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Review

Muddy Waters: Refining the Way forward for the "Sustainability Science" of Socio-Hydrogeology

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Abstract: The trouble with groundwater is that despite its critical importance to global water supplies, it frequently attracts insufficient management attention relative to more visible surface water sources, irrespective of regional climate, socioeconomic profile, and regulatory environment. To this end, the recently defined sub-discipline of "socio-hydrogeology", an extension of socio-hydrology, seeks to translate and exchange knowledge with and between non-expert end-users, in addition to involving non-expert opinion and experience in hydrogeological investigations, thus emphasising a "bottom-up" methodology. It is widely acknowledged that issues pertaining to groundwater quality, groundwater quantity, climate change, and a poor general awareness and understanding of groundwater occurrence and movement are global in their scope. Moreover, while effective communication and engagement represent the key tenet of socio-hydrogeology, the authors consider that multiple actors should be identified and incorporated using stakeholder network analysis and may include policymakers, media and communications experts, mobile technology developers, and social scientists, to appropriately convey demographically focused bi-directional information, with the hydrogeological community representing the communication keystone. Accordingly, this article aims to highlight past and current work, elucidate key areas of development within socio-hydrogeology, and offer recommendations to ensure global efficacy of this increasingly important and growing field going forward. The authors seek to assist in protecting our global groundwater resource for future generations via an improved framework for understanding the interaction between communities and hydrogeological systems.

Keywords: socio-hydrogeology; groundwater management; communication; engagement; socio-economic aspects

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Preface:

While socio-hydrology is a well-established paradigm for the incorporation of sociological factors into water resource management, the sociological nuances associated with the subsurface environment and hydrogeological phenomena are frequently under-represented within management strategies. In response to this, 'socio-hydrogeology' as distinct from socio-hydrology, has been argued within the literature, and represents an opportunity to guide the development and optimization of inter and multidisciplinary paradigms that focus on the subsurface environment. However, to date, there has been limited discussion contextualizing the myriad challenges facing socio-hydrogeology and it is clear that solutions need to be offered in order to move towards a cyclical paradigm that integrates both scientific and non-scientific stakeholders. As such, this paper aims to highlight past and current work, elucidate key areas of development within socio-hydrogeology, and offer recommendations to ensure global application of this increasingly important and growing field going forward. The structure of this paper (represented graphically in Figure 1) incorporates five main thematic areas, moving from the genesis of the concept of socio-hydrogeology to its global significance and the challenges and opportunities for socio-hydrogeological development in a connected, high-tech world. These three areas culminate in highlighting the need for heightened stakeholder engagement and network analysis to achieve sustainable groundwater management, which we discuss. Finally, the ideas and knowledge presented are synthesized towards an improved socio-hydrogeological paradigm that incorporates a circular socioeconomic approach that aims to put the 'socio' in socio-hydrogeology and move towards integrated groundwater resource management.

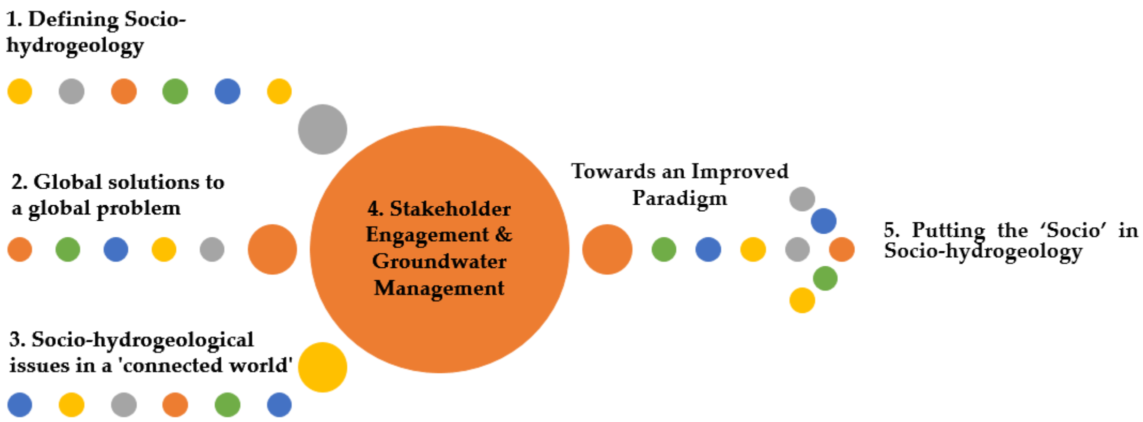

Figure 1. Overview of paper structure: We present the evolution of the definition of socio-hydrogeology, its importance in a global context, as well as challenges and solutions for socio-hydrogeology. We highlight the importance of stakeholder network analysis, culminating in a move towards a new paradigm that puts the socio in socio-hydrogeology.

1. Hydro-Sociology, Socio-Hydrology, and the Genesis of Socio-Hydrogeology

Four decades ago, Widstrand (1978) [1] recognised the need for multidisciplinary methodologies when managing interactions between people and water, and more specifically, the importance of integrating the social sciences. Shortly after, hydro-sociology, with an overarching objective of improving analysis of the social consequences of water related projects, was introduced by Falkenmark (1979) [2]. Many studies since then have addressed these concepts, albeit in the absence of concrete terms or models [3,4]. The term socio-hydrology, first coined by Sivapalan et al. (2012) [5], refers to the myriad of interactions and feedback loops between social and hydrological processes and pressures, and was introduced to the hydrological lexicon as a response to the discipline's perceived failure to adequately examine and address human-modified water sources. At its core, socio-hydrology comprises two social components: (i) absorption of people and their activities into hydrological science, and (ii) ensuring that water-related decisions take the stakeholder perspective into consideration, that is, how and why water is used [6]. Furthermore, socio-hydrology focuses on observing, understanding, and predicting future trajectories of human–water system interactions and the relationships between the two [5,7]. Socio-hydrology thereby represents an interdisciplinary field that attempts to integrate the dynamic reactions and interactions between water and people. For example, process-based models of coupled human-water systems seek to include societies and communities as internal model variables, as opposed to boundary conditions [8]. As such, increasingly accurate long-term predictions pertaining to issues including flooding and water quality may become achievable, as the socio-hydrological perspective seeks to capture the co-evolution of human-water system dynamics [5], for example, water usage, demands, migration, infrastructural development, and so on. However, as recently noted by Pande & Sivapalan (2017) [9], use of the term has been inconsistent.

The challenges facing (non-expert) communities and policymakers regarding groundwater, as opposed to surface water, resource management are quite unique; it is difficult to comprehend and consequently to garner support for the maintenance and remediation of a resource that cannot be easily seen. As a result, while pressures and approaches to the assessment and use of groundwater remain at the global scale, remediation measures have taken a socio-integrative shift.

With the continuous refinement of socio-hydrology, it was perhaps inevitable (and necessary) that a groundwater specific branch would develop. While Burke et al. (1999) [10] were perhaps the first to make the distinction between socio-hydrological and socio-hydrogeological systems and processes, the term "socio-hydrogeology" was first introduced by Re (2015) [11] in the *Hydrogeology Journal*. Re (2015) presents the Bir Al-Nas (bottom-up integrated approach for sustainable groundwater management in rural areas) approach, which seeks to integrate socio-hydrological and science-based groundwater management practices. The Bir Al-Nas (Arabic translation—"the peoples well") approach comprises a strong social component (Figure 2), including stakeholder analysis, public engagement, and socio-economic assessment, and as such, differs from many developed socio-hydrology models [12] in that it places a particular emphasis on surveying, stakeholder network analysis, and local consultation. Re (2015) refers to socio-hydrogeology as "*a way of incorporating the social dimension into hydrogeological investigations*", similarly, Limaye (2017) [13] notes that the basis for any socio-hydrogeological intervention is effective communication. As such, and as substantiated by Re (2015), this represents one of the primary differences between socio-hydrology and socio-hydrogeology; because of widespread misunderstanding of hydrogeological principles (irrespective of location, socio-economic status, and/or geopolitical setting), higher levels of awareness nurturing via translation and communication are required. Moreover, it seems that a distinct definition of, and model for, applying socio-hydrogeology is required to address the inherent differences between hydrological and hydrogeological systems and processes.

Traditionally, models used in hydrological studies have often assumed stationarity as opposed to temporal variation. Additionally, human-induced water resources management activities are included as external variables in water cycle dynamics. However, in considering the human population's current impact on the water cycle in terms of a growing population (and subsequent demands), increasing river basin management, and climate change, it is unclear whether this approach is still appropriate. Furthermore, research directed at the evolution of water resources and society has shown that the components constituting the human–water system are changing interdependently [14]. Thus, water cycle dynamics should be approached from an integrated perspective in which humans are considered endogenous forces to (and within) the system [14]. As noted by Gorelick & Zheng (2015) [15], and specific to hydrogeology, a new generation of aquifer management approaches and models are required to compete with the new (and existing) interconnected generation of groundwater challenges including global climate change, aquifer storage/depletion, land subsidence, saline intrusion, and hydro-ecology. These global issues require global solutions, which can only be developed and fostered through the application of malleable and evolving socio-hydrogeological principles.

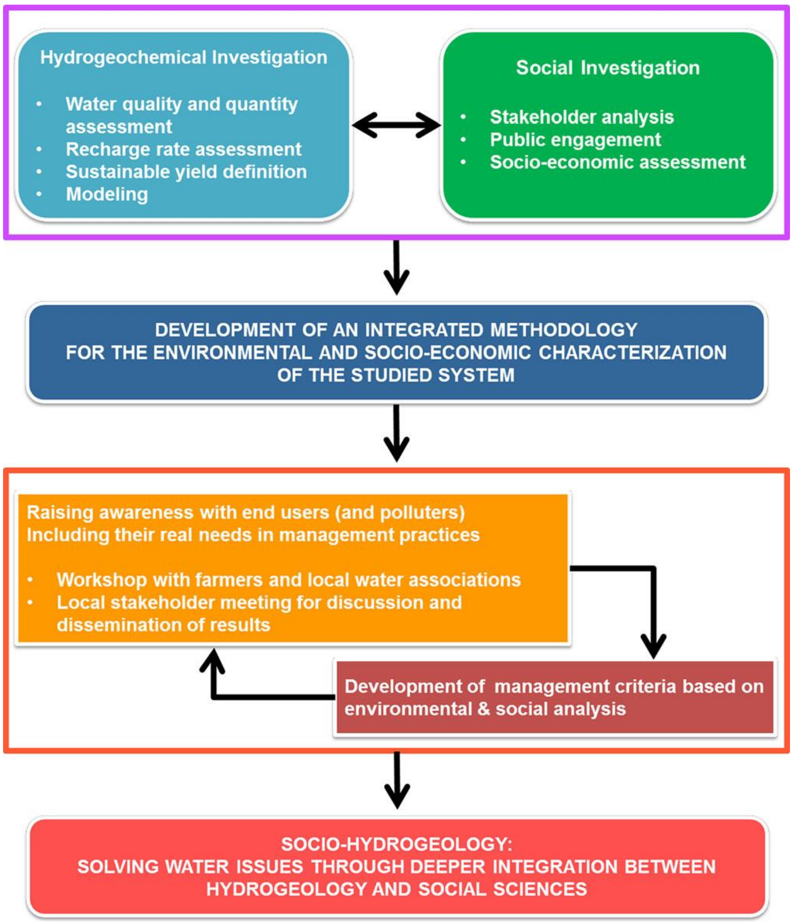

Figure 2. Schematic description of the bottom-up integrated approach for sustainable groundwater management in rural areas (Bir Al-Nas) approach for socio-hydrogeology (Re, 2015).

2. Socio-Hydrogeology: Global Solutions to a Global Problem

Current concerns regarding water scarcity and insecurity are both ubiquitous and varied, manifesting themselves in a myriad of respects worldwide [16]. This is particularly evident from a research perspective. As shown (Figure 3), the geographical distribution of published articles relating to groundwater contamination (from Scopus, the largest global abstract and citation database of peer-reviewed literature) demonstrates that groundwater issues occur across a range of socioeconomic and geo-political regions. However, to date, the majority of socio-hydrogeological applications have occurred in low income countries (Table 1), thus potentially painting a picture of socio-hydrogeology as a science relevant to the "developing" world primarily. However, this is not the case; most, if not all, of the studies employ methodological approaches that are pan-global in terms of application, and recent work by Re et al. (2015) [11] has designed a replicable model for implementing a socio-hydrogeological approach in rural areas, regardless of location. For example, the majority of the issues discussed within these articles are not unique to low income regions, nor are pressures such as population growth, climate change, the shift toward increasingly water-dependent economies and societies, and reduced groundwater availability. Rather, it is evident that human social processes are catalysing hydrogeological degradation at a global level and, therefore, must also be the agents of change and remediation.

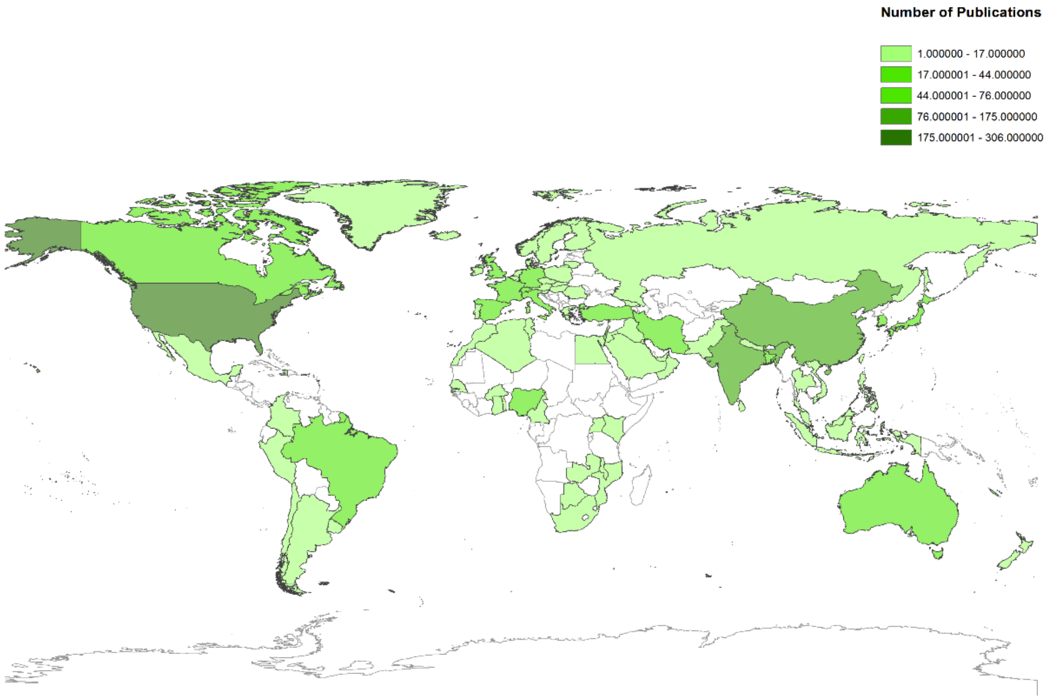

Figure 3. Geographical distribution and frequency of published articles relating to groundwater contamination (January 1975–September 2017).

Unfortunately, because of the inherent nature of groundwater occurrence and transport, the development and implementation of effective socio-hydrogeology management faces many barriers. For example, despite best efforts by the hydrogeological community, groundwater traditionally receives significantly less attention than surface water, inevitably resulting in lower levels of monitoring and management [11,17]. Moreover, as pointed out by both Re (2015) and Limaye (2017) [11,13], a global gap exists between academic research and the general population's awareness, understanding, and daily requirements in relation to groundwater; again largely due to the 'out of sight, out of mind' nature of the resource. For example, in a recent study by Hynds et al. (2013) [18], 245 private well owners from diverse hydrogeological settings in the Republic of Ireland were interviewed; findings indicate that while just 1.2% of respondents had involved an accredited hydrogeologist during the design phase of their domestic water source.

Compounding these issues, physical barriers also exist and need to be accounted for that largely do not exist for surface water; for example, access to groundwater resources may be limited; boundaries are more difficult to establish among and between users; and human–water relationships more likely occur at the micro-level, that is, individual private well-owners [19]. Accordingly, development and implementation of appropriate socio-hydrogeological practices seeks to surmount or dispense with these barriers and promote increased awareness of groundwater-related issues and needs among local communities [11,13,20]. Moreover, research relating to groundwater resources in medium- and high-income countries has shown that contamination, and particularly microbiological pollution, is a recurring problem leading to endemic and epidemic waterborne infectious diseases in these regions [21–23].

Table 1. Articles published to date (2015–2017) applying socio-hydrogeological methods.

Study	Study Year	Country/Region	Field of Study	Engagement with Socio-Hydrogeology
Re [11]	2015	Italy	Groundwater Management, Rural Development	Discussion
Re & Sacchi [24]	2017	Morocco	Groundwater Isotopes, Salinity, Coastal Aquifers	Application
Leduc et al. [25]	2017	Mediterranean	Groundwater Resources, Exploitation, Management	Introduction
Re et al. [20]	2017	Tunisia	Nitrate Contamination	Application
Rodrigues-Capítulo et al. [26]	2017	Argentina	Coastal Aquifers, Urban Development	Introduction
Limaye [13]	2017a	India	Risk Awareness and Communication	Application
Limaye [27]	2017b	India	Rural Communities, Communication, Water Management	Application
Tringali et al. [28]	2017	Tunisia	Groundwater Management	Application
López-Corona et al. [29]	2018	Mexico	Statistical Theory of Groundwater Management	Application
Re [30]	2018a	Myanmar	Water Resources Assessment	Application
Re et al. [31]	2018b	Italy	Climate Change, Future Hydrogeologists, Engagement	Discussion

We consider that researchers, hydrogeologists, and policy-makers should not view socio-hydrogeology or human–water systems as separate entities in different regions. For example, while two socio-hydrological basin processes may not be hydro(geo)logically connected, they may be joined socially or economically by basin consumers. Increased understanding of these spatial socio-hydrological connections will assist socio-hydrogeology in becoming a frequently and consistently employed discipline between countries, regions, economies, and communities. The belief that high-income countries' 'technical capabilities' to 'make several alternative solutions' may be an inappropriate assumption, given the uncertainty associated with the extent to which technology can ensure a sustainable future. As previously stated by Pahl-Wost (2002) [32], while problems were once resolved with purely 'top down' approaches (e.g., increasing treatment sophistication, changing legislation, etc.), it is increasingly apparent that those no longer suffice. As such, it is important to discuss what socio-hydrogeology and alternatives to 'top down' management look like in a high-tech, 'connected' world.

3. Socio-Hydrogeological Issues in a 'Connected World'

Communication is the most vital element for effective socio-hydrogeological applications and interventions [11,13], as lack of knowledge surrounding groundwater resources is a limiting factor for social integration. Therefore, accessibility to information tailored to non-expert audiences, appropriate local/regional translation, and face-to-face communication of research is imperative to stimulate hydro-geological awareness and education [13] and emulate the successes of hydrological awareness. However, in light of significant technological advances during recent decades, communication with the general public has become increasingly complex, demographically distinct, and challenging. There is a vast range of approaches for science communication within the general public. As such, many fundamental difficulties have and will continue to arise when attempting to insert society or sociology into the realm of hydrogeological modelling and research [25]. Compounding this, the media can also play a key role in shaping the perceptions and/or misconceptions of hydrogeological science; for example, groundwater contamination in one area may affect groundwater perceptions in another. As such, the challenges of communicating hydrogeological science are multifaceted, but must be overcome.

For example, high levels of media exposure and education, in addition to technological and intellectual developments, shape responses to socio-hydrogeological interventions, thus science communication can and does frame the way these interventions occur. For example, through media exposure and education, public opinion is currently being molded towards increased environmental awareness [33]. This is undoubtedly advantageous in terms of the development and integration of socio-hydrogeology, if it can be utilised effectively. However, despite all the inherent advantages experienced through media exposure, particularly in high economic regions, a surprising direct effect of financial security and media presence is that it decreases people's likelihood to act when there are changes in hydrological (and hydrogeological) conditions [12]. In other words, communities and individuals in financially secure regions with consistent media exposure have a higher threshold to change and require a greater stimulus to undertake socio-hydrogeological interventions. A solution to this disengagement may lie, perhaps counter-intuitively, in the evolution of handheld mobile technology (e.g., tablets and smartphones), which has allowed collaborative engagement and knowledge transfer to become an everyday reality. At present, there are approximately 20 countries worldwide with levels of smartphone utilisation above 65%; 90% of these are considered high-income regions, with a strong correlation (R^2 = 0.87) also found between per capita income and internet usage [34]. However, the rest of the "emerging world" is catching up; in 2015, a median of 54% of those surveyed reported occasional internet usage or smartphone ownership, an increase of 9% compared with 2013, with much of the increase coming from large emerging economies including Malaysia, China, and Brazil [34].

Inevitably, this will result in members of the public not only consuming scientific knowledge, but contributing their own unique ideas, views, and criticisms via blogs, podcasts, and social media. As such, while communication remains a central challenge for effective socio-hydrogeology, scope also exists for the development of citizen science strategies to move the discipline forward, particularly in medium- and high-income regions. Pragmatically, increased usage of mobile technology represents a novel data source and could assist in reducing the burden of large data requirements for socio-hydrogeological models [35]. Examples of the use of technology for safeguarding water quality can be seen all over Africa. For example, the use of mobile transmitters has made selected handpumps 'smart' by automatically sending usage data via short message service (SMS). Trials ran by Oxford University in Rwanda and Kenya suggest the technology can work and delivers promising results, offering data in four areas: (1) objective monitoring of daily water use; (2) use of monitoring data to rapidly identify and repair broken handpumps; (3) condition monitoring to predict failure prior to occurrence; and (4) non-intrusive, shallow aquifer monitoring [36]. However, further work is needed to elucidate the efficacy of this approach in varied societal and socioeconomic structures.

Furthermore, as illustrated by Re (2015) [11], many hydrogeologists spend substantial time in the field, and as such, they should be the first point of contact for well owners, farmers, and other groundwater users. However, as previously outlined, research by Hynds et al. (2013) [18] reports that only 1.2% of private well utilisers surveyed in the Republic of Ireland consulted with a hydrogeologist, with many citing lack of communication as a deterrent. The authors consider that appropriate development of interactive applications that embrace the communication of socio-hydrogeology in a highly technological world may facilitate hydrogeologists to act as mediators between theory and practice, or between the problem and the (potential) proposed solution to issues of resource quality; quantity; and above all, sustainability. However, the efficacy of socio-hydrogeological interventions are predicated on the identification of the key stakeholders; unlike surface water, groundwater is not as familiar to many people, and thus socially driven groundwater management requires carefully planned stakeholder engagement to ensure sustainable and continuous development of socio-hydrogeological paradigms that impact those most affected.

4. Socio-Hydrogeology, Stakeholder Engagement, and Groundwater Management

The value of the functions provided by freshwater ecosystems, such as rivers, wetland, and floodplains, has gained significant prominence in recent years as these "ecosystem services" represent a vast invaluable resource with respect to regional/national economies and human well-being [37].

However, the ecosystem services of groundwater, and particularly the provision of drinking water, are largely ignored; likely because of its hidden, and often complex nature, which can be difficult to manage. While groundwater resource management undoubtedly requires the technical skills of hydrogeological and engineering professionals, the spatially and temporally heterogeneous characteristics of groundwater flow and a myriad of environmental interactions actually necessitate active community and stakeholder engagement, arguably to a greater extent than surface water. However, the stakeholders for groundwater resources are not as obvious or various. As a result, at the forefront of all groundwater management strategies should be stakeholder network analysis; a process that investigates and categorizes the relationships between stakeholders [38] and identifies the key actors likely to positively influence the implementation of new management practices resulting from a hydrogeological investigation. Importantly, groundwater management and stakeholder identification must be holistic in its approach, considering environmental degradation in addition to resource assessment and engage a wide range of parties ranging from those who physically use and extract groundwater to those who manage and are affected by the benefits granted by groundwater influenced ecological systems (Figure 4). While detailed stakeholder analyses can be costly, they are also extremely valuable; a professionally facilitated process that begins with a carefully conducted stakeholder network analysis can help ensure that all interests are adequately met and that those affected by future groundwater policy have the opportunity to decide who will govern groundwater use. For example, in contrast to surface water (or hydrological) stakeholder network analysis, which frequently identifies engineers and water managers as the 'key actors' [39], hydrogeologically associated stakeholders tend to include residents and water user groups as key considerations [40]. This is one of the key differences between surface and groundwater users; for well owners, their supply is entirely personal and is typically not governed by an overarching management facility. As such, well owners are often the most valuable stakeholder in assessing quality and guiding policy and, therefore, should form a key component of 'integrated water resource management (IWRM)' planning [10,40]; an increasingly deployed approach to managing the water cycle in both high [41] and low-income countries [42]. However, groundwater is still frequently under-represented in water management plans, including IWRM and indeed, often added only as an afterthought [40].

Nevertheless, effective and sustainable management of water resources is vital for ensuring sustainable development [43,44]. However, while physical problems are well understood by the technical and scientific community, the range and complexity of socio-economic responses to these physical problems are not immediately recognised [10]. It has been reported that the failure to effectively engage stakeholders and communities in the planning and implementation of infrastructural projects of varying scales can prove costly, resulting in public controversy, and delayed or abandoned projects [38]. Previous studies have found that social, institutional, and political factors represent the primary obstacles to sustainable management of the world's groundwater resources, and typically lag behind technological and technical developments in hydrogeology [10,45]. Stakeholder and community involvement are thus crucial in the decision-making process [44] and to the successful development of any project, particularly ones involving groundwater that must engage a large number of individual users [10]. Accordingly, while water management is typically driven by top-down government approaches, participatory bottom-up approaches are now increasingly employed to involve local stakeholders, such as farmers, in the decision and planning process, and have been demonstrated to be a successful management strategy [45].

As constantly alluded to throughout the current article, sustainable current and future groundwater management strategies are confronted with momentous challenges [46]. Frameworks for sustainable groundwater management must respond to these emerging hurdles, while adhering to policy and legislative directives and the needs of communities and stakeholder bodies, thereby integrating important elements of engagement and technical insight. Moreover, stakeholders not directly using groundwater, such as river and conservation managers, must also be incorporated into framework development as they too have a voice and role in long-term resource sustainability.

Developing frameworks for management assists in avoiding situations where the public becomes engaged with groundwater only after a 'failure' occurs, such as the excessive exploitation of aquifers in countries with a high dependency on potable groundwater [46], meaning it is important to establish standards and principles for long-term monitoring and sustainable use. Social barriers to water management must thus be addressed. In recent years, social research and theory has been employed as an increasingly important factor in understanding and responding to the challenges associated with evolving a more sustainable society [39,47]. An example of this approach is the application of 'transition theory', which is generically defined as "*a gradual, continuous process of structural change within a society or culture*" [40,41], and may well provide a useful framework for socio-hydrogeology to go forward, in that it provides a basis for coherent, consistent public policy, which is not deterministic, but rather offers a range of possible pathways for change [40,41]. This social model facilitates community and stakeholder engagement by providing pathways between different levels of social structure (Figure 4), permitting transformative change [48]. The model contains three tier levels [48], as follows:

1. Technical learning and outcomes associated with implementing and refining technologies and policy instruments (first-order learning);
2. Conceptual learning associated with questioning (reconceptualising) the fundamental policy aims and objectives (second-order learning);
3. Social learning (third-order) providing the opportunity and leverage to promote regular shifts (transformation) in the sophistication of learning, from technical to conceptual. Indeed, it is suggested that without 'social learning', conceptual shifts in understanding will only occur following a crisis or persistent policy failure [42].

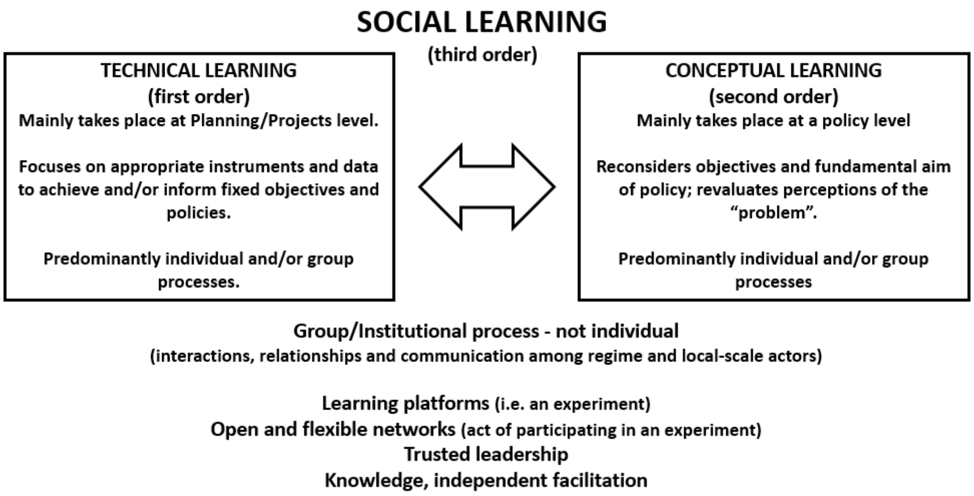

Figure 4. Social learning and transformative change, adapted from the literature [48].

This learning must be fostered by effectively communicating with stakeholders and end-users, which requires a nuanced approach if it is to foster stewardship and engagement on the part of the wider (non-expert) community [49–51]. This is one of the obvious spaces for the communication and social sciences to contribute to positive outcomes in socio-hydrogeology research. As such, a brief comment on some of the psychological factors related to this domain is warranted, before a wider discussion of the inclusion of sociological elements.

As stated earlier, one of barriers to effective communication is the combination of 'invisibility' and complexity, which can make it difficult to convey information in a way that is comprehensible. For a number of reasons, each of which must be addressed, this can make it challenging to garner enthusiasm and commitment to maintenance on the part of stakeholders. One key example is the fact that groundwater-related concerns, like many environmental issues, may be too "psychologically distant" [52] to be perceived as meaningful to end-users. For example, the comparative infrequency of waterborne infection across an individual lifespan, the ratio of instances of safe to unsafe water exposure, could be said to reduce the 'closeness in probability' experienced by those with more established access to groundwater resources. This may be further compounded by the ostensible randomness of events that pose an acute threat to groundwater sources such as extreme weather and flooding, as well as industrial or agricultural accidents. Additionally, a lack of understanding of the severity of the potential harm caused by waterborne disease such as Verotoxigenic *Escherichia coli* (VTEC) may decrease the degree to which people experience it as 'socially close'.

Although it may seem that simply presenting the reality of each of these components should result in more engagement on the part of end-users, a wide body of health and social psychological research has not only indicated that this is not the case [53], but has also enumerated a number of psychological models and socio-cognitive factors that must be taken into consideration [54].

Kasl & Cobb (1966) [55] define health behaviours as those undertaken by healthy individuals to promote continued wellbeing. A number of psychological models have been developed to explain the performance of such behaviours, such as the Health Beliefs Model [56] and the Theories of Reasoned Action and Planned Behaviour [57,58]. Although these theoretical frameworks diverge in some ways, one of the key areas of overlap, which is also of key concern to those wishing to communicate effectively on environmental issues, is that of perceived self-efficacy and control, which can cause social actors to disengage from an issue if not managed correctly [59]. Hydrogeological information may be particularly prone to reducing self-efficacy and perceived control on the part of end-users if not managed effectively. This is potentially best illustrated with a specific example.

The same features that may increase the 'psychological distance' for groundwater users, the randomness of weather and the socio-political space between end-users and policy making, may contribute to a sense of helplessness or extreme difficulty if communication is not adequately tailored to the target audience. This perceived difficulty has been shown to cause individuals to actively disengage from health behaviors [60], even so far as inhibiting physiological responses. The aim then must be that research is communicated to the wider community, rather than at the wider community in order to promote hydro-geologically related 'health behaviours' [61] and truly put the 'socio' in socio-hydrogeology. Communicating in this balanced way can help to foster the sense of shared social identity, inclusive of both the hydrogeological research community and the wider public, which will reinforce and bolster the sense of individual and group efficacy [62].

5. Putting the "Socio" in Socio-Hydrogeology

Ruddell & Wagener (2015) [63] assert that the solution to many of the 21st centuries grand challenges in hydrological education lie in the establishment of educational networks and partnerships between different strands within and beyond hydrology. To better serve and understand society, hydrogeology, distinct from hydrology, must thus draw impetus from previous and ongoing developments in social and communications science, and attempt to weave together findings from socio-hydrological investigations [11,28]. Hydrogeologists can, and indeed must, be leaders within socio-hydrogeology via advocation, mediation, translation, and promotion of best practice; they are in a unique position to advocate for appropriate groundwater management and protection, promote and develop experience at the local/catchment scale into regional or national management strategy, and assist in translating between the ideal (science) and the achievable (practise) [11,13]. However, in a rapidly changing world, it may be difficult for hydrogeologists to act as "social hydrogeologists", and more so when not operating within multi- or transdisciplinary teams.

A recent study by Hynds et al. (2018) [64] surveyed 1634 domestic wastewater treatment system (septic tank) owners from the Republic of Ireland, the majority ($\approx$65%) of whom derived their household water supply from a private borehole. While approximately 5.5% of respondents acquired relevant information (septic tank management, etc.) from public meetings and/or face-to-face interaction, approximately 37% of respondents obtained their information from the Internet, with a further 8% acquiring it directly from social media. Moreover, and perhaps more crucially, respondents ascribed a significantly higher level of efficacy (vis. trust and accuracy) to information from the Internet (89.5%) than from personal contact (83.3%). O'Dwyer et al. (2014) [65] found that proactivity (consumption avoidance) among Irish private well users (n = 132) as a direct result of individual-level knowledge (microbiological quality of their supply) was not evident across an entire survey cohort. As such, the authors consider that the "all things to all men" socio-hydrogeological approach likely does not represent the ideal; hydrogeologists may not have the time to act as social hydrologists, and in many cases, will not possess the necessary expertise with regard to appropriate scientific translation and communication.

Thus, the authors recommend an approach that truly "puts the "socio" in socio-hydrogeology", whereby hydrogeologists utilise and translate their sectorial expertise and local experience for social, communications, and media experts, thus fostering inclusion of the social dimension in hydrogeological investigations and ensuring appropriate demographically-focused information finds its way to the appropriate audience as efficiently as possible. As such, we present (Figure 5) a prototype circular socio-economy that incorporates both a "bottom up" and "top down" dimension, but importantly, also acknowledges that there must be a symbiosis between these two through 'multi-level governance'. For example, hydrogeologists, working in cooperation with social scientists and media/communications experts, in concurrence with continuing bi-directional stakeholder interaction and traditional scientific communication, permits an open discursive dialogue that can be augmented proportionally as needs arise. This inclusion of a communication loop (Figure 5) allows for continuous engagement and knowledge exchange, which can be used to stimulate new ideas and solutions as well as to develop bespoke groundwater management strategies at the local level. Importantly, and as shown within the model, interdisciplinary within hydrogeology should be encouraged, appropriately acknowledging it as a "community-facing" scientific discipline. As such, hydrogeologists require training in the integration of social and physical sciences, thus producing effective socio-hydrogeologists, and ensuring successful realisation of the hydrogeology-sociology-local knowledge feedback and knowledge exchange loop. However, even with appropriate training, interdisciplinary collaboration, particularly between the natural and social sciences, is crucial to solving the significant challenges facing humanity [66]; socio-hydrogeology would appear to be a perfect example of this, with the inclusion of social and communications experts also likely taking pressure off the hydrogeological community in both the short- and long-term.

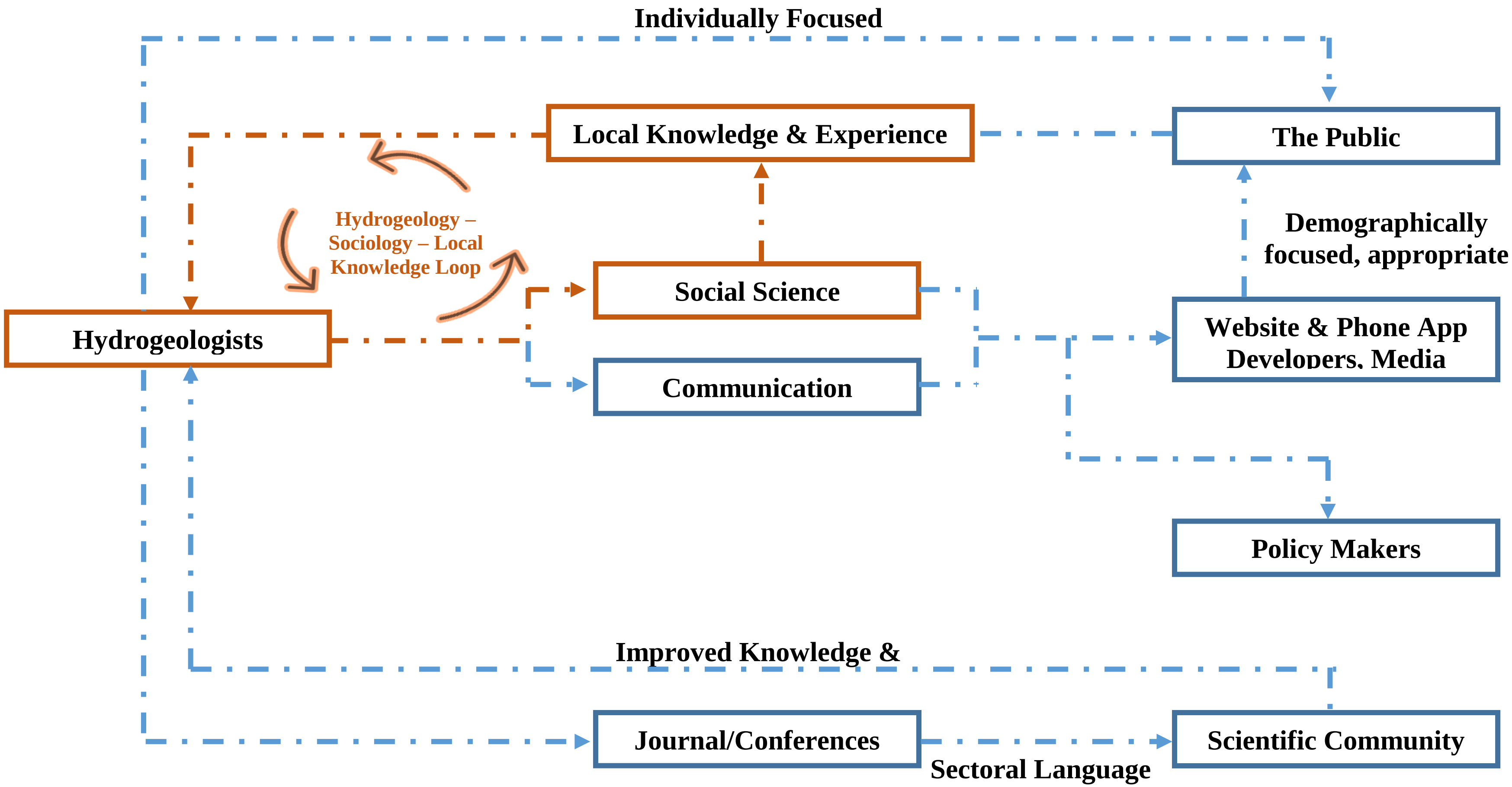

Figure 5. A proposed circular socioeconomy incorporating both "bottom up" (participatory) and "top down" (legislative/policy-driven) elements with hydrogeologists encompassing the communication keystone.

6. Conclusions

As recently noted by Reddy and Syme (2014) [67], sustainable groundwater usage and management likely represents the most difficult challenge within the broader field of water resource management, not only because of its global volumetric significance, but, perhaps more importantly, because of a widespread lack of mechanistic awareness and information, that is, occurrence, transport, and vulnerability to contamination. Similarly, necessary communication and engagement between experts and non-experts within the domain of socio-hydrogeology comprises an inherently higher level of complexity than that encountered within socio-hydrology, and, therefore, cannot employ analogous methods to bridging current gaps between geoscience and society. Previous studies have quite rightly called for an increasingly sociological mentality in attempting to alleviate groundwater-related issues [11,67] and this must continue to be fostered. It is apparent that the "all things to all men" approach may not be appropriate as it places pressure on the hydrogeological community to be societal, sociological, and linguistic experts, in addition to presuming high levels of homogeneity that are not present, socially, geographically, or hydrogeologically. Instead, we recommend that circular socio(hydro)economies comprising all affected and influential actors (hydrogeologists, groundwater users, policymakers), in addition to experts within the social and communications sciences, in order to ensure effective translation and demographically focused message framing. This approach would be particularly effective within medium and high-income countries that are no less reliant on groundwater resources, and no less sensitive to groundwater pressures; however, the demographic and cultural profiles within these regions are vastly different to those in developing countries. As such, effective bi-directional provision of information, experience, guidance, and recommendations should be both regionally and demographically bespoke, accounting not only for hydrogeological setting, but also for regional demographics, socioeconomics, and media preferences. As noted by Hynds et al. (2017) [68], "hydrogeologists possess an inherent understanding of the complex and unpredictable nature of groundwater contamination, and thus in collaboration with microbiologists, epidemiologists, geochemists, medical practitioners, and policy makers have an opportunity to help achieve global public health goals". While this sentiment undoubtedly remains true both now and into the future, it may pertinent to add social, management, mobile technology, and communications experts to this mix.

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