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Groundwater Ecosystem Services: Redefining and Operationalizing the Concept

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Abstract: In the last decade, the publication of research studies in the field of groundwater ecosystem services and their classification has increased dramatically. Several academic and other institutions have developed ecosystem service classification systems for use in environmental policy research. However, the existing classification systems need to be optimized in the following areas: (a) the weak correlation between concepts and the definitions assigned, which creates double counting in economic valuation, (b) the absence of correlation of the concept of use value with the ecosystem service, (c) the non-categorization of final and intermediate services, and (d) the overlapping of wetland, soil, and groundwater regulating ecosystem services. Our research aims, through the results of a literature analysis and the synthesis of the results of an expert consultation process, to develop a unified categorization system for groundwater ecosystem services. In the context of the conceptualization of groundwater ecosystem services, this research implemented an expert judging elicitation process where subject discussions and targeted interviews were performed, combined with a literature review analysis. Through the completion of a specific questionnaire and expert interviews, a new groundwater ecosystem services classification system, namely GROUNDWES, was established.

Keywords: groundwater; ecosystem services; expert judgment

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1. Introduction

Ecosystem services are the benefits derived from ecosystems that directly impact human well-being and are intimately linked to the functions, processes, and structures of the underlying ecosystems [1]. The conceptualization of ecosystem services dates back to the 1980s, but it was the Millennium Ecosystem Assessment [2] that brought to the forefront the critical connection between human well-being and ecosystems. This pivotal moment catalyzed research and spurred efforts to classify and categorize ecosystem services, as more than 60% of these services were found to be deteriorating or changing, impacting present and future generations [2].

Since then, ecosystem services research has evolved significantly, progressing from theoretical conceptions to real-world applications [3–5]. Supported by initiatives like The Economics of Ecosystem and Biodiversity [6], the UK National Ecosystem Assessment [7], and European Union research programs, as well as modeling tools like the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST®) [8], ecosystem services' valuation has emerged as a practical means to mitigate ecosystem decline and climate change impacts [9].

While numerous Payment for Ecosystem Services (PES) programs worldwide address various challenges, such as carbon sequestration, conservation easements, biodiversity conservation, and watershed protection, they often rely on integrated modeling. These models simulate complex systems, incorporating multiple ecosystem services and considering factors like land use, resource utilization, commodity prices, and climate change [10].

However, validating the outputs of integrated environmental models (IEMs) remains a significant challenge, leading to calls for a more robust handling and reporting of uncertainty throughout the modeling process [11,12].

Despite these advancements, groundwater ecosystem services, specifically those related to the saturated zone, present unique challenges and have not received the attention they deserve. Existing classifications and integrated valuation models do not fully align with the complexities of aquifers and groundwater ecosystems. Recognizing these gaps, our research endeavors to bridge them by formulating a systematic classification system exclusively for groundwater ecosystem services within the saturated zone. Specifically, our research aims to address the weaknesses identified in the current literature's classifications of groundwater ecosystem services. To achieve this, we conducted extensive surveys and interviews with groups of experts. By analyzing the results, we developed a new classification system tailored specifically to groundwater ecosystem services. This new system seeks to advance the understanding and classification of groundwater ecosystem services and categorizes these services as either final or intermediate, providing a more comprehensive and relevant framework for economic valuation and management policy research.

2. Ecosystem Services' Classification Systems

The profound dependence of humanity on nature for its survival and well-being has been a constant throughout the history of civilization. From the earliest days when individuals sought resources and shelter from the elements to the dawn of agriculture and animal husbandry, which allowed for a more direct manipulation of nature's services, humans have recognized the intrinsic value of what we now refer to as ecosystem services. Historical examples, such as the ancient Greeks' understanding of soil retention and the plight of Easter Island's population, illustrate the consequences of neglecting the importance of healthy ecosystems [13].

Diamond [14], in his 2005 book, chronicled how societies throughout history disregarded the value of healthy ecosystems, leading to their eventual decline. These losses encompassed critical aspects of well-being, including habitat loss, soil retention, biomass production, and water regulation, among others. The concept of "ecosystem services" has gained prominence in recent decades, highlighting the intricate connections between human welfare and ecological systems [15]. However, the literature on ecosystem services struggles to provide a standardized definition. Various interpretations have emerged, leading to differences in terminology and understanding [16,17]. Three commonly used definitions include ecosystem services as (1) the circumstances and mechanisms through which ecosystems and their species sustain human life [18]; (2) the benefits obtained from environmental activities, either directly or indirectly [15]; and (3) the advantages derived from ecosystems for human well-being [2]. These definitions, while highlighting the consensus on the concept, also underscore the variations in its interpretation.

With increasing research on the linkages between ecosystems and human welfare, the need for a robust classification system for ecosystem services has become apparent. Different classification systems have emerged in the literature [19,20], many of which were developed within the framework of The Economics of Ecosystems and Biodiversity [6] and derived from the Millennium Ecosystem Assessment [2]. The Common International Classification of Ecosystem Services (CICES v5.1), the most recent version of which is represented by Haines-Young and Potschin [21], strives to establish international consensus on ecosystem service evaluation. CICES offers a high level of detail, categorizing ecosystem services into three levels: "provisioning services," "regulatory and maintenance services," and "cultural services." It serves as the reference classification system for internationally recognized instruments like the System of Environmental-Economic Accounting (SEEA) [22].

Despite these efforts, inconsistencies persist in the framework development for ecosystem services research and policy evaluations. Multiple conceptualizations, definitions, and classifications have led to a lack of clarity in the terminology and application of ecosystem services [23]. These discrepancies blur the lines between intermediate and final services and hinder accurate classification. While CICES has emerged as a critical framework, it is evident that ambiguity in the ecosystem services landscape must be resolved to create a more rigorous and universally applicable framework. In light of these challenges, our research aims to contribute to the development of a comprehensive and standardized classification system for ecosystem services, fostering a more cohesive and transparent approach to evaluating ecosystems at both national and global levels.

3. Groundwater Ecosystem Classification Systems—Some Remarks on Existing Research

Groundwater is the water found beneath the Earth's surface in the pores and crevices of soil, sediment, and rock formations. It constitutes one of the Earth's essential freshwater resources and plays a crucial role in supporting ecosystems, providing drinking water, and sustaining various human activities such as agriculture and industry. Groundwater originates from the infiltration and percolation of precipitation (rainwater or snowmelt) into the subsurface, where it accumulates and forms underground reservoirs known as aquifers. These aquifers can range in depth from shallow to deep underground, and groundwater can be accessed through wells or naturally occurring springs. Groundwater moves slowly through the subsurface, and its availability and quality can vary depending on the geological and hydrological conditions in a given area.

Groundwater bodies and their associated systems are integral components of the hydrological cycle, serving critical functions such as facilitating the discharge and recharge of water. This, in turn, sustains the health of other freshwater bodies such as rivers and streams. Additionally, groundwater ecosystems play a crucial role in mitigating the impacts of drought by regulating the flow of freshwater during extended and severe dry seasons [24]. Groundwater ecosystems provide a range of essential services that hold significant societal and economic importance, including (i) water purification and storage: groundwater ecosystems excel in purifying water, maintaining its quality over extended periods, often spanning decades or even centuries; (ii) contaminant biodegradation: these ecosystems actively engage in the biodegradation of human-made contaminants, effectively neutralizing and eliminating harmful substances; (iii) nutrient recycling: groundwater ecosystems play a vital role in recycling nutrients, contributing to the ecological balance of nutrient cycles; and (iv) flood and drought mitigation: they also act as natural safeguards, helping to mitigate the impacts of both floods and droughts, thereby enhancing resilience in the face of extreme weather events.

While explicit classifications of groundwater ES are not common in the literature, attempts have been made to implicitly categorize them within the broader concept of freshwater [25], based on the classification of the ecosystem services of groundwater [26]. In the existing literature on groundwater ecosystem service classifications, several noteworthy observations and points have been made. Stuurman and Griffioen [27] offer a classification of groundwater ecosystem services into categories such as provisioning, regulating, supporting, and cultural. However, this classification omits storage-related services from provisioning services, and features an absence of services related to flood prevention, seawater intrusion, microclimate regulation in regulating ecosystem services, and insufficient documentation regarding the inclusion of water supply in seepage areas in relation to wetland conservation. Bergkamp and Cross [28] present a classification of ecosystem services into provisioning, regulating, supporting, and cultural categories. However, their classification does not adequately document the inclusion of genetic resources under provisioning. Additionally, the ecosystem service related to maintaining the hydrological cycle is categorized as regulating rather than supporting, which could potentially lead to double counting. Keeler et al. [29] propose a framework that approaches the value of ecosystem services by correlating key chemical parameters. However, this framework primarily focuses on assessing groundwater quality variations, limiting the determination of the value of ecosystem services solely through changes in groundwater quality. Griebler et al. [30] developed a classification system primarily based on the classification of the Millennium Ecosystem

Assessment (MEA). They mention bio-colonies as the sole mechanism for the ecosystem service of maintaining hydraulic conductivity. However, their classification lacks several critical groundwater ecosystem services, such as seawater intrusion control, flood control, subsidence control, carbon storage, and microclimate regulation. While Guswa et al. [31] establish a correlation between hydrologic modeling and payments for watershed services for land management decisions, they do not contribute significantly to the development of a comprehensive classification system for groundwater ecosystem services. Their work does not differentiate groundwater ecosystem services from the main classifications like MEA, TEEB, or CICES. Lijzen et al. [32] present a classification of groundwater ecosystem services into three categories (provisioning, regulating, cultural) but do not include a category for supporting services. Additionally, they only mention the general concept of water availability in the provisioning services without categorizing it into specific uses. Tuinstra and van Wensem [33] present a classification of groundwater ecosystem services into provisioning, regulating, supporting, and cultural categories. However, they do not adequately analyze why the ecosystem service related to maintaining the biogeochemical cycle is categorized as regulating rather than supporting.

The existing literature on groundwater ecosystem service classifications reveals various classifications with their respective strengths and weaknesses. While some classifications offer valuable insights, there is a need for a more comprehensive and standardized classification system that encompasses the full range of groundwater ecosystem services while addressing potential inconsistencies and gaps. To summarize, it could be stated that there exist groundwater ecosystem services that are not enlisted in the current classifications, as follows:

- Seawater intrusion control: seawater intrusion control, which is vital for preserving groundwater quality and preventing saline water from infiltrating freshwater aquifers, is not consistently included in some classifications.
- Flood control: the ecosystem service associated with flood control, which involves regulating and mitigating the impacts of flooding events, is not consistently incorporated into certain classifications.
- Subsidence control: services related to controlling land subsidence, which can result from excessive groundwater extraction, are often overlooked in existing classifications.
- Carbon storage: the ecosystem service of carbon storage, wherein groundwater ecosystems can play a role in sequestering carbon, is not consistently addressed in some classifications.
- Microclimate regulation: the regulation of microclimates, which can be influenced by groundwater systems and their thermal properties, is not consistently considered in existing classifications, and generally referred to as a temperature regulator.

These services are crucial for understanding the full spectrum of ecosystem services provided by groundwater and should be adequately recognized and categorized within groundwater ecosystem service classifications.

Furthermore, there are groundwater ecosystem services that are at risk of double counting or potential overlap in existing classifications. For example, in [28], the ecosystem service related to maintaining the hydrological cycle is categorized as "regulating" rather than "supporting". This classification could potentially lead to double counting when assessing ecosystem services that contribute to both regulating and supporting the hydrological cycle. Tuinstra and van Wensem [33] categorize the ecosystem service related to maintaining the biogeochemical cycle as "regulating" rather than "supporting". Similar to the hydrological cycle, this classification may raise concerns of double counting when evaluating services that support both regulating and supporting aspects of the biogeochemical cycle. It is therefore important to address these classification discrepancies to avoid potential double counting and ensure a more accurate assessment of groundwater ecosystem services in future studies and policy decisions.

4. Methodological Approach

Expert judgment elicitation is a valuable methodology used in various fields to gather insights and opinions from knowledgeable individuals, or experts, on specific topics or issues. It involves a structured approach to harness the expertise of individuals to make informed decisions, predictions, or assessments. Krueger et al. and Meyer and Booker [34,35] give an overview of the expert judgment elicitation methodology. The assertion is that experts, compared to the general public, demonstrate superior information recall, an enhanced ability to apply knowledge to novel scenarios, and refined critical thinking skills concerning data and methodologies within their field [36]. Nonetheless, it is argued that experts may be susceptible to various heuristics (such as representativeness, availability, anchoring and adjustment, and overconfidence) and may be influenced by cognitive biases (e.g., underestimation of uncertainty, anchoring) and motivational biases (e.g., wishful thinking, misinterpretation, misrepresentation). These factors can potentially compromise the accuracy of their reported beliefs (e.g., [35,37]).

To mitigate these biases, structured elicitation protocols have been developed with the goal of generating more reliable and well-calibrated results [37]. While expert judgment is not a substitute for conclusive scientific research, it can provide valuable insights for policymakers, particularly in situations where ongoing research has not yet yielded definitive results [38]. Despite its limitations, it is recognized that expert judgment proves beneficial in providing estimates for cases involving new, rare, complex, or poorly understood phenomena. Therefore, it is utilized to shape the framing of problems and solutions, make predictions about future events in the absence of robust data, and synthesize qualitative information or combinations of qualitative and quantitative data to form decision-making frameworks [35,39,40].

The expert judgment elicitation methodology followed in this research is described below. The objective was to gather insights and opinions regarding groundwater ecosystem services and specifically to refine our understanding of ecosystem services related to groundwater, including the identification of relevant services, exclusions, and potential additions. The expert judgment approach involved a panel of seven experts in the fields of hydrogeology or water resources engineering, who were carefully selected based on their expertise and qualifications, e.g., education, professional experience, and involvement in relevant programs and/or associations. The experts selected all hold Ph.D. degrees in hydrogeology or water resources engineering. Their strong educational background suggests that they are well versed in the theoretical aspects of groundwater resources and their academic foundation ensures a high level of expertise and subject knowledge, crucial for evaluating the complexities of groundwater ecosystem services. Furthermore, the experts, through their involvement in research projects, demonstrate a broader perspective and interdisciplinary thinking, aligning with the holistic nature of ecosystem services. At the same time, although coming from academia and research organizations, all experts have professional experience and participate in national associations in their respective field (e.g., the Hellenic Chapter of the International Association of Hydrogeologists), bringing a practical viewpoint to and a deeper understanding of the real-world challenges related to groundwater ecosystem services.

In accordance with [38], we conducted a methodical elicitation of individual expert judgments, emphasizing the absence of a necessity for consensus or iterative communication among experts. This procedural choice aimed to safeguard the independence of expert judgments by mitigating potential biases stemming from interactive group dynamics, such as the 'social pressure' bias identified by [35]. The interviews were facilitated by a skilled moderator who ensured that the discussions remained focused and productive. All responses, suggestions, and justifications provided by the experts were documented meticulously to maintain a record of the expert judgment process, and the data collected were synthesized and analyzed.

Regarding the interviews, initially, the experts were provided with a detailed presentation about groundwater ecosystem services, which were the outcome of an in-depth literature review analysis. This analysis was conducted through the main literature journal databases, ensuring the highest level of rigor and accuracy. The results of this analysis are detailed in Table 1 below. The presentation aimed not only to share the outcomes but also to provide a thorough exploration of key concepts, definitions, and underscored the paramount significance of groundwater in bolstering a wide array of ecosystem services. This approach aimed to familiarize the experts with the intricacies of the subject matter, ensuring a well-rounded understanding and fostering productive discussions. In addition to the informative presentation, the interviewees were introduced to the questionnaire format that would be employed in the following stage. This format allowed them to delve deeper into the structure and content of the questionnaire, ensuring their readiness to contribute their insights and expertise effectively.

Table 1. Groundwater ecosystem services included in expert judgment elicitation questionnaire.

Category A: Provisioning Ecosystem Services	**Category B: Regulating Ecosystem Services**
Drinking water Irrigation water Livestock water Water for industrial use—consumption Water for non-industrial use—consumption	Water purification Seawater intrusion control Flood control Subsidence control Carbon dioxide storage—anthropogenic Carbon dioxide storage—natural Hydraulic conductivity maintenance Microclimate mitigation
Category C: Supporting Ecosystem Services	**Category D: Cultural Ecosystem Services**
Groundwater-dependent ecosystems—biodiversity	Naturalist leisure activities
Water cycle support	Aesthetic enjoyment—spiritual well-being Education—research

After the initial presentation, the experts were presented with a questionnaire that focused on the specific groundwater ecosystem services. Each ecosystem service was individually analyzed and for each ecosystem service, experts were asked to provide their opinions on whether it should be included, excluded, or modified in its classification. Also, the experts had the opportunity to add new groundwater ecosystem services which they considered to be absent from the existing classification. Experts were encouraged to provide detailed justifications for their recommendations. This allowed for a clear understanding of their reasoning and facilitated discussions. As part of this expert elicitation judgment interview process, the classification of groundwater ecosystem services into intermediate and final ecosystem services was also an essential component. Experts were reminded that intermediate ecosystem services are those that contribute to the provision of final ecosystem services. They act as intermediaries in the process, supporting the delivery of the ultimate benefits. In contrast, final ecosystem services are the direct benefits that humans consume, enjoy, or utilize. This distinction helped refine their understanding of the groundwater ecosystem services within the context of their definition and purpose.

The responses were categorized into exclusions, additions, and modifications for each groundwater ecosystem service. Common themes and patterns in expert recommendations were identified, and areas of consensus or disagreement were documented. The results of the expert judgment elicitation process were validated by comparing them to the existing literature and research in the field of groundwater ecosystem services. A final report was prepared, summarizing the findings, including the recommended exclusions and additions to the classification of groundwater ecosystem services. The report emphasized the value of expert opinions in refining our understanding of groundwater-related ecosystem services. Further details regarding the output of the expert elicitation process are presented in the next section.

5. Results

5.1. Developing the GROUNDWES (GroundWater Ecosystem Services) Classification

This section provides a comprehensive presentation of expert opinions and insights on groundwater ecosystem services, which formed the basis for the creation of the final classification system.

The initial question concerned the strategic water resources/storage capacity ecosystem service, which holds substantial importance in the domain. Expert (1) advocated for its inclusion within the provisioning services category, echoing the consensus that it serves as a critical storage service furnished by groundwater. Expert (2) underscored its association with infrastructure designed to stock resources for future use. Expert (3) defined storage capacity as the proportion of water surplus not utilized in daily consumption. Expert (4) highlighted the exclusion of geological reserves from water storage under environmental legislation. The necessity for this service in meeting emergency needs or expanding existing services was emphasized by Expert (5). Further discussions raised the concept of a steady state for this service (Expert 6) and the proposal to distinguish between strategic and non-renewable stocks, especially during water crisis situations (Expert 7).

In addressing the water purification ecosystem service, Expert (1) recommended its classification as a regulating service, primarily due to its role in natural pollution control. Expert (2) shed light on the intricate interaction of systemic processes and the filtering function of groundwater. Expert (3) offered a concise definition, characterizing it as "physicochemical processes due to subsurface flow". Expert (4) emphasized the geological medium's role as a filtering agent, while Expert (5) underlined the dissolution of pollutants and improvements in water quality through natural enrichment. An innovative suggestion came from Expert (6), who proposed renaming this ecosystem service as the "maintenance of groundwater quality composition/natural water purity".

The discourse surrounding the flood protection ecosystem service centered on a detailed examination of its underlying mechanisms. The experts concurred that the effectiveness of this ecosystem service is contingent upon factors such as porosity, topography, flora, and the presence of the water table. The degree of groundwater's contribution to flood protection was explored within the context of varying geological conditions and hydrogeological factors. Expert (1) initiated a discussion on the contentious topic of the subsidence control ecosystem service. While the consensus was that this service relates to the prevention of differential sedimentation by maintaining active porosity, Expert (3) suggested a renaming as the "maintenance of active porosity of the water body". Expert (4) proposed the elimination of the term "subsidence" from the discourse due to its association with certain rock types and geological factors.

In considering the hydraulic conductivity maintenance ecosystem service, Expert (1) emphasized groundwater's pivotal role in preserving porosity and hydraulic conductivity. There was a discussion regarding the impact of overpumping on hydraulic conductivity across various hydrogeological settings. The experts agreed on the notion that hydraulic conductivity maintenance may be contingent on local conditions.

The microclimate regulation ecosystem service prompted deliberation on the influence of aquifer systems on local microclimates. Expert (1) contended that the existence of aquifer systems is intrinsically linked to microclimate regulation, particularly in areas directly influenced by groundwater. Expert (2) explored the impact of shallow aquifers on microenvironments, while Expert (3) discussed capillary upwelling and its contribution to microclimate regulation. Additionally, Expert (4) highlighted the role of the capillary zone and micro-flora in the intricate process of regulating microclimates.

The conversation surrounding the anthropogenic carbon dioxide storage ecosystem service was marked with its relevance and functionality. Expert (1) opined that this service is facilitated through water storage capacity. Nevertheless, some experts questioned the direct relevance of this service to groundwater ecosystem services (namely Expert 2). The experts concurred that a healthy aquifer plays a pivotal role in the prevention of quality degradation and the maintenance of natural equilibrium. The discourse also extended to the factors influencing the control of sea water intrusion, including petrology and piezometry.

Expert (2) underscored the benefits of the provisioning water/industrial use/consumed ecosystem service, including food production and bottled water. The experts explored the addition of aquaculture as a new provisioning service, with Experts (3) and (4) providing detailed insights. Additionally, Expert (5) introduced new provisioning services related to transitional waters and geothermal springs, while Expert (6) proposed identifying intermediate services, including those involving biological, physical, chemical, and geological processes.

Taking into consideration the opinions of the experts and the current literature on the subject, the classification system was finally formulated under the authors care, namely the GROUNDWES (GroundWater Ecosystem Services) classification, which is presented in Table 2.

Table 2. The GROUNDWES classification.

Provisioning Services (provisioning)—ESp	
ESp1	Drinkable water (drinking water): groundwater for human consumption.
ESp2	Irrigation water (irrigation water): groundwater for agricultural activity.
ESp3	Livestock water (water for livestock): groundwater for livestock activity.
ESp4	Water for industrial use—consumable (water for industrial use—consumptive): groundwater for industrial production, e.g., in the food industry.
ESp5	Water for industrial use—non-consumable (industrial water—non-consumptive): groundwater for industrial processes, e.g., a natural resource to achieve cooling system.
ESp6	Thermal storage (thermal storage in the aquifer): groundwater for the storage of thermal energy.
ESp7	Strategic water resources (strategic water reserves): groundwater stored in the form of strategic water reserves for possible future use (e.g., in times of drought).
ESp8	Storage capacity (storage capacity): capacity of the water body to retain and store water resources.
Regulating Services (regulating)—ESr	
ESr1	Water purification (water purification): purification of groundwater through filtration, action of micro-organisms, etc.
ESr2	Seawater intrusion control (prevention of marine infiltration): protection of groundwater from waterlogging.
ESr3	Flood control (flood protection): protection against scouring through absorption and infiltration.
ESr4	Subsidence control (differential sedimentation avoidance): avoiding ground subsidence by maintaining the water table level.
ESr5	Carbon dioxide storage—anthropogenic (anthropogenic carbon dioxide storage): storage of carbon dioxide by artificial methods. (Groundwater aquifers are potential reservoirs for the artificial storage of carbon dioxide through drilling, see 'Groundwater and Ecosystem Services: towards their sustainable use' by Bergkamp and Cross [28])
ESr6	Carbon dioxide storage—natural (carbon dioxide storage—physical): carbon dioxide storage through biosynthetic processes.
ESr7	Hydraulic conductivity maintenance (conservation of hydraulic conductivity): maintaining the downward permeability of the water body.
ESr8	Microclimate mitigation (microclimate regulation): maintaining stable temperature levels and heat capacity at a local level.
Fundamental or Supporting Services (supporting)—ESf	
ESf1	Groundwater-dependent ecosystems—biodiversity (ecosystems dependent on groundwater—biodiversity): maintaining groundwater-dependent ecosystems such as rivers, lakes, springs, wetlands, etc.
ESf2	Water cycle support (water cycle support): supporting the biogeochemical cycle, supporting the nutrient cycle, etc.
Cultural Services (cultural)—ESc	
ESc1	Naturalist leisure activities (nature-based activities, recreation—tourism): recreational and tourism activities, such as visiting underground caves, diving in underground caves, etc.
ESc2	Aesthetic enjoyment—spiritual well-being (aesthetic enjoyment—spiritual well-being): non-material benefits derived at a spiritual level from the existence of groundwater (e.g., religious values, source of inspiration, etc.).
ESc3	Education—research (education—research): non-material benefits derived at the cognitive level from the processes that provide the basis for formal and informal education, the development of knowledge systems, etc.

5.2. Final and Intermediate Groundwater Ecosystem Services

In the analysis of groundwater ecosystem services, a crucial step involved classifying these services into the two key categories, i.e., intermediate and final, with the aim to avoid, or at least reduce, double counting in ecosystem services' valuation via stated (e.g., contingent valuation and choice experiments) and revealed preference (e.g., travel cost, hedonic pricing, and production function) approaches [41–44]. Although this problem is widely recognized, particularly among economists, it has not been adequately addressed as a significant factor contributing to the inaccuracy and unreliability of ecosystem services' valuation [16,41,44]. For example, water purification (through filtration, the action of micro-organisms, etc.) and hydraulic conductivity maintenance (i.e., maintaining the downward permeability of the water body) are regulating services, while drinkable water is a provisioning service. Aggregating these services would lead to double counting because water purification and hydraulic conductivity maintenance contribute to the final product, that is, drinkable water. To prevent double counting, only the benefits stemming from final services should be considered and valued, just as economists include only the value of final goods in GDP accounting [41]. However, it should be noted that the distinction between intermediate and final services is a necessary but not a sufficient condition for avoiding double counting. For instance, Fu et al. [41] argue that that numerous factors contribute to the occurrence of double counting in the assessment of ecosystem services. These factors include the lack of clarity in defining ecosystem services, the intricate interconnections inherent in ecosystems, the spatial–temporal dependencies of these services, and the inappropriate choice of non-market valuation techniques, among others. Regarding valuation methods, the authors highlight that double counting issues may arise not only across various valuation approaches but also within specific methods. Consequently, the selection of methods should align with the specific context of the research, taking into account factors such as the estimation of direct, indirect, or non-use values and the type of services being valued.

Focusing on the categorization of groundwater ecosystem services, the experts' consensus and varying perspectives reveal a comprehensive understanding of the diverse roles that groundwater plays in supporting life, fostering economic activities, and preserving the environment. The classification of groundwater ecosystem services into intermediate and final aligns with the established literature status of the ecological functions and international and national practices. Unanimously, drinkable water is recognized as a final ecosystem service, with experts underscoring groundwater's pivotal role in providing safe and potable water for human consumption. Similarly, irrigation water garners unanimous agreement, highlighting groundwater's crucial contribution to agriculture and food production. Livestock water also receives unanimous recognition as a final ecosystem service, emphasizing its role in sustaining animal agriculture. The significance of water for industrial use as a consumable is acknowledged by practically all experts. Leisure activities associated with groundwater-dependent ecosystems are also universally acknowledged as final ecosystem services, contributing significantly to the quality of life and recreation. In the intricate classification framework of groundwater ecosystem services, experts converge on designating non-consumable industrial water, for its intended purposes, as a final ecosystem service. Opinions, however, diverge when confronted with the classification of thermal storage, as certain experts classify it as a final ecosystem service, exemplifying the nuanced nature of this service category.

A consensus emerged through classifying storage capacity as an intermediate ecosystem service, although a few of the experts hold that it should be categorized as a final ecosystem service. In contrast, a steadfast unanimity exists regarding water purification, which was uniformly categorized as an intermediate ecosystem service by all experts.

Similarly, a universal consensus prevails in acknowledging seawater intrusion control as an intermediate ecosystem service. Nevertheless, flood control is the subject of discourse among experts, with some attributing it to the realm of final ecosystem services, wherein groundwater plays a pivotal role in mitigating flood-related issues. Without variance, subsidence control garners unequivocal recognition as an intermediate ecosystem service, elucidating groundwater's role in averting land subsidence. Moreover, the classification of anthropogenic carbon dioxide storage stands unopposed, as it was unanimously designated as an intermediate ecosystem service by all experts. The sentiment of unanimity extends to the classification of natural carbon storage in groundwater systems as an intermediate ecosystem service. While most experts concur in considering hydraulic conductivity maintenance an intermediate ecosystem service, a degree of discrepancy becomes evident in the perspectives of Expert (5) and Expert (7). Microclimate mitigation unanimously secures consensus as an intermediate ecosystem service facilitated by groundwater across all expert evaluations. Groundwater-dependent ecosystems, in their totality, collectively emerge as intermediate ecosystem services, recognizing their paramount function in preserving biodiversity.

An indisputable consensus emerges, acknowledging the regulation and support of the water cycle through groundwater as an intermediate ecosystem service, underscoring the essential role played by groundwater in this context. Further, the spiritual pleasure emanating from groundwater ecosystems secures collective consensus, standing as an intermediate ecosystem service across all expert assessments. Furthermore, the domains of education and research, which find nourishment in groundwater, are universally recognized as intermediate ecosystem services, accentuating the diverse capacities groundwater has within the purview of educational and research endeavors. This encompassing spectrum of categorizations underscores the intricacies of groundwater ecosystem services, and the manifold roles groundwater assumes in a broader context.

The categorization of GROUNDWES services into intermediate and final is summarized in Table 3.

Table 3. Categorization of GROUNDWES services into intermediate and final.

Provisioning ES		**Intermediate**	**Final**
ESp1	Drinkable water		X
ESp2	Irrigation water		X
ESp3	Livestock water		X
ESp4	Water for industrial use—consumable		X
ESp5	Water for industrial use—non consumable		X
ESp6	Thermal storage		X *
ESp7	Strategic water resources	X	
ESp8	Storage capacity	X	
Regulating ES			
ESr1	Water purification	X	
ESr2	Seawater intrusion control	X	
ESr3	Flood control	X *	
ESr4	Subsidence control	X	
ESr5	Carbon dioxide storage—anthropogenic	X	
ESr6	Carbon dioxide storage—natural	X	
ESr7	Hydraulic conductivity maintenance	X *	
ESr8	Microclimate mitigation	X	
Fundamental or Supporting ES			
ESf1	Groundwater-dependent ecosystems	X	
ESf2	Water cycle support	X	
Cultural ES			
ESc1	Naturalist leisure activities		X
ESc2	Aesthetic enjoyment—spiritual well-being	X	
ESc3	Education—research	X	

*: for these ESs there was no consensus when categorizing them into intermediate and final.

All in all, although GROUNDWES is a first step, and surely not the last one, in the classification of groundwater ecosystem services, it holds certain advantages and offers a more granular and context-aware classification compared to existing frameworks. It acknowledges and addresses critical gaps regarding missing ecosystem services, which are crucial for understanding the diverse role played by groundwater resources in ecosystems and human welfare. For example, GROUNDWES offers clarity on the inclusion of water and carbon storage-related services and fills gaps related to flood control and seawater intrusion prevention, and microclimate regulation. Also, GROUNDWES introduces a useful distinction between final and intermediate ecosystem services, emphasizing the importance of their diverse roles in avoiding the risk of double counting.

6. Discussion and Conclusions

This research serves as a platform to unveil GROUNDWES, an intricate tapestry that weaves together the scientific understanding of groundwater with the broader context of ecosystem services. As we navigate through the GROUNDWES framework, we embark on a journey that traverses the realms of science, policy, and human well-being.

The GROUNDWES system is an ambitious effort as it represents a comprehensive framework that endeavors to categorize and elucidate the multitude of ecosystem services that groundwater provides. It is the result of extensive research and collaborative efforts, drawing from a multitude of sources and expert perspectives. Its foundation lies in a thorough literature review, which involved synthesizing existing knowledge and identifying the shortcomings in the prior classifications of groundwater ecosystem services. This process served as a critical starting point, enabling us to pinpoint areas where refinement and enhancement were needed. It was through this research analysis that GROUNDWES emerged, seeking to provide a more comprehensive and nuanced understanding of the ecosystem services delivered by groundwater.

One of the primary motivations behind the development of GROUNDWES was the recognition of critical gaps in the existing classifications of groundwater ecosystem services. While various frameworks had previously addressed the provisioning, regulating, supporting, and cultural services associated with groundwater, GROUNDWES aimed to offer a more granular and context-aware classification. Through GROUNDWES certain gaps have been meticulously addressed. For instance, it has offered clarity in distinguishing between final ecosystem services and intermediate ecosystem services, providing a more nuanced understanding of the role groundwater plays in our ecosystems and societies. It has also elucidated the intricate relationships between groundwater and services such as subsidence control, microclimate regulation, and carbon storage, which had previously received insufficient attention.

The proposed classification has the potential to contribute to better groundwater policymaking and management, helping policymakers to make more informed decisions. For instance, by understanding the roles of groundwater in services like water purification, flood control, and microclimate regulation, to mention few, policymakers can implement measures (e.g., environmental legislative acts, monitoring systems, land-use plans, etc.) that maintain or even enhance these 'out of sight, out of mind' groundwater services, while balancing competing demands for the more visible uses of groundwater (e.g., water for human consumption, irrigation, etc.). Also, highlighting the role of groundwater in services like carbon dioxide storage positions GROUNDWES as a tool for climate change adaptation. More importantly, the proposed classification offers a basis and a more accurate assessment for valuing groundwater ecosystem services while minimizing the risk of double counting. Monetizing the benefits derived from maintaining healthy groundwater resources supports arguments for their conservation and sustainable management based on their economic importance and contribution to societal well-being. Last but not least, by communicating the diverse role and importance of groundwater ecosystem services, the GROUNDWES classification can be used to enhance public awareness and education programs.

In this paper, we reflect on the journey that led to the creation of GROUNDWES, its contributions to filling critical gaps in the classification of groundwater ecosystem services, and the exciting prospects it presents for the future of sustainable water management. Nevertheless, there are certain limitations that should be explored in future research, to refine, improve, and better integrate the GROUNDWES classification into policy and environmental management processes. First, the GROUNDWES classification relies on the insights and opinions of a specific group of limited experts from a narrow scientific domain. Although their expertise is valuable, the system's applicability and comprehensiveness could be influenced by the perspectives and biases of this expert group. For instance, the experts may suffer from regional bias, meaning that they rely on knowledge and experiences related to Greece's geological and hydrogeological strata. Groundwater ecosystems can vary across different geological and hydrological contexts, and, thus, the proposed classification may not fully capture this diversity. Furthermore, our study primarily involves only expert judgment. The inclusion of input from other stakeholders, such as local communities or environmental NGOs, could provide a more holistic understanding of groundwater ecosystem services. Finally, it should be noted that the effectiveness of GROUNDWES has not been empirically tested in real-world applications, and such validation exercises could enhance its robustness. In this direction, future research could conduct empirical analyses to assess the reliability of GROUNDWES in different geographic regions and hydrogeological settings and expand stakeholder engagement to include perspectives from local communities, environmental advocacy groups, and other relevant stakeholders. The next challenge on our horizon is the development of a software tool that will harness the power of this classification system. This tool will serve as a dynamic resource, enabling stakeholders involved in water management projects to make informed decisions that promote environmental sustainability.

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