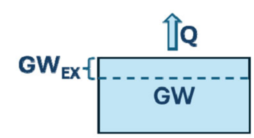
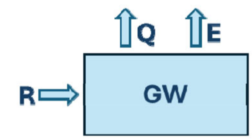
translation of the Water Scarcity Index (WSI) for groundwater resources, being defined (Table 2) as the ratio of the total anthropogenic groundwater withdrawals (Q) over the renewable groundwater resources, namely total aquifer recharge (R). Given the broader meaning of renewable groundwater, the availability (denominator) is not strictly the natural recharge but involves all components, such as recharge from irrigation, leaks, and MAR, unless differently specified. WTR allows the quantification of the pressure on the available groundwater and, only indirectly, on the ecosystems that rely on it. When withdrawals equal the renewable supply, WTR tends to 1 and the system is in equilibrium; WTR values greater than 1 imply that withdrawals exceed recharge, leading to aquifer depletion; values lower than 1 suggest that the exploitation is being conducted in a sustainable way, at least from a quantitative point of view, resulting in an increase in the stocked resource.

The ***Consumption To Renewable water (CTR) index*** estimates groundwater stress as the ratio of the (ground)water consumption (C) to the total recharge (R) [26]. The adoption of the consumption C, instead of the total withdrawals Q, indirectly includes the different roles played by human sectors in the (ground)water cycle: agriculture, industry, and households, which are the most water-demanding sectors, respectively return about 40%, 90% and 95% of their water withdrawals to the water cycle, with a significantly different impact on the medium- and long-term balance. Consequently, the CTR index could as well be interpreted as a proxy of water use efficiency.

The ***Aquifer Stress Index (AQSI)*** [18] and the ***Groundwater Stress (GW Stress) index*** proposed by the International Groundwater Resources Assessment Centre [27] both subtract the environmental flow (E) to recharge at the denominator. E includes the outflows of groundwater to its dependent ecosystems (such as stream baseflows, wetlands, and springs), and the share of groundwater evapotranspired by vegetation, and consequently these two indices acknowledge that the amount of water necessary to ensure the ecological integrity should not be considered a resource available to human activities. Conversely, the two indices differ in the approach adopted to define withdrawals, and consequently recharge: AQSI assumes that the recharge contributing to the renewable resource is given by natural recharge (R_{NAT}) and excess irrigation (R_{IRR}), while GW Stress takes into consideration the total recharge (R), but defines withdrawals net of the leaks (L). The comparison of these two indices is a good example of how conceptually similar approaches (namely, considering environmental flows not available for human consumption, and taking into consideration return flow due to leaks) may result in substantially different formulations of a stress index, and consequently in different quantitative results when the two indices are applied.

Other indices have been proposed by Tabarmayeh et al. [17]. Among them, it is worth mentioning the

Table 2. Summary of the presented groundwater (GW) stress indices.

Classification	Groundwater stress index		Formula	Reference	Graphical scheme
Flux-based indices					
	WTR	Withdrawal To Renewable (ground)water	$\frac{Q}{R}$	[25]	
	CTR	Consumption To Renewable (ground)water	$\frac{C}{R}$	[26]	
	AQSI	AQuifer Stress Index	$\frac{Q}{R_{NAT}+R_{IRR}-E}$	[18]	
	GW Stress	GroundWater Stress	$\frac{Q-L}{R-E}$	[27]	
	WTNR	Withdrawal To Natural Recharge	$\frac{Q}{R_{NAT}}$	[17]	
	NSE	Nonrenewable Storage Extraction	$\frac{\sum_{t=0}^{t=n}\left(R(t)-Q(t)\right)}{GW_{NRt=0}}$	[17]	
Storage-based indices	SGI	Standardized Groundwater level Index	Normal scores transform	[28]	
	RGS	Renewable Groundwater Stress	$\frac{\Delta GWSA}{R}$	[13]	
	GGDI	GRACE Groundwater Drought Index	$\frac{GWSA_{i,j}-\bar{GWSA}_j}{\sigma_{GWSA,j}}$ (*)	[29], [30]	
Hybrid indices	WTE	Withdrawal To Exploitable groundwater	$\frac{Q}{GW_{EX}}$	[15]	
	GF	Groundwater Footprint	$A\frac{Q}{R-E}$	[16]	

(*) Note that in the table i and j count, respectively, the years and the months.

Withdrawal To Natural Recharge* (*WTNR*) *index, a conservative variation of WTR that considers only the natural components of the recharge (R_{NAT}): WTNR approaching 1 suggests that natural recharge alone is sufficient to counterbalance the withdrawals, whereas values greater than 1 imply that uptakes exceed the renewable groundwater supply. This makes WTNR particularly useful to assess scenarios in which the return flows, due to leaks of the water supply system (L) and irrigation (R_{IRR}), are reduced or canceled due to network improvements or changes in irrigation practices. It is also worth citing the ***Nonrenewable Storage Extraction* (*NSE*) *index***, which quantifies the impact of abstractions on the nonrenewable storage (GW_{NR}) over a period of interest, and can be used to visualize temporal trends of groundwater stock, expressed as a percentage of the initial nonrenewable stock (GW_{NR} at $t = 0$).

The flux-based approach bypasses the challenge of estimating the total groundwater volumes: natural fluxes are computed thanks to hydrological models and/or direct measurement of environmental variables, whereas water uptakes, leaks, consumption, and exploitable flow rates are determined from databases, direct measurements, or water permits. As a general rule, flux-based indices are highly sensitive to the assumptions used in estimating the fluxes that are not measured directly, in particular the recharge. Several studies adopt long-term average recharge values derived from hydrological models (e.g., MODFLOW or SWAT), empirical relationships, or water table fluctuation methods, each introducing substantial uncertainty [9,31].

Flux-based indices are often employed to obtain an evaluation of the current groundwater stress, but they can also be used to observe temporal trends, to identify sustainable or unsustainable use of the resource, and to predict the future stress of the aquifer system under study, coupling for example hydrological and climate models to forecast future recharge and withdrawals under different climate change scenarios, and integrating them with projected water demand.

3.2. Storage-based indices

Unlike flux-based indices, which rely on fluxes (typically abstraction and recharge), storage-based indicators assess groundwater stress through observed or inferred changes in aquifer volume. These indicators reflect the cumulative effect of abstraction over time and can be particularly useful in identifying long-term trends and irreversible depletion by evaluating how the index varies on an annual or seasonal basis. They typically rely on either direct measurements (e.g., groundwater level time series) or remote sensing data, most notably from GRACE satellite missions.

The ***Standardized Groundwater level Index* (*SGI*)** was proposed to emphasize anomalies in the groundwater level time series [28]. It is computed by applying a non-parametric normal scores transform to the groundwater level at the monthly scale, following the same approach adopted for the Standardized Precipitation Index (SPI), commonly employed in hydrology [32]. SGI therefore represents the average rate of decline in water table depth, normalized to a reference threshold or time window (Table 2). As a result, drought periods are characterized by negative SGI, with increasing intensity as the values decrease. The SGI shows a correlation with the SPI, eventually with a time lag, and its alarming values are found to coincide with documented droughts. SGI is very often used in combination with other hydrological standardized indices [33,34], and it was successfully adopted also for future predictions under climate change scenarios [35]. Note that SGI results vary depending on the length of groundwater level time series if the monitoring period covers few years [36], while the influence of seasonal fluctuations, particularly for shallow aquifers with limited extent, is still under debate [28,37].

The SGI has been widely used in research since it was proposed thanks to the simplicity of its computation. However, its integration into groundwater management policies and regulatory frameworks remains limited, primarily because of the low density of monitoring wells—especially in low-income countries or regions where environmental monitoring is not a governance priority and incentives to expand monitoring networks are scarce.

Where groundwater level monitoring data are scarce, or when groundwater stress is evaluated at regional or national scale, an alternative approach is to use indices based on satellite gravimetry measurements combined with hydrological models [13]. On one hand, satellite gravimetry and, particularly, the GRACE missions conducted by the US National Aeronautics and Space Administration (NASA), provide mass anomalies over time in a given region, which are associated to the total water storage change in the area of interest. On the other hand, hydrological models (such as the Global Land Data Assimilation System—GLDAS [38]) estimate surface water, snow, and soil moisture contributions to the time series of the total water stock, which can be used to depurate non-groundwater contribution from mass anomalies, thus leading to an estimation of the temporal variation of the groundwater stock, better known as GroundWater Storage Anomaly (GWSA). As a result, the GWSA trend can partly remedy the lack of direct field measurements of groundwater levels, particularly when the studies involve large areas with limited monitoring. Conversely, the main limitation of this approach is the coarse resolution of the satellite data, currently $1/4$ of a degree [39]. As a result, applications to small-scale catchments are inhibited and a variety of downscaling methods are being proposed [40–42].

Among groundwater stress indices based on satellite gravimetry, it is worth mentioning the ***Renewable Groundwater Stress*** **(*RGS*)** ***Index*** and the ***GRACE Groundwater Drought Index*** **(*GGDI*)**. The RGS is the direct application of GRACE data to the WTR index as the withdrawals, at the numerator, are quantified by the GWSA. In contrast, the GGDI is very similar to the SGI, but it is based on the GWSA. The GGDI time series is computed (Table 2) by subtracting from each value of the GWSA monthly time series the mean for that same month calculated over all the available years, normalized to the standard deviation for that month calculated again over the years [29,30]. As a result, the GGDI is dimensionless and drought levels are identified for values lower than −0.50.

Compared to flux-based indices, storage-based approaches offer the advantage of capturing the actual response of the aquifer systems, rather than relying on estimates of recharge often derived from models. However, GRACE data are currently limited to relatively coarse spatial resolution, making them unsuitable for local-scale applications [39]. Moreover, the indirect derivation of groundwater storage from water mass anomalies may introduce significant uncertainty, especially in areas where the other water storage components included in GLDAS or similar models (e.g., snow or surface water) fluctuate seasonally and spatially with great variability, and therefore may not be fully described by such models [42]. All in all, storage-based indicators can be considered particularly suitable for large-scale assessments and for evaluating cumulative impacts over a medium or long time scale. Their robustness could be improved, for example, by integrating satellite data with ground-based monitoring, where possible, as proposed by some authors in recent years [43].

3.3. Hybrid indices

In order to integrate multiple aspects of the sustainability of groundwater exploitation, in the last few years several authors have proposed composite indices that combine hydrological, ecological, socio-economic, or regulatory variables. This trend reflects a growing recognition of the fact that groundwater stress is not only a physical phenomenon but also the result of socio-economic pressures and management practices [16,44]. These indices offer a more comprehensive picture of groundwater sustainability, but they are often more complex to compute and interpret compared to the most traditional flux-based and storage-based approaches. Nevertheless, hybrid approaches represent a more holistic view in groundwater stress assessment, especially in contexts where governance aspects are as significant as hydrological ones. The literature on hybrid indices is expanding quickly, and we highlight two representative examples here.

The ***Withdrawal To Exploitable groundwater (WTE) index***, proposed by J. Vrba and A. Lipponen [15], represents an extension of the classical WTR. In WTE, the recharge (R) is replaced by the exploitable groundwater: the quantity of groundwater that can be withdrawn according to technical, economic, legislative, and environmental conditions over a reference period—typically, over one year (GW_{EX}). The definition of this last variable depends on the technologies available on site, the socio-economic capabilities, and the legislation in force (e.g., the definition of the permitted withdrawals, also according to the degree of sensitivity to environmental protection). To allow the quantitatively sustainable exploitation of the resource, GW_{EX} should be smaller or, in the worst-case scenario, equal to the recharge (R). For instance, drinking water utilities could apply the WTE to compare their permitted withdrawals to the recharge, thereby enabling the monitoring of their supplies and the development of mitigation and adaptation strategies to safeguard the needed groundwater to guarantee the service to the population they serve.

To facilitate the communication of anthropic pressures on natural capital, a set of footprint indicators has been developed. Indeed, the ***Groundwater Footprint*** **(*GF*)** [16] represents the widely recognized application to groundwater of the classical water footprint (WF), which quantifies the amount of virtual water used by a population to produce goods, commodities, and services along their production chain. Gleeson et al. [16] argued that the WF does not account for water availability and, therefore, does not provide information about the consumption of natural stocks and flows. Conversely, the GF evaluates the anthropogenic footprint on groundwater resources, defined as the area (A) required to sustain a given level of groundwater abstraction (Q), accounting for recharge (R) and environmental flow (E). If the ratio GF/A is greater than 1, the footprint exceeds the actual recharge area, the aquifer is considered under stress, and the exploitation of groundwater is unsustainable, with consequences on its dependent ecosystems. If $GF/A \gg 1$, fossil groundwater mining (i.e., depletion of groundwater that was recharged under past climatic conditions) could be occurring.

The GF is recognized as an effective indicator thanks to its scientific robustness and communication clarity [45], and is particularly suitable as a support for decision making in groundwater exploitation. It was successfully employed, for example, to evaluate the benefits of corrective measures, such as the implementation of artificial recharge, for shifting the exploitation of the aquifer to sustainable conditions [46] and to perform global assessments of aquifer stress [16].

Several variations of the GF have been proposed over the past decade to address specific applications and contexts. One example is the ***integrated Groundwater Footprint*** (***iGF***) [47], which incorporates groundwater quality as an additional component, offering a more comprehensive approach that promotes the protection of groundwater. In this formulation, the GF is adjusted by a factor weighted according to the extent of contamination. However, this version is considerably more data-demanding and requires a detailed, site-specific understanding of contamination plumes. Another variant, the ***crop-specific GF***, is particularly suitable in regions where agriculture is the predominant groundwater user [48]. This formulation integrates fine-scale data on crop water requirements, as well as coefficients that account for irrigation efficiency and the proportion of irrigated land dependent on groundwater. Consequently, it enables the identification of the most groundwater-intensive crops and the aquifer areas under greatest stress.

4. Discussion and conclusions

The assessment of groundwater stress has evolved significantly over the past two decades, reflecting advances in hydrogeological understanding, the development of new monitoring approaches and data-processing techniques, and a growing need for robust and meaningful methods to quantify current water availability and stress, providing at the same time reliable projections in future scenarios, particularly in the context of negative effects of climate change. A diverse set of indices has emerged, ranging from simple water-flux balance formulations to satellite-derived anomaly indices and integrated hybrid approaches that account for hydrological and socio-economic components. These groups of indices are based on significantly different methodological frameworks and are designed for applications at different spatial scales and with varying objectives.

Simple flux-based indices continue to be widely applied due to their clarity in the formulation and ease of application, especially in the context of regulatory and policy studies. However, their static structure often fails to capture the complexity of groundwater dynamics and makes them poorly suited for temporal trend analysis or future projections. The WTR index is still the most widely applied in groundwater assessments, due to its simple yet meaningful conceptualization, limited data requirements, and straightforward implementation. Nevertheless, the availability of GRACE data greatly promotes the research on satellite gravimetry for groundwater-related studies, particularly for evaluating global trends in sustainable (or unsustainable) aquifer exploitation [49]. Among the indices based on satellite gravimetry, the GGDI is the most commonly used, also thanks to its relative ease of implementation. However, despite providing an integrated and dynamic perspective, GRACE-based approaches remain limited by their coarse spatial resolution and reliance on models for the estimation of non-groundwater contributions.

Despite the impressive efforts in the expansion of this field of research, the overall picture remains fragmented. The reviewed literature highlights the absence of a standardized and universal methodology to assess groundwater stress. Major obstacles include: heterogeneity of groundwater systems, limited data availability, lack of methodological consensus, unclear definition of core variables, and diverse data collection and aggregation practices. Indeed, different approaches to defining and estimating core parameters introduce uncertainty, which subsequently propagates into the results of the indices. For instance, groundwater recharge is computed by Borzì and Bonaccorso [50] by means of a hydrogeological balance carried out in a geographic information system, while other studies use a three-dimensional flow model of the aquifer system (implemented with MODFLOW) to tune groundwater levels and recharge [31,51]. In contrast, more conventional methods such as the hydrogeochemical analysis (e.g., chloride mass balance) or the Water Table Fluctuation (WTF) analysis are promoted [52]. WTF in particular has a relatively standard and easy-to-implement formulation that only requires groundwater level and aquifer specific yield. Moreover, historical time series allow to point out long-term climatic effects on recharge [53].

The interpretation and comparability of index results are further limited by heterogeneous methodologies used for data collection and aggregation, especially at the local scale. For instance, the evaluation of return flows or leaks as part of withdrawals or recharge depends on local environmental agencies and guidelines. Hybrid approaches integrating, for example, satellite gravimetry with physically based models (e.g., MODFLOW) can partly overcome these issues, but their robustness is still affected by data availability and model calibration, which greatly vary across different regions [41,54]. Consequently, indices that are expected to provide similar results can in fact produce substantially different stress classifications when applied to the same region [55]. For instance, Yang et al. [56] computed a flux-based index similar to AQSI and compared it with the GF and GWSA. Results showed that the GF underestimated the groundwater stress in the study area, whereas the GWSA and the flux-based index were in agreement with in situ observations. Such inconsistencies can limit the impact of these indices on decision-making processes [17].

Another unsolved issue is the designation of the spatial extent over which these indices should be computed—that is, over the entire aquifer system or limited to specific administrative borders. In addition, distinguishing between unconfined and confined aquifers is also key for the accurate estimation of recharge and consequently groundwater stress, leading to distinct adaptation actions as the two compartments might be stressed by different drivers (e.g., shallow aquifer stressed by abstractions for agriculture and deep aquifer exploited by industry). A deep knowledge of the hydrogeology of the systems and their hydraulic connection, as well as parallel monitoring networks, are necessary.

The literature is evolving toward a more holistic assessment of groundwater supply vulnerability, where indices include ecological, environmental, socio-economic, and political factors and regulatory constraints [11,16]. New indices often account for exposure, sensitivity, and adaptive capacity of aquifers in response to climate change and anthropic pressures, such as temporal trends in recharge and rainfall, sea level rise, coastal proximity, pollution, surface-groundwater interaction, MAR potential, population growth, and education about environmental protection [57–60]. This framework will allow evaluating the hotspots of groundwater supply vulnerability under different scenarios and promoting mitigation actions, as well as remediation, and climate-adapted solutions such as MAR. In the near future, indices, in particular hybrid ones, are expected to reach high resolution and incorporate real-time data assimilation [61].

In the regulatory context, global water stress assessment is well established, and the use of indices such as the WEI+ and SDG Indicator 6.4.2 can be considered a relatively common practice. Conversely, to the authors' knowledge, approaches specifically dedicated to the assessment of groundwater stress have not been implemented yet, revealing a policy gap.

To address this lack of standardization, we believe that the policy gap should be addressed by starting simply. Among available groundwater data, direct measurements of groundwater level are the most reliable, as they avoid all modeling uncertainties. Therefore, given its ease of implementation, the SGI could become the first standardized groundwater stress index to be adopted in policies. Indeed, a dense cloud of monitoring wells is necessary to ensure homogeneous, reliable, and robust monitoring networks. Undoubtedly, establishing such networks requires a significant financial investment, which might represent a difficult obstacle to the improvement of data availability in the coming years, especially in low-income regions. To address this, community engagement and citizen science initiatives could be the key to accelerate the process. For instance, at least for unconfined aquifers, existing domestic wells could be incorporated into participatory monitoring programs, greatly increasing data availability. As a result, time series (or seasonal measurements at least) of SGI could be collected and would allow for concrete actions in groundwater protection. Starting from here, a gradual shift toward more comprehensive indices may support more robust groundwater governance, promoting water reuse and conservation and preventing overexploitation—for instance, by implementing changes in irrigation practices, promoting MAR, or migrating crops with higher water demand to more resilient aquifers.

Author contributions

CRediT: **Alessia Amendola**: Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing; **Tiziana Tosco**: Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing; **Alessandro Casasso**: Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing; **Rajandrea Sethi**: Conceptualization, Methodology, Supervision, Writing – review & editing.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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