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Proposal of Groundwater Governance Indexes: Application to Nine Spanish Aquifers

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Abstract

Groundwater management and governance have properties related to the long renewal time, evapo-concentration processes in the soil and interaction with the rock, and dispersion, mixing and degradation of possible contaminants. Groundwater is part of the hydrologic balance, with specific properties and different behaviours from that of surface water, although there are interconnected. These differences also appear in other aspects related to economy, society, norms and administration, and to water ethics and morality. These differences are not always taken into account by water managers and decision makers. A methodology is being used to evaluate quantitatively groundwater management and sound governance. A score of themes are classified into aspects and categories, including hydrogeological knowledge, administration and socio-economics aspects. Three indexes are presented, the most developed of them correcting reserve depletion, unavoidable discharges and legal restrictions. The proposed indexes were tested in nine pilot areas in Spain, representing different circumstances, scales and environmental conditions. The discussion refers to aquifers and aquifer systems, considering the corresponding groundwater bodies and their quantitative and chemical status. It is not possible to condense the reality into one or a few figures. Comparisons have to be considered cautiously as a broad guide, with possible notable deviations, especially considering the groundwater average renewal time. There is not a well-defined correlation between groundwater management - governance evaluation and groundwater body's status, but they have some common aspects that are relevant to improve groundwater management and governance.

Keywords Groundwater Governance Indexes · Water Management · Semiarid Stressed Areas · Groundwater Average Renewal time · Spain

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1 Introduction and Objectives

The dramatic worldwide development of groundwater is a fact, especially in arid and semi-arid areas with good conditions for irrigated agriculture, where surface water is scarce. This development was occurred mostly since the mid-20th century. Currently groundwater is a very relevant source of water for human needs, competing with its important role in nature and as a generator of ecological services to humanity. In water scarce areas, groundwater exploitation should be integrated with other water resources, sometimes with a complementary role. Often groundwater has a dominant role, depending on local circumstances, management goals and pluviometry, especially in the case of droughts or recurrent seasonal constraints.

Groundwater abstraction often interferes with nature and surface water resources. This interference can sometimes be positive, such as favouring land drainage, although it is often negative and leads to the depletion of groundwater reserves and impairment of water quality, including salinization.

Groundwater science and the technology for groundwater exploitation, monitoring, integration and management, are well-established. However, as groundwater cannot be directly seen, it often goes unnoticed by most citizens, water managers, administrators and users, which sometimes hold misconceptions about the existence and functioning of aquifers (UNESCO 2022).

Groundwater is an essential component of the water balance, but it behaves differently from surface water. This difference is not only hydrological, but also encompasses economic, social, administrative, legal and ethical issues. Groundwater has a slow renewal rate, is subjected to evapoconcentration during diffuse recharge and can present chemical interaction with minerals.

Aquifers and aquifer systems can be defined according to their hydrogeological properties and constraints. However, the concept of a groundwater body is currently used in water administration and water planning in the European Union states, as stablished in the European Water Framework Directive. Groundwater bodies are defined according to administrative convenience, although trying to preserve hydrogeology as much as possible. In this work, the concept of aquifer and aquifer system is preferred, among other reasons, because it provides a broader view by considering both the unsaturated and the saturated zone.

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As compiled by Akbar et al. (2022), numerous indexes have been defined to assess groundwater sustainability, scarcity and stress (Gleeson et al. 2012; Zeng et al. 2013; Sanginabadi et al. 2019; Somaratne 2019; Gomez and Pfister 2012; Wada and Heinrich 2013; Nayyeri et al. 2020). These indexes include terms such as groundwater abstraction, groundwater levels, natural and irrigation returns recharge and those involved in groundwater footprint. Groundwater quality aspects are seldom considered (Kourgialas et al. 2018) and only Jia et al. (2019) include economic data. Nevertheless, groundwater management and governance aspects have not been considered in these indexes.

The aim of this paper is to present groundwater governance indexes that help in comparing different groundwater systems, considering aspects listed by Foster et al. (2009). This new and innovative methodology allows to evaluate the degree of water stress, management and sound governance of groundwater in aquifers and aquifer systems, with especial regard to arid and semiarid areas, which can be used to compare cases, taking into account as much as possible scale and characteristics of water use. These indexes are tested in nine reference cases in peninsular and island aquifers in Spain, covering a wide range of situations. A second objective is to derive general comments on aquifer management and governance taking advantage of the extensive review of written and oral information.

1.1 The Concept of Governance and Groundwater Governance

Governance can be defined as the rules of political systems, (a) to resolve the conflicts among stakeholders and make decisions (legal perspective), (b) to ensure the appropriate functioning of institutions, with public acceptance (legitimation perspective), and (c) to achieve consensus through democratic ways (sharing perspective).

Sound governance is a kind of governing model that differs from public administration control, as there is greater interaction between the state administration and stakeholders and cooperation among stakeholders, by means of decision-making organisations. Governance is a multifaceted concept that includes many points of view: hydrological and ecological sciences, economics, social welfare, legal and institutional aspects, policy and inter and intra-generational solidarity (Llamas et al. 2007).

Governance has the capacity to create processes through which the community develops its own rules as the social basis, and the connections with the different actors involved in governance. Science and technology are needed and help to show options and alternatives, but they do not dictate the path to be followed. This responsibility lies with individuals and implies political decisions.

Groundwater resources can be considered a classical example of common pool resource. Their collective management is the most basic form of decentralized management with possible co-management, monitoring and control shared between the water administration and stakeholders. Groundwater governance is the process through which groundwater is managed in accordance with the legal framework. International organizations, especially FAO and UNESCO, with the GEF (*United Nations Global Environmental Facility*) support, as well as the OECD, have given special attention to groundwater governance.

After GEF (2015), groundwater governance has four components: (1) A legal framework, (2) Comprehensive and shared knowledge of groundwater systems, (3) An institutional framework that includes leadership, good organization, ability to involve stakeholders, and functional mechanisms to coordinate groundwater with other sectors, and (4) Policies, incentives and plans that align with the goals of society. Essential issues are protection of groundwater dependent ecosystems and long term vision (FAO 2015; Varady et al. 2012).

Groundwater governance must consider the environment and the services it provides, the scale of the problem, the implications at a larger scale, the economic, social and administrative framework, policy goals, traditions and local customs, and ethical and moral principles of management. Uncontrolled groundwater development has led to serious social and environmental problems, which include reserve depletion and water quality impairment, but there are some social benefits. Other considerations refer to the fact that groundwater is not visible. It flows through wide territories and down to great depths, with a 3-dimensional pattern, and it transports and discharges large quantities of solutes. Groundwater is linked in quantity and quality to surface water, depending on the type of aquifer and exploitation status. Groundwater residence (renewal) time is commonly much longer than one year. Groundwater knowledge involves uncertainty, although not ignorance. Monitoring groundwater is expensive and specific, and its contamination is slow and often of difficult and costly reversal. For damage correction to begin and management to be implement, some degree of degradation has to became evident and be recognized by the water administration and stakeholders. However, when groundwater shows signs of general contamination, the process is often advanced and difficult to stop, as it involves large volumes. Therefore, early warning systems are needed, derived from adequate monitoring systems and data analysis.

Some of the main barriers to sound groundwater governance are poor knowledge, regulator malfunctioning, unawareness that groundwater is a common pool resource, lack of leadership, authoritarian attitudes of public water administration, and political interference.

1.2 Groundwater Governance Evaluation

Groundwater governance indexes should be free of bias and subjectivity and should address both actions and solutions, including failures. In principle, indexes help in water planning and finding solutions to problems. These indexes are mostly relative values, not absolute ones. Therefore, to make possible comparisons, a norm has to be used.

Each case is singular. Actions and evaluations must be tailored to each case. While there is the possibility of finding commonalities among cases that can be used to fill gaps, similarities must be carefully established and used cautiously.

Good indexes, if available, help simplify water administration. However, existing experience assigns them a low intrinsic value, and its indiscriminate use may be an excuse to void responsibility or conceal poor knowledge. It should be noted that a groundwater index refers to a given scale and it may change when it refers to a wider scale, as then it integrates other considerations. Furthermore, groundwater quantity issues are simpler than groundwater quality issues and incorporating water quality into indexes may be complex and difficult, if feasible at all.

It is impossible to condense the large complexity of the real world –in this case, aquifers- into a single or a few figures. However, existing approaches are useful for comparisons and classification, if used with caution, although they should not be used for decision-making.

2 Methodology to Set a Groundwater Governance Index

2.1 General Considerations

The proposal of methodology to establish a groundwater governance index is based on selecting a set of topics to be evaluated according to a scale of scores, with weighting factors if needed, and a rule to aggregate them.

FAO (2015) mentions a non-categorized list of topics related to groundwater. Foster et al. (2009) classified them in four groups of criteria, containing 20 topics: (1) technical, (2) legal and institutional (3) inter-sectoral coordination policy, and (4) operational.

The present groundwater governance index builds on previous experience and is adapted to common situations of semiarid, water-stressed areas with favorable conditions for intensive agriculture, with particular focus on peninsular and insular Spain. It expand on aspects that go beyond hydrogeological science and technology.

2.2 Topics to be Evaluated

The list of criteria is presented in Table 1, with various aspects and diverse topics, designed to assign a score that increases the more positive is the answer. This list is limited and in some cases, relevant data are not included.

A numerical score must be assigned to the different topics, according to: 1 No, inexistent or not interesting; 2 Incipient, only as a preliminary approach, poor influence; 3 Partial, insufficient; 4 Can be improved, good as a first approach; 5 Yes, satisfactory, sufficient.

2.3 Integrated Valuation

In European water planning it is often used the exploitation index, EI, as in Spain. For groundwater, GWEI = B/R, where B = total yearly abstraction and R = total annual recharge of the aquifer or area considered. B includes pumping and other abstractions through water galleries (tunnels) and drains to get groundwater or to control the water table in fields, civil works and houses. R is not an aquifer property as it changes with the exploitation status of the moment, especially in aquifers linked to rivers and with water inflows and outflows through the boundaries. When groundwater is not exported and used in the area, return irrigation flows, and storage and transport leakages contribute to R, sometimes significantly and even dominantly, especially when water is imported. The GWEI varies from ~ 0 when groundwater exploitation is very small to >1 when there is depletion of groundwater reserves.

The GWEI does not represent well the system water stress, as it does not take into account neither the aquifer outflow to the sea or to continental water bodies, nor the progressive groundwater depletion, nor the effects on ecology, water quality and water use that have to be protected through legally established discharge thresholds. Therefore, the GWEI has been changed to corrected exploitation indexes taking into consideration what has been said above, at least as an approach. They refer to a given moment in the aquifer or other territorial space considered. Indexes may not be clearly defined conceptually and include uncertain terms. They are introduced below for groundwater:

1. -Simple exploitation index: GWSEI = B/R.
2. -Extended exploitation index: GWEEI = (B + D)/R; D = unavoidable discharge naturally produced under a given exploitation of the aquifer and not considered in R. D includes unaccounted groundwater evaporation in shallow water table aquifers, discharge in subsisting springs, and the outflow to the sea or to a large surface water body, plus the imposed discharge after legal regulations.
3. -Water stress index: GWSI = (B + D)/(R - V), where V = yearly groundwater reserves depletion, which can be considered a decrease of recharge. V is relevant in the case of sustained large depletion of groundwater levels and groundwater mining. V is negative in the case of a sustained groundwater level recovery after a period of intensive abstraction.

Table 1 Criteria (in bold), aspects (underlined) and topics (normal) considered to calculate the proposed indexes

1 Basic hydrogeological knowledge
1.1 Quantity of the aquifer system
1.1.1 Availability of hydrogeological and supporting geological mapping
1.1.2 Sufficient delimitation of hydrogeological units
1.1.3 Availability of good piezometric monitoring, both in space and time
1.1.4 Availability of hydrogeological recharge data and water balance information
1.1.5 Existence of operative groundwater flow models
1.2 Quality of the aquifer system
1.2.1 Availability of water quality and vulnerability-to-contamination maps
1.2.2 Sufficient and adequate quality monitoring
1.2.3 Information on soil and unsaturated medium characteristics
1.2.4 Existence of sufficient and operative groundwater quality and mass transport models
1.3 Knowledge of groundwater resources
1.3.1 Adequate knowledge of existing springs, wells and boreholes
1.3.2 Knowledge and quantification of abstractions and drainage flows
1.3.3 Knowledge of groundwater use
1.3.4 Knowledge of groundwater abstraction costs
1.3.5 Knowledge and monitoring of effects of groundwater exploitation
2 Administrative, legal and economic-social issues
2.1 Administrative aspects
2.1.1 Adequate system to inventory and record groundwater abstraction permits
2.1.2 Control of groundwater abstractions and survey of illegal and unauthorized extractions
2.1.3 Effective surveillance of potentially contaminant activities affecting the aquifers
2.1.4 Effective land surveying
2.1.5 Expert and sufficiently doted groundwater administration
2.1.6 Ability to tax any kind of groundwater abstraction
2.1.7 Ability to tax any kind of contaminant activity affecting groundwater
2.2 Legal aspects
2.2.1 Compliance of groundwater with legislation
2.2.2 Efficient systems to solve conflicts through the courts
2.2.3 Effective enforcement of penalties for non-compliance or illegal actions
2.2.4 Past and present prosecution of quantity and quality abuses
2.3 Social-economic aspects
2.3.1 Recovery of costs associated with the negative effects of groundwater exploitation
2.3.2 Application of tax revenues to benefit users and the aquifer
2.3.3 Existence of social conflicts among stakeholders and the general population
2.3.4 Adequate financing for monitoring, studies and data elaboration
2.3.5 Direct and indirect subsidies to improve use and sustainability
2.3.6 Willingness of users and population to pay in exchange for improvements
3 Management and sound governance
3.1 Aspects related to groundwater management
3.1.1 Existence of an organisation responsible for management
3.1.2 Availability of expert human resources and economic means for management and monitoring
3.1.3 Existence of user associations participating in water management
3.1.4 Effective partnership with users in monitoring
3.1.5 Consideration of groundwater in water security
3.1.6 Consideration of integrated water resources management
3.1.7 Proposals for sustainable groundwater use to mitigate droughts

Table 1 (continued)

3.1.8 Water planning for infrastructural management
3.1.9 Water planning for non-infrastructural management, with noticeable effects
3.1.10 Water planning free from over-concession of groundwater rights
3.1.11 Water management within the framework of user-agreed restrictions
3.2 Aspects of groundwater governance
3.2.1 Participation of civil society institutions
3.2.2 Ability of the management organisation to coordinate with other plans
3.2.3 Effective coordination with the agriculture sector
3.2.4 Specific and integrated water planning compatible with sound governance
3.2.5 Easy access and transparency of information
3.2.6 Information made accessible and understandable to non-experts
3.2.7 Existence of an independent institution to evaluate moral and ethics considerations
3.2.8 Consideration of territorial and time equity in groundwater access
3.2.9 Existence of an institution to ensure and preserve sound governance
3.2.10 Minimization of political and unions' interferences

In the cases where the area receives other water resources, such as imported water, seawater desalinated water or reclaimed water, water stress refers to the integrated system. Therefore, the GWEI does not characterize the aquifer and it is only an indicator of possible ecological, quality or geotechnical physical or legal problems. Taking into consideration these effects, the GWEI can be nuanced by appropriate weighting.

The different indexes, normalized to values from 1 to 5 are given in Table 2.

The valuation consists of scores that are identified by three digits: i (criteria, 1 to I), j (aspect, 1 to J), and k (topic, 1 to N), and 5 options in each section, designed 1 to 5. In what follows, valuations are not weighted according with the assigned relevance. If needed, the weighting can be easily done.

To obtain an integrated final value, the average values (m) of each grouping of topics and aspects are calculated. For the topic groupings, variability (σ) is taken into account by means of a coarse estimation of the standard deviation. A homogeneous group has a small (close to 0) coefficient of variation (CV = σ/m) and then m is appropriate. However, in case of a large CV, it is assumed that m – σ is more appropriate to represent the score. To coarsely estimate σ, the procedure is, (a) delete the maximum and minimum values, (b) determine the maximum difference, (d) among the remaining scores, and (c) take σ = d/2, with only a decimal figure and rounded down to the nearest lower value.

The calculation procedure is as follows:

$$\text{Value of aspect ij, } v_{ij} = m_{ij} \text{ or } v_{ij} = m_{ijk} - d/2$$
$$\text{Value of criteria I, } v_i = m_i \text{ for } v_{ij} = m_{ij} \text{ or } v_{ij} = m_{ijk} - d/2 \text{ without the variation}$$

Gross value of governance: $g = m_i$ for the two values of criteria, without the variation.

The gross value of governance does not consider the exploitation state of the aquifer. A small value for a scarcely exploited aquifer with good quality water can indicate sound governance, as there is no need for special actions. However, a low value for an intensively exploited aquifer indicates poor governance.

The average p has been introduced to nuance the water stress and security, being used to calculate the correction factor (f) of the governance value, as indicated in Table 2. Finally,

Table 2 Calculation of normalized water stress indexes for the aquifer or aquifer system

	Range	Formula	Comments
Normalized indexes			
Simple exploitation index i=B/R (0 to >1=1)	1 to 5	GWSEI=1+4i;	If>5 is =5
Extended exploitation index i= (B+D)/R (0 to >1=1)	1 to 5	GWEEI=1+4i	If>5 is =5
Water stress index i= (B+D)/(R-V) (0 to >1=1	1 to 5	GWEI=1+4i	If>5 is =5
Nuancing terms			
Effects on usable water quantity discharge	1 to 5		
Effects on usable water quality discharge	1 to 5		
Effects on ecological conditions	1 to 5		Including discharge to the sea and in the continent
Effects on water availability for supply	1 to 5		Urban, tourist and industrial water supply
Effects on water availability for agriculture	1 to 5		Drying up of agricultural wells
Negative geotechnical effects	1 to 5		Subsidence, sliding and others
Integration			
Average of the nuancing terms (p)	1 to 5		Without correction for dispersion of values
Correction factor	1 to 2	$f = (9 - p)/4$	With modifying terms
Corrected water stress index	1 to 5	CGWEI=f·(B+D)/(R-V)	

Indexes cannot be applied in the case of integrated water resources. Values range from 1 (no, non-significant) to 5 (high). B = abstraction; R = recharge; D = unavoidable discharge; V = yearly depletion of reserves

a Corrected groundwater stress index (CWSI) can be derived from the Groundwater stress index (GWSI) and this correction factor (f).

The evaluation of water stress refers to water quantity, which is the dominant aspect in arid and semiarid areas at early times. Therefore, this is a partial point of view and often insufficient, as salinity and quality are key aspects as well. They are susceptible of impairment, which can be difficult and costly to repair. This issue is not included in this work. It is difficult to devise a water stress index for quality, which requires knowledge of the natural quality and the use of abstracted water, as each use has its own requirements.

3 Pilot Areas on which the Groundwater Governance Index is Tested

The proposed groundwater governance index and the related indexes refer to a well-defined territory. To test the application to real cases, several territories in Spain were selected as pilot areas. They are hydrologically, administratively, and institutionally well-defined groundwater management systems in the water plans, aquifer, aquifer systems or groundwater bodies. From an institutional point of view, a small territory may be part of a larger territory with existing institutions capable of supporting groundwater governance. However, in small territories, there is the possibility of institutions to support local aspects of groundwater governance, generally by statutory delegation of a higher-ranking institution.

The information on the pilot areas derives from existing publications and available reports, mostly related to the water plans of the basin authorities, academic studies, presentations at meetings, the experience of the authors and the comments from reviewers. Not all needed information is equally accurate and sometimes is estimated. No specific complementary studies have been carried out, but the information has been partially completed through oral and written notes from experts based on a previous text prepared by the first author.

As the compilation of data is a slow and arduous process, only nine pilot areas were selected, aiming to cover a wide rank of circumstances. Complex and politically sensitive areas in peninsular and island Spain were discarded to avoid biases. The selected areas are compiled in Table 3 and their location is shown in Fig. 1.

Table 3 List of selected pilot areas to evaluate groundwater governance

1	Baix Llobregat (Barcelona, Internal Basins of Catalonia)
	Intensively exploited small aquifer system in a large metropolitan area. Integrated water resources management, managed recharge and exploitation, and good institutions. Problems with water quality.
2	Campo de Cartagena and Mar Menor (Murcia, Segura Basin)
	Intensively exploited aquifer system with groundwater mining, salinization and water quality problems due to intensive agriculture. Emblematic coastal lagoon with significant degradation. Water transfer.
3	Campo de Dalías (Poniente almeriense, Almería, Mediterranean Basins of Andalusia)
	Intensively exploited aquifer system with groundwater mining, seawater salinization and incipient water quality problems due to intensive agriculture.
4	Cuenca del Bérchules-Careos de Sierra Nevada (Granada, Mediterranean Basins of Andalucia)
	Small managed aquifer since ancient times to make possible seasonal groundwater by recharge enhancement in channels. Small population bordering a Natural Park.
5	Tenerife (Canary Islands)
	Volcanic aquifer system. Unsustainable groundwater development through water galleries. Continuous depletion of reserves. Groundwater trading. Agriculture, tourism and urban supply, combined with industrial water production: seawater, brackish groundwater desalination and reclaimed water reuse.
6	Gran Canaria (Canary Islands)
	Volcanic aquifer system. XX Century groundwater development mainly with deep wells. Spring desiccation. Groundwater trading. Agriculture, tourism and urban supply, combined with industrial water production: seawater, brackish groundwater desalination and reclaimed water reuse.
7	Parque Nacional de Ordesa y Monte Perdido, PNOMP (Huesca, Ebro Basin)
	Carbonated aquifer system almost in a natural state, but at risk of drought effects. National Park. Very small population.
8	Alto and Medio Vinalopó (Vinalopó Basin, Júcar Basin) and neighbouring Altiplano of Murcia (Segura Basin).
	Carbonate aquifers of southeaster Alacant (Alicante) and shared aquifers with the neighbouring Segura Basin. Intensive exploitation, including groundwater mining and water transfer.
9	Medina del Campo (Valladolid, Duero Basin)
	Groundwater body in a detritic aquifer system. Intensively exploited for agricultural irrigation. Water quality problems.

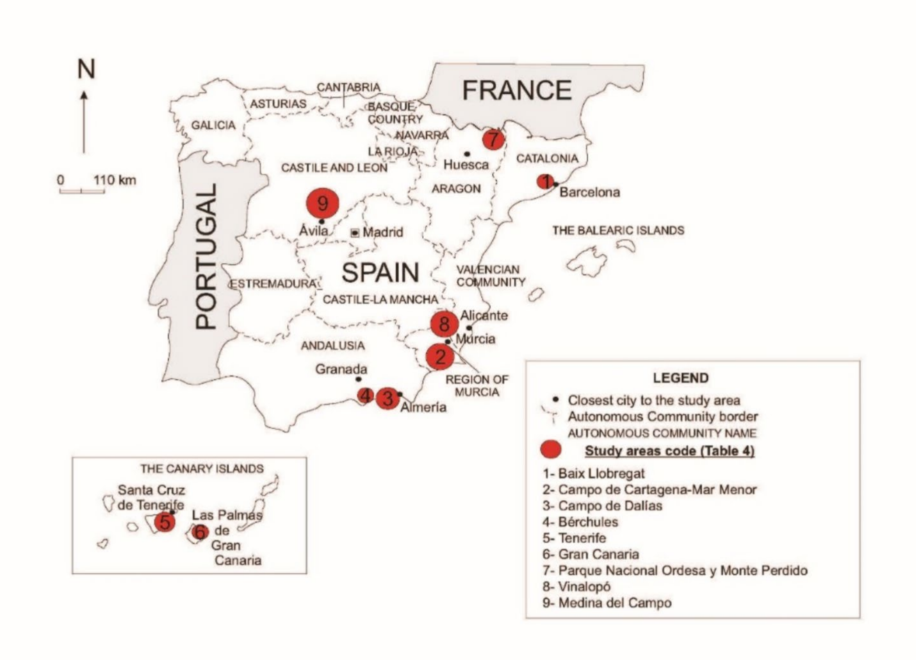

Fig. 1 Approximate emplacement of the nine pilot areas

Table 4 shows the main characteristics of the pilot areas and the different calculated indexes referred to the current situation (EGASE 2022). The focus is quantity of groundwater resources, and only secondarily to groundwater quality and ecology.

4 Comments to the Summary of Results

Despite the numerous topics considered and valued, along with a wide spectrum of viewpoinqts, it is not possible to obtain a sufficiently accurate representation of the complex reality of a given case and its dynamics when expressing results as a single figure. Therefore, the ranking by index is at most indicative.

The results may reveal paradoxes that arise from an unsound consideration of the aquifer renewal time, salinity and hydrochemical composition. For example, a low water stress level is calculated in the small Bérchules basin, when in reality there is significant water stress in summer, when river flow ceases at the basin outlet, despite the increased recharge contributed by the “careo” channels. In this case, yearly results are of little practical interest for assessing the groundwater body status.

A high water stress index is commonly associated with bad quantitative status. However, there are exceptions, as explained above for the Bérchules basin. The Parque Nacional de Ordesa y Monte Perdido (PNOMP) has a yearly good quantitative status, which does not reflect the moderate water stress during the summer period, dependent on diffuse recharge from snowmelt. Some moderate seasonal water stress during the summer months, is a com-

Table 4 Summary of data on the main characteristics of the pilot areas and the approximate values of the calculated indexes, giving the average value and the bias-corrected value

Concept	Baix Llobregat	Campo de Cartagena-Mar Menor	Campo de Dalías	Bérchules	Tenerife	Gran Canaria	PN Ordesa-Monte Perdido	Vinalopó	Medina del Campo
Province	Barcelona	Murcia-Alicante	Almería	Granada	Sta. Cruz de Tenerife	Las Palmas	Huesca	Alicante-Murcia	Ávila
River basin district	CICatalonia	Segura	CMA	CMA	CIATF	CIAGC	Ebro	Júcar-Segura	Duero
Surface area km^2	16,438	19,025	17,952	17,962	2034	1560	85,634	42,756	98,400
10^3 inhabitants	7097	1976	1305	1305	928	860	3193	5506	2205
Pilot area	coastal	coastal	coastal	interior	island	island	inland	inland	inland
Surface area km^2	156	1602	1037	68	2034	1560	157	1441	3700
10^3 inhabitants	800	430	230	0,8	928	860	0,05	224	130
Activity	S+I	A+T	A	E+A+T	S	S	E+(A)	A+S	A+(I+S)
Agriculture % GAV(2)	1	37	22	na	2	2	0	<3	na
Agriculture % GW	5	90	70(a)	90(b)	45(c)	80(d)	50(4)	80	na
Nº GWB	1	4	1	(1)	4	10	(1)	9+5c	1
τ, years(3)	4	10–20	10–20	0,5	20–30	20	0,02–3	10–30	
GW stress Index	**5.0**	**5.0**	**5.0**	**2.0(1)**	**5.0**	**5.0**	**1.9**	**5.0**	**5.0**
GW management Index	**4.3**	**1.7**	**1.7**	**2.9**	**2.7**	**2.3**	**3.0**	**3.2**	**1.7**
GW governance Index	3.5	1.9	1.7	2.8	2.6	2.3	2.9	3.1	1.9
Corrected GW governance Index	**3.5**	**1.9**	**1.7**	**4.9**	**2.6**	**2.4**	**5.0**	**3.1**	**1.9**

Table 4 (continued)

Concept	Baix Llobregat	Campo de Cartagena-Mar Menor	Campo de Dalías	Bérchules	Tenerife	Gran Canaria	PN Ordesa-Monte Perdido	Vinalopó	Medina del Campo
GWB quantitative status (5)	B	B	B	(B)	B	G + (B)	G	B	B
GWB chemical status (5)	B	B	G+B	(B)	G + (B)	B + (G)	G	B	B

B Bad, *G* Good, *na* Not available, *GW Groundwater* Groundwater resources, *GWB* Groundwater body, Activity: A = agricultural; S = services; I = industry; T = tourism; E = environmental, GAV = gross added (economic) value

(1) Low yearly water stress index, but water scarcity in summer, compensated through the "careos" recharge in Bérchules aquifer

(2) Contribution to the GAV as primary sector; figures greatly increase if contribution to the tertiary sector is included

(3) τ, GW renewal time

(4) Important role of non-concentrated cattle

(5) Groundwater status

a) exported for supply; b) mostly river water originated by natural recharge and "careos"; c) part of groundwater is for supply; d) most of groundwater is for crop irrigation while supply is mostly by seawater desalination mon situation in systems where the seasonal water demand is much greater than in the rest of the year.

The groundwater management index is relatively high in the Baix Llobregat and it is also relatively high in the Alto and Medio Vinalopó when receiving water from outside. In both cases, the existence of Groundwater Users Associations improves management, as they work properly. In the other cases, the indexes tend to be small (poor or insufficient management) or there is no enough investment or non-structural management.

The groundwater governance index is moderate in the Baix Llobregat and the Alto and Medio Vinalopó and Medina del Campo, although when corrected by water stress index, the evaluation improves. The index is low in the Campo de Cartagena-Mar Menor, Campo de Dalías, Tenerife and Gran Canaria. In the Mar Menor the eutrophication process is driving numerous research projects and the conceptual hydrogeological model of the Campo de Cartagena-Mar Menor aquifer and the nitrates monitoring network are being revised (García Aróstegui et al., 2023 and 2024). In the Campo de Dalías, the need for sustainability actions to preserve water quality against irrigation return flows and seawater intrusion is not taken into account. In Tenerife, the low index is due to the large proportion of groundwater that is inevitably discharged to the sea along the coast, as a large part of abstraction is done at medium and high altitudes by means of water galleries. With a framework of groundwater stress, Gran Canaria needs more transparency in the technical information and its continuous analysis to implement a truly more participative system.

The groundwater governance index calculated represents the case when groundwater is the dominant water resource. The consideration of surface water, groundwater and industrial water production as complementary resources changes the evaluations, which also depend on the year. Then, the numerical value obtained is inadequate for comparisons and water planning, as is the case in the Baix Llobregat, the Campo de Cartagena, and the Alto and Medio Vinalopó.

A correlation between the groundwater body status and the calculated indexes is not expected, although low management and governance indexes are often related to poor quantitative status. The chemical status also depends on external circumstances, such as the excess of nitrates in areas with irrigated agricultural activity and the salinization in very thick or coastal aquifers.

Possible future improvements in the design of indexes can be obtained by splitting the topics referring to the area in consideration from the topics relative to the wider area in which there are organizations with interests and viewpoints at a larger scale. Another improvement can be separating the quantity, quality and environmental aspects of the hydrological topics. It seems relevant to reflect in the water quality topics the evolution trend at mid-term evolution trend and the ability to modify the tendency. For a better and clearer evaluation of groundwater stress, it may be convenient to consider the role of the unsaturated zone of the aquifer in the renewal time of groundwater.

Climate change affects evaluations, as the mid-term average values are different from the past ones. It implies that the calculated indexes are representative of an area in a certain moment considering its hydrogeological history, but natural circumstances that affect recharge or exploitation can change in relatively short times.

5 General Comments

For this work, a large volume of published and grey information has been studied and synthesized, along with comments from experts. This is an important by-product, which in some cases may be more valuable than the calculation of the indexes. The considerations refer to Spain, especially to the water stressed areas, although similar considerations can be done for other countries in Europe and worldwide, irrespective of their economic and social development.

There is a growing understanding of the role and importance of groundwater in nature and as a water resource with specific characteristics, but this knowledge has not commonly permeated among groundwater users and the water administration. Currently, the situation seems to be worsening. This is reflected in a decrease of study and monitoring effort and in environmental protection efforts that can ignore the growing problems. Groundwater exploitation is often carried out without studies or knowledge of the water balance and with the assumption that these resources are unlimited. Soil and recharge processes are seldom known and considered. This causes and explains poorly devised decisions regarding groundwater resources and diffuse contamination by agriculture.

The slow pace of change in groundwater systems due to the large water storage relative to yearly recharge is not fully understood, and future changes are not considered a present problem; instead, it is assumed that the future will address this. To know and measure the evolution, water managers need clear signals derived from monitoring systems to start action. However, a good monitoring system is often not a current priority due to its cost and specific design. It is often not participated by users and data are not quickly synthesized in a way that is understandable by non-experts. The general concern is fulfilling apparently what is regulated while paying little attention to the accuracy of what is monitored.

Updated inventories of springs and groundwater abstractions are not fashionable nowadays and are usually not available, incomplete and prone to errors. New wells are frequently missing, either because they are illegal or because they are not registered. A serious handicap in the inventories is that only legal abstractions are considered, with no information about wells in other circumstances.

Managed artificial recharge is often a solution to increase the quantity and quality of groundwater resources, although feasibility studies are commonly lacking.

To solve groundwater stress in a given area, a frequent solution is to propose the transfer of water from outside. In many cases, the goal is to replace groundwater abstraction, but a local increase in water availability often results in more population and economic activity. This leads to increased recharge of shallow aquifers with return irrigation flows that causes contamination. These externalities are not considered until serious negative effects appear.

Diffuse groundwater contamination by agricultural practices, especially nitrate pollution and agro-sanitary chemicals may negatively affect agriculture. However, changes in concentrations from one year to another are a poor indication of their evolution and the implementation of limitations does not immediately lead to a reduction of concentration due to the recharge delay.

It should be noted that monitoring networks may not be adequate and samples do not always represent the aquifer conditions. In some cases, the sampling method and procedure condition affect the results, making them incomparable between campaigns or sampling points. This negatively impacts the data elaborated, both now and in the future. The same situation applies to piezometric data, although to a lesser extent.

Groundwater management is, in many cases, a new duty assigned to water administrations. Therefore, they do not have experience in groundwater management nor in dealing with the often-numerous stakeholders and sometimes significant complaints, and they also lack enough trained personnel. The poor political interest and commitment to addressing this issue explains the reluctance to implement improvements in water administrations. The reduced interest shown by the water administration towards groundwater often persists despite the well-developed use of groundwater by private and non-governmental entities. Consequently, water administrations often try to limit their action to the strict fulfilment of legal rules.

Obtaining a good status of groundwater bodies before 2027, as ruled by the European Water Framework Directive, is a challenging task. There is the possibility of obtaining less strict conditions if this is compatible with the general goals and the social context of laws when studies supported by sufficient reliable data are conducted. However, the proposal of such reductions often lacks the support of adequate hydrological, environmental, social and legal studies. These proposals appear to be an attempt to shift the responsibility for achieving good status under current requirements and externalities to future water administration. Complaints and fines are preferred over a sound consideration of the problem. Besides, there is no political wills to launch structural and non-structural actions, which are often unpopular, and whose benefits may only be realized to future administrations. Bold proposals to the European Union are missing, partly to maintain a favourable image and partly due to the difficulty of justifying proposals when knowledge and data are insufficient.

Mountain block-depression aquifer systems are common in the mountainous Spanish territory, and enable the implementation of dual aquifer management strategies, including full protection in the mountains and headwaters, and less strict requirements in basins that do not transfer water to down flow concerning aquifers, water bodies and wetlands.

Aquifers are not only a source of water resources, but also serve as natural infrastructures to store, transport, treat and regulate water resources, as well as to control water quality. Aquifers are an alternative to artificial water works, often at a lower cost and less environmental impact. However, they are managed differently, requiring studies and monitoring that are more complex, and out of sight, making them politically unattractive to society. This is not new, but it is insufficiently addressed in water regulations. There are examples, mainly driven by non-official initiative. Water regulations are often an obstacle to good groundwater management and may contain unrealistic rules, usually designed and oriented toward surface water. The use of aquifers as natural infrastructures is not explicitly considered in the European Water Framework Directive, which tends to oppose this use based on environmental restrictions that could be relaxed without causing further degradation. There are no initiatives from the European Union members to modify the regulations to facilitate possible the use of aquifers as natural structures.

Spanish water regulation gives excessive authority to the Water Administration, leading to an ambiguous attitude among stakeholders toward administration. Some stakeholders cooperate, but others remain passive, expecting the water administration to take all actions necessary to sustain and protect the use and quality of the resource. Farmers, in particular, often oppose the proposed solutions.

It is currently recognised that good groundwater management required the participation of users and stakeholders, as well as other sectors of the public administration, economy and society. However, this participation is often the result of mere compliance with legislation, but with poor implementation. The result is the involvement of individuals and associations in consulting committees, without any real influence on decision-making. True participation is still a rarity.

Groundwater users' associations are needed for sound groundwater governance. They are supported by legislation. However, the implicit stance of the water administration often perceives these users' associations as undesirable, as they resist transferring some power and are seen as competitors that the administration cannot fully control. This has been observed in water stressed areas, where groundwater users' associations promoted by the Spanish water administration in compliance with legislation have not been effective, except when created solely to manage economic resources provided by public funds. In contrast, groundwater users' associations created independently by groundwater users are much more effective, especially when the number of possible stakeholders is small.

Water trade refers primarily to water quantity in arid and semiarid areas, especially when groundwater was historically part of the private domain. Currently, groundwater is classified as public domain, and abstraction is generally the result of permits and concessions from the water authority. This framework often prohibits water trade outside of well-regulated public transactions. A notable example of groundwater trade, involving both water and rights, can be found in the Canary Islands, a legacy of the region's former system of private groundwater ownership. However, in highly water stressed areas, unregulated and illegal groundwater trade of permits and water still occurs. The water administration is often powerless to address this issue due to insufficient resources or political pressure.

6 Conclusions

It is impossible to condense the complexity of a real case into an index of sound groundwater governance for an aquifer. To develop an index with quantitative meaning and practical utility for comparisons, various aspects must be taken into account, including hydrologic, hydrogeological, economic, social and administrative aspects. To improve the index's relevance, circumstances such as inevitable groundwater discharge to other aquifers, administrative restrictions and changes in reserves (depletion or increase) have to be taken into account. Nevertheless, the result carries some uncertainty, so comparisons among different cases are not absolute.

The proposed methodology is applied to nine pilot areas of Spain, covering a wide range of scales and circumstances, and corrections enhance comparability.

There is no definite relationship between the groundwater governance index and the groundwater status defined after the European Water Framework Directive, although areas with high water stress and low index tend to correspond to bad status. The index primarily addresses water quantity. Considering water quality in an index is more challenging and has not yet been attempted.

A large volume of information and data is required, along with expert evaluations. A by-product is the identification of general communalities in groundwater management. In Spain, the water administration often makes decisions independently of stakeholders, so stakeholders and users are not adequately involved in groundwater governance and tend to be ignored or utilized primarily to compensate for the scarce human resources of water administrative bodies.

Groundwater monitoring may be sufficient in terms of the number of points, but data obtained are often not representative and sometimes even inaccurate. Efforts to improve monitoring often focus on increasing the number of observation points rather than ensuring better placement or obtaining higher-quality data. Monitoring data require more robust and efficient processing, and the results should be available to stakeholders.

Short-term water policies are not accompanied by mid- and long-term perspective, with frequent political interference, resulting in “Short-term gain, long-term pain”.

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