

Review

What We Know about Water: A Water Literacy Review

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Abstract: Water literacy, or the culmination of water-related knowledge, attitudes and behaviors, is a relatively new field of study with growing importance for sustainable water management and social water equity. However, its definition and use across existing literature are varied and often inconsistent. This paper seeks to synthesize and streamline the conception of water literacy. We conducted a systematic review of literature that defines or describes in detail either “water literacy” or “watershed literacy”. From this, we suggest a new holistic framework for water literacy to guide a more inclusive, relevant use of the concept. We utilized the framework to examine existing surveys and studies of water knowledge, attitudes and behaviors in both student and adult populations, and summarized water literacy levels and knowledge gaps that exist around the world. To address knowledge gaps, we suggest using a suite of approaches drawn from the published literature, including enhanced visuals, place-based learning, interdisciplinary curricula, and reflective and iterative development of future water literacy initiatives.

Keywords: water literacy; water education; hydrosocial; water sustainability; conservation

1. Introduction

Water is a key component for a sustainable future as a human, industrial, and ecological resource. Indeed, the United Nations’ Sustainable Development Goals (SDGs) for 2030 have expanded in SDG to “ensure availability and sustainable management of water and sanitation for all” [1]. However, recent scholarship has demonstrated that a large contributing factor to unsustainable water management and use is the poor understanding of water resources and systems. This includes depictions of water systems as isolated and separate systems from human activities [2], and the treatment of water systems as constant and self-regulating rather than dynamic and complex [3]. Additionally, water management practices often neglect the increasing globalization of water resources, where international water flows and virtual water extend beyond geographical boundaries and water scarcity issues stem from interjurisdictional processes [3,4]. Such research demonstrates that water sustainability must be founded on clear knowledge and understandings of our water resources and their relationships with humans and global systems. Moreover, the need for such knowledge is not confined to water managers, researchers, and decision makers, but also includes every citizen and user of water. Scholars have advocated for environmental efforts that mobilize widespread public support and action, even from those who “may not consider themselves ‘environmentalists’” [5] (p. 2). Sustainable water management is no exception to this idea and thus requires broad understanding and engagement across the masses.

There are several other important reasons why knowledge is a critical factor when it comes to sustainable water management and use. Water managers who engage their customers with knowledge and information are believed to be more transparent and trustworthy [6–8]. Additionally, public support for water management decisions is greatly increased when people understand the various issues and risks associated with options for action, or lack thereof [7–9]. Particularly in

democratic countries, this can lead to political will [10], public willingness to “pick up the tab” for new water projects [11] (p. 7), and even correlation with uptake of water conserving behaviors [7].

Sustainability also extends beyond this westernized approach of managing water as a good on which to capitalize. Mustafa and Halvorson [12] highlight how water resources and their various hydrologic features are as much social elements as they are physical. Water knowledge is multiplicitous, emerging from not just western science but also historical hydrologies, cultural traditions, and spiritual knowledges [13]. Additionally, water resources are inherently tied to economic and social processes. Water sustainability must therefore acknowledge all types of water knowledge and their connections within and across sectors and cultures. Indeed, such approaches in similar fields have been found to boost public support for environmental policies, particularly within communities of color [5]. Moreover, they can lead to opportunities to contribute to social justice surrounding water resources. For example, Dean, Fielding and Newton [7] posit that higher levels of water-related knowledge among the public leads to more numerous and productive discussions and public engagement in both informal and formal processes. Such conversations can expose and work to overcome the structures of power, culture, and cognitive biases that ultimately shape how people engage with modern water governance [14].

A strong, interdisciplinary and widespread foundation of water knowledge among all water users is therefore a pivotal goal towards achieving water sustainability and social equity. Some of this foundation, particularly scientific knowledge, is included in most K-12 educational systems, as well as in college curricula. The specificity of water education, though, varies from requiring a “basic knowledge of the hydrosphere” [15] (p. 574) to an overall scarcity of water topics [16] and is rarely addressed across the curriculum in systematic or multidisciplinary ways [17,18]. Additionally, Dean et al. [19] draw on the field of educational psychology to state that efforts to build a water-sensitive and engaged citizenry must include cognitive, emotional, and behavioral domains. This approach mirrors the learning goals set forth by the United Nation’s Education for the Sustainable Development Goals (ESDGs) [20]. Yet current K-16 curricula tend to focus on the cognitive learning domain, often neglecting other learning domains that are necessary for achieving true sustainability [21]. Finally, though water knowledge emerges from experiences and interactions with water throughout childhood and adulthood [7], this experiential knowledge is often treated as separate from traditional classroom and textbook curricula. The disconnect results in important gaps in both water knowledge and the translation of water knowledge to actions that support sustainability.

Out of the increasing recognition of the importance of water knowledge emerges the field of “water literacy”. It is the culmination of water-related knowledge, attitudes and behaviors, setting apart its importance and uniqueness from other more commonly used labels such as ecological or environmental literacy. The use of the term “water literacy” is increasingly popular, mirroring the growth of water issues and conflicts around the world. It is utilized by academic scholars, e.g., [6], governmental departments and municipalities, e.g., [22], and community organizations and non-profits alike, e.g., [23,24]. However, among these groups there appears no consensus on how to define, apply and assess water literacy as a concept. If we hope to develop a common framework to improve water knowledge and achieve water sustainability, a more comprehensive analysis of the water literacy concept is needed. To this end, we conducted a systematic review of the available literature to define, assess the state of, and describe efforts to improve water literacy.

2. Methods

The scholarly and grey literature surrounding water knowledge is broad and multi-disciplinary. We focused our search of the literature in four main areas: efforts to define water literacy, efforts to describe K-16 student water knowledge, efforts to describe adult water knowledge, and approaches to improve water literacy.

Our initial sources were found by searching three primary scientific databases (Google Scholar, ProQuest, and Jstor). Given the similar connotations of the phrases “water literacy” and “watershed literacy”,

both were used as key terms for our initial search of water literacy definitions. This resulted in 55 sources that provided a focus on water literacy rather than a passing mention. We next excluded any sources in which water or watershed literacy was not clearly defined or described. In total, this left us with the collection of 26 definitions listed in Table 1, which we then subjected to a qualitative thematic text analysis [25] to understand how the terms are commonly defined and applied. This approach involved first identifying terms and phrases and interpreting the intent of their use in each definition. We then generated themes using an inductive approach. We reviewed these themes within the context of other learning and knowledge frameworks and led to our final grouping and naming of eight unique themes.

Our searches also revealed a plethora of sources that draw on the concept of water knowledge and perceptions without explicitly using the phrase water literacy. While these papers do not provide an understanding of the definition of water literacy, they do still contribute to our knowledge of what people know or believe regarding water. Thus, in order to review the current levels of water literacy among student and adult populations, we searched any formally published or publicly available literature that also included the key terms “water knowledge”, “water education”, “water perceptions” and/or “water attitudes”. We started with these key terms, and then expanded our collection by reviewing the reference lists of the primary sources. When recent and comprehensive reviews of water knowledge elements were available, we referred to these in place of additional primary sources. We also obtained several surveys from www.waterpolls.org [26], a website that aggregates, analyzes and shares data from public surveys about water.

We recognize that some very specific aspects of water literacy have been investigated in great depth. For example, there is a large body of work that investigates attitudes and knowledge of alternative water resources, like recycled wastewater or desalination. As our focus is on water literacy as a whole, a full review of the literature in these specific areas was viewed as beyond the scope of this review and thus excluded.

This search brought us to our final count of 35 student and 35 adult water knowledge studies and surveys, authored by academic scholars, nonprofit organizations, water utilities, and local governments. This collection included journal articles, white papers, reports, and websites. We acknowledge that this review cannot possibly include every piece of literature that has been written about water knowledge and perceptions. For example, we are confident that there have been numerous, small-scale surveys completed by local municipalities of their customers’ water knowledge and behaviors, which have not been published or made easily accessible. Additionally, most of this collection details water literacy among the westernized regions of the world, with very little data emerging from developing countries.

Table 1. Definitions of water literacy from the 26 identified sources, which were used in the qualitative thematic text analysis to better understand how water literacy is collectively being defined and used.

Authors	Definition Provided in Source
Ewing and Mills [27] (p. 37)	"Roth (1991) suggests that functional literacy includes the ability to communicate the substance of an account to another person. In the case of water knowledge, we believe functional literacy entails ability to communicate an accurate understanding of processes such as condensation and evaporation as phase changes of water."
Covitt et al. [28] (p. 37)	"Possessing an understanding of water in environmental systems is a necessary, though not sufficient, component of environmental water literacy. Understanding how water moves through environmental systems and interacts with other substances is critical for making informed decisions about water at an individual or societal level."
Dolman [29] (pp. 99–100)	"In 1878, Thomas Henry Huxley involved watershed as a landscape entity or catchment basin, stating it is 'all that part of a river basin from which rain is collected, and from which therefore the river is fed.' This definition encapsulates the basic physical definition of a watershed in common parlance today. Our challenge is to move beyond a static, hydrologic definition toward a dynamic understanding of the wholeness of watersheds and how they literally underlie all human endeavors."
Eldridge-Fox et al. [30]	"level of water-related knowledge . . . on a local and global scale" and includes things like, where does Ann Arbor water come from, do you drink bottled water, do you conserve, access to water in different countries.
Project WET ¹ [23,31] (p. xiii)	Seven Essential Principles of Water Literacy: "(1) Water has unique physical and chemical characteristics; (2) Water is essential for all life to exist; (3) Water connects all earth systems; (4) Water is a natural resource; (5) Water resources are managed; (6) Water resources exist within social constructs; (7) Water resources exist within cultural constructs."
Su, Chen and Wang [32] (p. 518)	"It is suggested that understanding the usage of water, the health implication of water quality, and the overall impacts as a result of water shortage or extreme precipitation should all be part of the curriculum delivered effectively to students of all levels and the general society"
Laporte et al. [33] (p. 3)	"a water literate citizen understands essential principles and concepts about the Great Lakes' functions and value and can accurately communicate about the Great Lakes' influence on people and systems. However, what truly makes a person water literate is application of such concepts; making informed and responsible decisions regarding the Great Lakes."
Wood [34] (p. 7)	"I suggest that a water literate citizen is someone who is informed and knowledgeable about water use and issues, and is applying this knowledge to their values and their actions, whether that is achieved actively or subconsciously"

Table 1. Cont.

Authors	Definition Provided in Source
Hensley [35] (p. 29)	“Watershed literacy is the ability to understand the hydrological systems that make life possible within, and beyond, our water basin. Watershed literacy necessitates the ability to comprehend what a watershed is and “connect the dots” by recognizing the impact that human choices have on local, regional, and global water systems (Hensley 2011). A watershed-literate person can tell you in which watershed he or she lives and articulate the forms of point source and non-point source pollution that affect its integrity, balance, and health. Furthermore, a watershed-literate individual can articulate the opportunities to revitalize, protect, and restore water quality within his or her watershed while knowing how to reduce individual and collective impact.”
Duda et al. [36] (p. i)	“knowledge of and attitudes toward watershed health, knowledge of basic watershed concepts, and activities or behaviors that may impact the watershed’s environment.”
Fielding et al. [37] (p. 6)	“In the current report we will use the term ‘water literacy’ to refer to Australians’ water-related knowledge.”
Reenberg [38] (p. 185)	“In the Global North (www.allianceforwatereducation.org), the notion of water literacy has been developed and defined to mean ‘knowing where your water comes from and how you use it’. This includes but is not limited to, a basic understanding of water footprints, virtual water, groundwater recharge and consequences of over-drafting, how to move and control surface water, competing demands for water, and water conservation... broader notion of literacy is thus perceived as the capacity to assess (a) the impact of spatial and temporal rainfall patterns on the comparative advantage of different agricultural micro-strategies, (b) alternative ways of maneuvering to adapt to site-specific production potentials defined by water, and (c) long-term consequences of contemporary water use strategies”
Zint, Kraemer and Heimlich [18] (p. i)	“a watershed literate individual should be able to: (1) define the term “watershed”, (2) identify their local watershed(s), (3) identify how watersheds are connected to the ocean via streams, rivers, and human-made structures, (4) identify the functions that occur in a watershed (transport, store, and cycle water), (5) recognize that both natural processes and human activities affect water flow and water quality in watersheds, (6) identify connections between human welfare and water flow and quality, (7) identify possible point and non-point sources of water pollution, (8) identify actions individuals can engage in to protect/restore water quality in watersheds, and (9) identify how humans seek to manage watersheds”
Otaki, Sakura and Otaki [39] (p. 36)	“we define water literacy as the ability to feel familiar with water, get actively involved in water and face the issue of water as one’s own issue. Being water literate means understanding how the water we use daily is delivered and treated, as well as knowing the quality and safety of that water, how much water we use daily and exactly what we use it for.”
Alberta Water Council [22] (pp. 6–7)	“Being ‘water literate’ means having an understanding of the significance of water in life, and understanding where water comes from and how to use it sustainably . . . Water literacy can include aspects of air, water, land and/or biodiversity, which are inter-connected; it can also relate to discussions around sustainable development.”

Table 1. Cont.

Authors	Definition Provided in Source
Dean et al. [7] (pp. 2–3)	“The concept of ‘water literacy’, and other forms of literacy such as health literacy, integrate topic knowledge and the capacity to apply this knowledge to decisions [20,21]. The literature has not identified specific areas of knowledge considered necessary for adequate water literacy. The emerging emphasis on sustainable water management suggests that key areas of individual-level water knowledge include the urban water cycle and impacts of urbanisation on waterway health via stormwater pollution, in addition to issues related to water demand, supply and treatment”
Sherchan et al. [40] (p. 173)	“we see a need for a general education course that focuses on strengthening every student’s understanding of water literacy: its properties, sources, uses, issues, and the implications of these factors for informed decision making in the 21st century.”
Huxhold [41] (p. 2)	“Water literacy . . . refers to the amount of knowledge one has about the water system; it encompasses knowledge ranging from the state of water system infrastructure, the availability of water in an area, the quality and cleanliness of the water, the types of treatment used, the environmental impact, and what source the water comes from and/or where water goes when the individual is finished using it.”
Febriani [42] (p. 15)	“Water literacy covers basic knowledge of water sources and other aspects that interconnected with it (management and related issues), and being water literate means having a basic understanding of how to use or manage the water sustainably as a manifest of understanding the importance and significance role of water in life”
Mackenzie [43] (p. 18)	“Water literacy is the knowledge one has about the earth’s water sources: how they are used and how to use them”
Singh et al. [44] (p. 153)	“Water literacy is having an understanding of where the water that we consume or use comes from and how we use it.”
He [45] (p. 486)	“water literacy is a composition of necessary water knowledge, scientific water attitude, and normative water behavior... Water literacy, composed of water knowledge, water attitude and water behavior, is related to social economics, living habits, water ecological environment, water conservancy propaganda and education”
Roncoli et al. [46] (p. 575)	“Defined as knowing where your water comes from and how to use it, it denotes an analytical capacity unrelated to formal education or technoscientific expertise, being rather grounded in farmers’ understanding of the interconnectedness of water, natural landscapes, and human practices (Hastrup and Hastrup 2015: 19). Specifically, water literacy entails the ability to assess the impacts of climate variability on water supplies and use, to identify place-specific adaptive options, and to consider their effects on environment and community”
Ternes [47] (p. 349)	“the understanding of water supplies and how water is used”
Ripple Effect [24]	“A water literate person recognizes the impacts of climate change on real people and real communities, understands the role of water in shaping those impacts, and has a strong sense of civic responsibility to help redesign our relations to a changing environment.”
Wang, Chang and Liou [48]	“Water literacy should include variables such as water knowledge, attitude, and appropriate water behavior.”

¹ Project WET (Water Education Today) principles were developed in 1991 but were more recently renamed as “water literacy” principles.

3. Defining Water Literacy

Our first goal for this review was to provide a deeper understanding of how water literacy has been defined and applied up to the present moment. To this end, we conducted a thematic text analysis of 26 sources that either explicitly defined or very clearly described water or watershed literacy. The analysis resulted in the identification of eight unique and overarching themes that were mentioned within at least two different definitions, with the most frequent theme present in 17 different definitions. The emergent themes, hereby referred to as knowledge sets, are visually depicted and grouped in Figure 1 by both the level of detail and the learning domains present in each knowledge set. From the cognitive domain, we identified four separate knowledge sets: science and systems knowledge, hydrosocial knowledge, local knowledge, and functional knowledge. From the behavioral domain, we identified two knowledge sets: individual action and collective action. From the affective domain, we identified one knowledge set: attitudes and values. The unequal division between these three learning domains reflects a common issue among sustainability education literature, which emphasize cognitive learning over behavioral and affective learning [21]. Yet, our analysis indicates that water literacy practitioners still acknowledge the importance of the latter two domains.

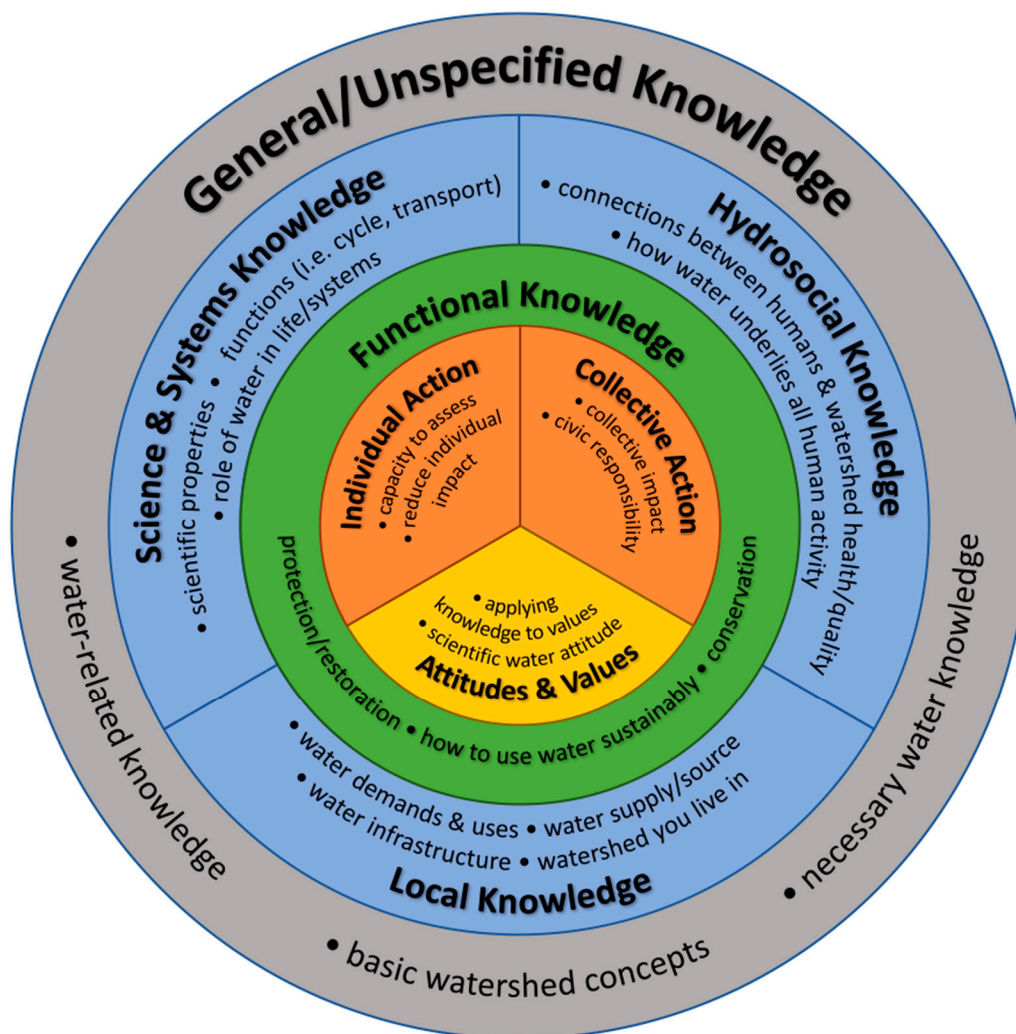


Figure 1. Key knowledge sets that emerged from a text analysis of water literacy definitions from 26 sources. This figure highlights the level of agreement regarding specific topics or requirements for water literacy within available definitions. More complete conceptions of water literacy draw on all or most of these knowledge sets.

In the gray, outermost ring of Figure 1 are the definitions that evoke simplicity and conciseness. For example, one of the broadest and most thorough water literacy surveys to date was conducted by Fielding et al. [37] in Australia, and yet they define water literacy as “water-related knowledge” (p. 6). This is one of the shortest and vaguest definitions we found, with little indication of what learning domains are included. Fielding et al. [37] are not alone in a preference for simplicity, though. In total, nearly half of the sources reviewed mention general and un-specified knowledge as central to water literacy, including “basic watershed concepts” [36] (p. i) and “necessary water knowledge” [45] (p. 486). The draw of such definitions is obvious. As water intersects in so many ways with both the natural and human world, water literacy encompasses a vast array of topics. It is difficult to select which are most important, particularly when considering the wider public who may not have much experience nor interest in water. By being vague, water literacy acts as an umbrella for all of these water topics.

However, such vagueness also sacrifices the ability to easily compare water literacy among locations and populations. Thus, most authors expand upon the details and information that should constitute water literacy, particularly within the cognitive domain. Three cognitive knowledge sets are depicted in Figure 1 by the second ring of blue circle segments. The first we termed science and systems knowledge, which is based on water’s unique scientific properties and its significance for living systems, including the water cycle and water’s ability to transport dissolved and solid materials. This category encompasses ecosystem needs and flows, with five definitions [22,28,30,31,35] mentioning the role of water in life and one explicitly advocating for knowledge of interconnected aspects like “air, water, and/or biodiversity” [22] (p. 7). In addition, six definitions address hydrological processes, cycles and functions [7,18,28,31,33,38], but only three specify that water literacy includes knowledge at the level of water’s chemical and physical properties [27,31,40]. Interestingly, four definitions call specifically for an understanding of “watershed concepts” [36] (p. i) or ability to define watersheds [18,29,35]. Sources emphasizing science and systems knowledge imply that a base understanding of hydrologic and ecologic science along with systems thinking is needed for application within broader, overarching water issues [27].

In contrast to this idea is a popular push for a *local knowledge*. This category encompasses an understanding of local water sources [40,42], water infrastructure [7,18,38,39,41], and current water demands and uses [38–41,43,44,46,47]. The definitions emphasizing local knowledge do not often overlap with the definitions emphasizing science knowledge, which highlights a key divergence in the literature. Instead, these sources suggest that such technical scientific understanding of the minute complexities of water systems may actually be perceived as burdensome and discouraging [41]. A local knowledge is deemed more inviting to the general public because it highlights the more relatable and simplified water topics as they pertain to day-to-day life. Within the category of local knowledge, there is a particular focus on knowing where one’s water comes from [22,30,38,41,46], with two definitions honing in on the need for familiarity with the watershed one lives in [18,35]. Examples like these convey the importance of context within water literacy. Indeed, water is itself an extremely contextual resource, and what might be important for someone living in a rural setting to know is inherently different from what is important for someone living in an urban setting to know.

The third set of detailed cognitive knowledge we have termed as *hydrosocial knowledge* because it refers to the bi-directional and continuous interactions between society and water resources. Definitions that fell within this category emphasized how human actions impact water quality and health of water resources, and at the same time, how the health and quality of water resources directly impact human health and welfare [7,18,32,33,35,38,39,46]. Like local knowledge, these topics were also presented in a contextual manner, with authors emphasizing the hydrosocial setting within built environments [7] or the watersheds like those of the Great Lakes [33]. However, it is this knowledge set that really reveals why it might be so difficult to agree on one definition. Rather than a static and self-contained natural system, scholars are increasingly recognizing and emphasizing the hydrologic cycle as intricately intertwined within and around social processes [2,49,50]. Water fuels economic growth, and economic and political systems simultaneously influence the generation of pollution.

Social and cultural structures are the backbone of how water resources are valued and maintained, while the cleanliness and health of water resources often creates social value. Thus, what we know about water, and what we should know about water, depend heavily on the complex and iterative relationships between water resources and their political, economic, social, and cultural contexts.

While these three cognitive knowledge sets are often (but not always) mentioned separately from one another, it is obvious that they all offer something different to the concept of water literacy. Knowing the science of a water molecule is important, but not enough to create water stewardship. Local knowledge creates personal ties to water resources, but it also confines water knowledge to a very specific region. Moreover, understanding the hydrosocial context to water reveals the layered complexity of water issues, but without the scientific knowledge of how to address an issue and the local knowledge of whom it most directly affects. Together though, these knowledge sets create a complex understanding of water literacy that revolves around geographic and social contexts.

In addition to these three knowledge sets, we identified one more cognitive set that we called *functional knowledge*. It is represented as the inner green ring in Figure 1, separately from the first three, because it is fundamentally different. We consider this as a bridging knowledge set that connects water-related knowledge to real world applications by underscoring the difference between how water is used currently, and how water should be used. It is a conative element that highlights knowledge about how to act or use water with a long-term perspective of water resources such that there is still adequate quality and quantity to supply future generations. This includes awareness of how to use water sustainably [42,43,46], how to conserve [30,38,45], and how to protect and/or restore watersheds [35,36]. This knowledge set was the least mentioned among the cognitive domain, with explicit inclusion in only nine of the 26 sources. However, we suggest that functional knowledge is indirectly implied in more definitions that require a translation of water-related knowledge into water ideologies and behaviors. Either way, the functional knowledge set is unique because one generally has to understand how to act before action can actually occur.

The final three categories in Figure 1, depicted in the center circle, introduce the other two learning domains of water literacy. First, is the affective application of water-related knowledge to one's *attitudes and values*, represented by the yellow wedge in the center of Figure 1. Water attitudes refer to the way one thinks or feels about water resources, and several definitions specifically say that the application of water-related knowledge should be reflected in one's "attitudes toward watershed health" [36] or "scientific water attitude" [45]. In a discussion of environmental literacy, Elder [51] refers to the shifting of attitudes as a subtle and difficult process, but also emphasizes how important they are for shaping behaviors. Along a similar line are water values, which center around assigning importance to water resources. For example, one definition ties water literacy to the ability to value the role and function of the Great Lakes in the U.S. [33]. In total, seven of the 26 reviewed definitions refer to attitudes or values as a necessary component of water literacy.

Finally, we identified two behavioral domains of water literacy, including *individual action* and *collective action*. These are shown by the two orange wedges in the center of Figure 1. Individual action refers to "informed and responsible" [33] decisions about water resources, which have the capacity to "reduce individual ... impact" [35] on water quality and water quantity. Reenberg [38] extends this category to local farmers, who assess water application based on productivity requirements and long-term consequences. Either way, it is typically a single person or single household that is responsible for action. This is the most common application of water literacy mentioned in 11 of the 26 definitions. In contrast to this is collective action, which refers to the water-conscious actions of a large group of people. It is the act of making informed decisions not just as an individual, but also at a "societal level" [28] (p. 37), in order to reduce the "collective impact" of humans [35] (p. 29). This is by far the least mentioned application of water literacy, with only two of the 26 definitions explicitly calling for collective action [24,28,35]. Yet, it is important to distinguish this from individual action because it recognizes both the shared nature of water resources and the public responsibility to proper management and use. Collective action, like participation in a watershed group or pushing a

water-conscious political agenda, is usually a long, complex process with numerous moving parts, and the resulting impacts are often delayed [51]. As it can be hard to convince ourselves that it is worthwhile to change our lives for some future benefit, collective action is difficult to achieve. Yet, it is a crucial step towards achieving sustainability for our water resources.

Collectively, these definitions and knowledge sets highlight that the concept of water literacy is multi-faceted and complex. The development of the emergent framework from this literature review utilized a bottom-up approach to determine how water literacy is being defined and used. This approach points to a strong anthropocentric bias for the concept, where water literacy efforts tend to focus largely on human actions and relation to water resources. While the emergent framework still depicts the importance of water for the environment in its own right, existing literature emphasizes a human-centric approach to water literacy that could be placing the environment second to societies and human development. Additionally, the unequal weighting of the three learning domains within the emergent framework demonstrates that water literacy efforts reflect the same overemphasis on cognitive knowledge that exists through sustainability education literature [21]. While Dean, Fielding and Newton [7] suggested no clear identification of a knowledge body necessary for water literacy, our review sheds light on several commonly agreed-upon elements that constitute the emergent framework.

It is worthwhile to compare this emergent framework to others within environmental and sustainability education. For example, in 2016 the Alberta Water Council (AWC) proposed a water literacy ladder [22], adapted from the environmental literacy ladder [51], which details five essential steps to move citizens to water literacy: awareness of water, knowledge, attitudes, skills, and finally actions towards water stewardship. While the water literacy ladder highlights all three learning domains more equally than Figure 1, it does not elaborate well on the specific topics and details of each step, as the emergent framework does. Thus, interpretation of the water literacy ladder may differ substantially between contexts. Additionally, even though the AWC acknowledges that water literacy is not always such a linear development [22], the depiction of a ladder with specific steps implies a set progression of water literacy that rarely occurs in practice. A second framework is one developed by Project WET. Since its creation in 1984, Project WET (Water Education for Teachers, rebranded in 2020 as Water Education Today) has provided water education and resources to teachers, educators and the public across the United States and 70 other countries. Their work is centered around seven core water literacy principles that explicitly detail all of the cognitive knowledge sets depicted in Figure 1 [23,31]. However, the Project WET framework provides little-to-no acknowledgement of the affective and behavioral domains. More recent efforts have expanded the Project WET core mission to include local engagement and action through their “ActionEducation” efforts [31], which apply water knowledge to local community projects, but such a behavioral effort is not yet evident within the framework. Additionally, the Project WET framework lacks anything resembling functional knowledge.

The third framework worth considering is that provided by the United Nations (UN) in the ESDG. It is not specific to water literacy, but rather frames sustainability education more broadly. As mentioned, the framework is built on a combination of cognitive, socio-emotional, and behavioral learning objectives [20], colloquially known as “know, feel, act”. Compared to our emergent framework, the ESDG is more simplified and equally distributed across the three learning domains. However, the level of detail provided in the emergent framework provides greater specification about the range of topics within water literacy efforts, particularly within the cognitive domain. For example, the science and systems knowledge set, the local knowledge set, and the hydrosocial knowledge set are all cognitively based themes that would be lumped into the first learning objective of the ESDG. Breaking down these categories as we have in Figure 1 may enhance water literacy efforts by providing stronger guidance about what details to include. Additionally, a recent critique of the ESDG highlights a problematic emphasis on anthropogenic activities [52]. The emergent framework from our review presents a similar issue, although perhaps recognizes non-anthropogenic ethics marginally better within the science and systems knowledge set.

4. What We Know about Water Literacy from Surveys

Understanding how we define water literacy provides a standard by which we can evaluate the current water literacy levels and knowledge gaps of the public. Of course, there is no one survey or even a standard set of surveys that breaks down water literacy as we have, but there are many studies and surveys that have investigated sections of our water literacy framework for specific populations. Synthesizing this information allows us to see broadly the general strengths and weaknesses of current public water literacy, which can then guide us on how to move forward. Thus, we attempted to summarize water literacy levels through two additional reviews of water-related surveys. The first focused on students, from children in kindergarten to young adults in college, and the second focused on adults aged 18 years or older. The following sections detail the key findings of these reviews, divided into the knowledge sets identified in our water literacy definition review and summarized at the end.

4.1. Student Water Literacy

Students across the educational spectrum are considered the next decision makers, and their public and private civic engagement around water will be integral in developing a sustainable future for water resources. An understanding of their water literacy and conceptions, as well as their alternate, limited, naïve or misconceptions, is a critical basis for designing effective educational programs and interventions. In 1993, Brody [53] reviewed the literature on student understanding of water and water resources. This review helped set the foundation for the development of the Project WET learning goals and curriculum. His primary conclusions indicated that biological, chemical, physical, and earth system knowledge related to water was poor and misconceptions abounded. While advanced students who had taken science courses utilized scientific terminology, their conceptions remained linked to personal experience and perpetuated past misconceptions. Brody [53] suggested that for students, water concepts were abstract and disconnected from everyday life and experience. Additionally, complex and interdisciplinary topics related to water resources were found to have the lowest levels of understanding. Brody's [53] review highlighted a lack of longitudinal studies as well as a lack of breadth in research outside of physics and chemistry. In subsequent work, Brody [53] also critiqued the lack of geographical and cultural diversity in studies of student water knowledge.

Since 1993, studies of student (K-16) water literacy/knowledge have continued and diversified, particularly in geographic representation. The breadth of topics addressed in the literature has also expanded, though most studies remain focused on distinct scientific and systems aspects of water knowledge, such as groundwater or the water cycle. Fewer student studies address hydrosocial knowledge, local knowledge, or functional knowledge topics. Comprehensive or broad survey data remain rare. Mills [54] developed a Water Resource Knowledge Assessment for high school graduates, but it was not broadly adopted by others. Additionally, though pre/post learning intervention studies were common, there is a marked absence of longitudinal studies in conceptual water knowledge. What follows is a summary of the current standing of student water literacy, as determined from a review and synthesis of 35 different student surveys and research studies, broken down by the knowledge sets identified in Figure 1 (excluding general/unspecified knowledge).

4.1.1. Student Science and Systems Knowledge

Two recent efforts to develop learning progressions and frameworks around water for K-12 science education in the U.S. have synthesized many of the more recent studies of science and systems knowledge, particularly as they relate to environmental science literacy and science education standards [17,55]. Gunckel et al. [55] reviewed the naïve conceptions of upper elementary to high school students related to the science and systems of the water cycle (including atmospheric and groundwater elements along with processes such as evaporation, condensation and movement), watersheds (including links to the water cycle and biotic systems), and water properties (including

chemical processes and pollution). They highlight the challenges documented in understanding the cyclical systems and the invisible or unseen elements of water. Some progressions of learning are documented, such as students moving from conceptualizing pollution as visible trash in younger grades to recognizing invisible chemical pollutants and some of the broader complexities, hydrosocial drivers and impacts of pollution (e.g., economic effects) in upper grades [56–58]. Without naming it as such, the authors also recognize in the literature the disconnect between water and local contexts such as students envisioning rivers as existing in rural areas [59] or watersheds in mountainous areas [60] and more representative of textbook figures than their own watershed, e.g., [61]. Finally, they highlight that learning interventions and instruction have been shown to “develop more connected, sophisticated, and systems-oriented ideas about water” [55] (p. 846).

Sadler, Nguyen and Lankford [17] conducted a review of research on student’s (K-12) missing- and mis-conceptions within four natural water systems (surface water, groundwater, atmospheric water, and water in biotic systems) and water in engineered systems. They note that although water is an interdisciplinary topic, it is most commonly addressed in science classes, and that the treatment across U.S. science curriculum and standards is in no way systematic. Difficulties and misconceptions begin with the most common curricular aspect of water, the water cycle. Their review reiterates that students struggle to grasp the abstract and invisible aspects of energy and matter exchanges, as well as both water and chemical fluxes between atmospheric water, surface water, ground water and biotic systems.

Together, these two reviews summarize well the recent science and systems knowledge of students. To build on these reviews in the context of diverse definitions of water literacy, we looked explicitly for studies related to local, hydrosocial, and functional knowledge among K-16 students. Though somewhat limited in the literature, both of these represent key progressions of understanding that can link the natural/physical science and systems of water to human actions in a reflexive way. For example, Sabel et al. [62] suggest that college students’ difficulties with core hydrological concepts may contribute to findings that students are challenged to provide scientific support for decisions about socio-hydrological issues and to link these to hypothetical voting scenarios.

4.1.2. Student Local Knowledge

A final topic taken up by Sadler, Nguyen and Lankford [17] in their review is “water in engineered systems”. Several of these research themes fall under our local knowledge set. Research highlights that most students do not know where their drinking water comes from or the treatment processes it undergoes before and after use, e.g., [63–65]. Middlestadt et al. [66] found that high school students in Jordan recognized rainfall as a source of water, but even after a curricular intervention they remain deficient in a number of knowledge aspects, such as knowing that treated sewage is a source of water in Jordan. In some cases, life experience and observations may lead to better understanding. High school students in Ecuador showed a relatively good recognition of their local water sources, treatment and transport, however, they lacked the correct vocabulary to identify all of these elements [67].

A study of German undergraduates found that although most students were aware that in the urban water cycle used water is sent to a wastewater treatment plant, many held incorrect conceptions that waste was treated to drinking water quality standards and cycled directly back for distribution and use without discharging into natural systems [68]. Attari, Poinsatte-Jones and Hinton [8] asked U.S. college students to draw a diagram showing how clean water reaches a home and returns to the environment. They found that the majority of both environmental science majors and non-majors drew sources, water treatment, distribution and household use. However, the majority of non-majors did not show elements of wastewater collection, treatment or return to the environment.

The term “virtual water” refers to an important hydrologic concept that identifies how water is used in indirect ways. Two studies of German high school and college students found that only between 2% and 22% could identify or explain virtual water, even as linked to production [69,70]. A number conceptualized virtual water as associated with computers or the internet, as in virtual worlds or

data, or as somehow fake or not existing. Most provided no answer. Given that virtual water is not addressed in the German school curriculum, the authors [70] attribute the correct, limited and alternate conceptions to exposure and experience outside of school. Most students incorrectly estimated that their direct to indirect ratio of water uses were essentially equal [69]. When asked to list water-intensive products, the majority of responses focused on textiles and clothing (96%) followed by plant-based foods (88%). Animal foods was also a frequent response, though surprisingly, less common than vegetable foods in 75% of responses. Interestingly, while products associated with cattle/beef/burgers appeared in student responses, there were no mentions of other forms of animal products (e.g., poultry or pork) [69].

4.1.3. Student Hydrosocial Knowledge

The hydrosocial knowledge set is one of the least addressed among student surveys. While systems thinking about water is often included in science curricula and within the science and system knowledge set, hydrosocial knowledge highlights the importance of the reflexive and integral nature of humans within water systems. Shepardson et al. [60] found that when prompted to draw and explain the water cycle, human activities and impacts and human landscapes were largely absent and suggest that “students do not make the connection to their everyday world, where human activity alters the hydrologic cycle” (p. 1465). An important link between humans and their water systems involves water quality. Students in India could identify some human impacts on water quality such as chemical fertilizers, deforestation and sewage, but they missed others including thermal pollution from power plants and atmospheric pollution [71]. These same students identified a number of impacts of pollution on biodiversity and ecological systems, but only a third recognized that pollution could enter the food chain. Similarly, Jordanian students did not link actions such as dumping oil or groundwater overdraft to water quality and salinity [66].

4.1.4. Student Functional Knowledge

While student knowledge of how to sustainably use, conserve and protect water resources is not always studied explicitly as we have defined it, some themes can be pulled from the literature. Overall understanding of water resources management and decision-making processes is found to be low among a range of ages [54,56]. Gill, Marcum-Dietrick and Becker-Klein [72] utilized the Model-My-Watershed web and problem-based learning application to evaluate student knowledge related to management decisions in a watershed. While students showed improvements, most did not reach the highest levels of conceptual understanding. Benninghaus, Kremer and Spregner [69] asked students to define their conceptions of sustainable development within a broader survey of global water consumption knowledge. Half of the high school students surveyed were able to identify the long-term conservation of a resource and responsible use to avoid depletion as elements of sustainability. Specific conservation knowledge was shown to vary in one study as three quarters of students recognized that compost preserved soil water, but only half knew that overuse depleted a local water source [73].

4.1.5. Student Attitudes, Values, and Actions

As noted, studies of water-related attitudes and values among students tend to be sparse. Two studies surveyed college students in contrast to members of the public and provide some insights. Cooper and Cockerill [6] found, as compared to the public, students were less concerned about future household water supply and thought less about water conservation. Conversely, Eck et al. [74] found that of 27 water issues in Oklahoma, USA, two of the most important issues identified by students, the public, and professionals alike were clean drinking water and clean rivers and lakes. However, students diverged from the other groups in assigning particularly high importance to agricultural water and land preservation and practices.

Perceptions related to drinking water quality among students is also a topic that has been surveyed with some breadth. Students often show a high trust in the safety of drinking water [70,74], though high school students may still prefer to drink bottled water [72]. Either due to or regardless of misconceptions, German undergraduates accepted the idea of using recycled water, particularly for non-consumptive uses [68]. The majority (>50%) of surveyed college students in Oklahoma, USA, supported the use of recycled produced water from oil and gas for industrial or agricultural purposes unrelated to consumption, but only the minority supported the use for improving stream flows or for drinking water [74].

Several studies addressed affective and behavioral aspects related to water. Work by Pan and Liu [15] found a positive correlation between students' groundwater systems understanding and concern about conservation and use of groundwater. Middlestadt et al. [66] found that a high school curriculum aimed at teaching water conservation knowledge and behaviors was effective at improving both of these in the experimental group of Jordanian students as well as improving certain water conservation practices by their parents (e.g., watering gardens in the evening instead of during the day). Their study also found that even among the control group, certain water conservation behaviors were more common, such as shutting off the tap while brushing teeth or drinking refrigerated water. What might be perceived as more challenging tasks, such as collecting running tap water until it heats to the desired temperature or taking a shower rather than a bath, were less likely to be impacted by intervention. Keramisoglou and Tsagarakis [75] had similar findings with high school students in Greece regarding both the impact of educational program on parents and the low adoption rates of high-effort conservation activities, in their case primarily related to body hygiene. They infer that teenagers, specifically, may be influenced by social factors that override conservation knowledge. Additionally, Middlestadt et al. [66] (p. 43) note that "our results indicate that providing students with specific behavioral knowledge can lead to behavioral change before the development of concrete attitudes about the efficacy of those actions" highlighting the importance of teaching not just about water, but teaching the tools, actions, and behaviors needed to conserve.

4.1.6. Student Water Literacy Summary

Water is a particularly challenging topic due to its systems complexity as well as its interdisciplinary nature. While much of the hydrologic basis of water systems represents scientific literacy, the global water crisis also involves impacts and actions by both individuals and societies and requires cross-disciplinary literacy to promote a knowledgeable citizenry. There is a call for greater focus in education on hydrosocial aspects of water and a push to emphasize the economic and social aspects of sustainability in addition to the environmental [69]. The studies reviewed here help to identify knowledge gaps and misconceptions in student populations. However, our emergent framework also highlights that there are elements of water literacy that are in need of further study, particularly hydrosocial and functional knowledge as well as student attitudes, values, and behaviors regarding water.

Based on the literature, attention needs to be paid to helping students to better understand and conceptualize the unseen elements of hydrologic systems (e.g., groundwater) and hydrosocial systems (e.g., water pollution). More emphasis should also be placed on the systems nature of water that includes both ecological systems and human or hydrosocial systems. Finally, knowledge gaps must be filled for students to have a more complete understanding of water management systems such as addressing the fate of wastewater and investigating virtual water use.

The research reminds us that without curricular intervention and formal education, student conceptions and mental models are dependent on prior experience and substitute observed phenomena for the unobserved or unknown hydrologic processes. However, care must be taken in the education system to link with prior knowledge and local experience so as not to overgeneralize. As noted, a number of authors have drawn attention to textbook figures and representations of water topics that may create or reinforce simplified conceptions, misconceptions

and alternate conceptions in students [2,15,60,61,73,76]. These include an absence of diversity in landscapes (e.g., mountainous terrain rather than plains), the lack of built environments, preferential depiction of natural environments, limited pathways and storage examples (e.g., lakes, but not groundwater), and highly abstract representations. Even the typical arrows in diagrams may mislead students [73,77,78]. When these static visuals are used as a primary teaching tool, such as in a lecture, students may learn and reproduce the representation rather than necessarily learning the concept [78,79]. Topics and case studies in textbooks may skew or limit student recognition of water scarcity and use topics [69]. In some cases, teachers themselves may lack the training and understanding to significantly impact conceptual change in their students [73,80].

Finally, an important point is made in several studies that there may be further disconnect when disciplinary water education occurs in isolation. Fremerey, Liefänder and Bogner [70] make the observation that although German college students graduate with the chemical background to understand hard water, many still describe hard water as harmful to humans (while the same ions in bottled water may be regarded as healthy). Outside influences such as commercial media for bottled water or personal experience with calcification of washing machines can also skew conceptions of learned knowledge. Similarly, isolating cognitive knowledge from development of values, attitudes, and behavioral knowledge misses a key opportunity to set foundations, mindsets, and habits that can carry into adulthood.

4.2. Adult Water Literacy

As much as children and students represent the next generation of water users, adults represent the current generation of water users and decision-makers. Adults are responsible for paying water bills and managing household water use. Adults read the news, which highlights stories of drought, pollution, and various water crises around the world. Adults also have the opportunity to vote on new water measures and projects, including price hikes in water tariffs, construction of new dams, recycled wastewater facilities or desalination plants. In these ways, water literacy is of critical importance for adult populations because it informs and directs water-related attitudes and behaviors that make an immediate impact.

While much of the data describing student water literacy emerged from academia, data and surveys of adult water knowledge more frequently come from municipal and governmental organizations. The focus of these surveys tends to be on attitudes and behaviors rather than knowledge. Additionally, there is a lack of longitudinal studies that monitor water knowledge levels over time. What follows is a summary of the current understanding of adult water literacy, as determined from a review and synthesis of 35 different adult surveys and research studies, broken down by the knowledge sets identified in Figure 1 (excluding general/unspecified knowledge).

4.2.1. Adult Science and Systems Knowledge

While the science and systems knowledge set is well represented within student surveys and education, it is not the primary focus for adult populations. Moreover, the majority of survey data that fall within this knowledge set addresses systems knowledge rather than science knowledge. For example, some surveys demonstrate that certain water system terms are less well known than others. Surveyed Albertans were mostly aware of bogs, marshes and swamps, but knew little about fens [81]. Similarly, surveyed Americans were widely unfamiliar with river system terms like riparian, watershed, and floodplain [82]. Beyond basic vocabulary identification, surveys also demonstrate that adult populations have difficulty understanding concepts of water transport, particularly in regard to groundwater. For example, while the majority of surveyed Albertans understood that groundwater fills the pores and fractures of rocks and soils, most also believed that groundwater exists in underground rivers and lakes [81]. Another survey indicated that respondents are not aware of groundwater quality or challenges with contamination [83]. This points to an inability to connect surface water systems with groundwater or to understand the invisible or unseen water elements.

Certain adult populations, however, demonstrate higher understanding of specific topics within science and systems knowledge, which appears to be a result of contextual factors. For example, McDuff et al. [84] found that consumptive resource users (i.e., anglers and hunters) in the Orange Creek Basin in Florida were more aware of water flow patterns and connectivity of streams and lakes than were non-consumptive water users (i.e., boaters and picnickers). Reenberg [38] found that local farmers in a village in Burkina Faso were extremely knowledgeable about how soil types respond to different rainfall regimes. Ternes [47] found that well owners in Kansas were more knowledgeable about groundwater movement and contamination issues than those on municipal supply. All three of these examples demonstrate how water-related science and systems knowledge are tied to life experiences and interactions with water systems.

4.2.2. Adult Local Knowledge

While less prominent within student surveys, local knowledge is by far the most commonly surveyed knowledge category among adult populations. The literature frequently emphasizes the importance of adults knowing facts like the source of one's water [41] and the structure of one's local water system [85]. Interestingly, it is a common finding that adults believe they know where their water comes from [7,81,86]. However, most surveys do not actually confirm that participants are correct, and in fact many municipal water outreach campaigns find that most people do not know the source of their drinking water [47].

Similarly, the average adult is unfamiliar with the concept of a watershed [87]. The overwhelming majority cannot correctly define watershed, even when choosing from a list of choices [7,88]. In fact, several surveys from both Canada and the USA have indicated that many adults do not even know that they live within a watershed [36,81,89]. This is only possible because many do not understand that all land drains to somewhere, and thus inherently must be included within a watershed. Even those who know that they live within a watershed are generally unable to provide the name of that watershed [7,81,85].

Several surveys also depict widespread unawareness about municipal water systems. A poll of voters in western USA found that only half were able to provide a name of their local water agency, and of those who could, only 44% were actually correct [86]. Another survey revealed that only 57% of American respondents were able to recall their yearly water bill [90] which, when combined with an inability to name a water provider, indicates that most people do not pay attention to their water bills or may not pay a water provider directly. Finally, several other studies found that participants in both western USA and Alberta, Canada incorrectly identified another water user other than agriculture as the largest water user in the region [81,91,92].

One topic that adult survey respondents tend to know slightly more about is physical water infrastructure. Several nationwide surveys in the USA found that Americans are typically aware of the broad importance of water infrastructure, as well as current infrastructural issues like aging and contamination [90,93,94]. That said, the actual treatment and distribution system is often misunderstood. Two surveys, one in Colorado, USA, and the second in Texas, USA, revealed a significant gap in knowledge concerning the fate of water sent down the drain [89,95]. Similar results emerged out of a nationwide survey in Australia, where 26% of participants believed that wastewater was discharged into waterways with little-to-no treatment [7].

Finally, one last local knowledge topic that is fairly unique to adult populations is water laws and water rights. These topics typically do not appear within school curricula until college-level, and even then, they are not considered a standard component of curricula. Correspondingly, surveys indicate that adults tend to know very little regarding water laws. For example, survey participants in the western states of the USA were largely unfamiliar with legal terms like riparian right, prior appropriation, interstate compact, river call, conjunctive use, water decree, beneficial use, and more [91]. Another smaller study finds similar results in Alberta, Canada, where 62% of polled residents were aware that natural water resources are property of the Crown, but only 37% were aware

of the existence of independent non-profit organizations called Watershed Planning and Advisory Councils (WPACs) [81]. Overall, there is a broad lack of familiarity among adult populations with the legal processes governing their water systems. This is partially understandable given that municipalities and water utilities generally handle these processes on behalf of their urban, suburban, and sometimes rural customers. Yet, even just a minimal understanding of such knowledge is beneficial for both day-to-day behaviors (e.g., in Colorado, USA, where residential rain barrels were illegal until 2016) and broader understandings of water movements (e.g., why the city of Denver is in a drought when there is water flowing through the local South Platte River).

4.2.3. Adult Hydrosocial Knowledge

As in student studies, hydrosocial knowledge is a less common topic emphasized in adult surveys. Still, those that cover it demonstrate that adults often have difficulty with thinking of water and society as interconnected systems. For example, one study found the average American citizen was unaware of the connections between streams and developments, which increase pollutants and shift runoff patterns [87]. More recent studies indicate that this may be shifting, with the majority of participants in both Canadian and American surveys exhibiting awareness that human activities can impact the quality of nearby surface water [81,95,96]. However, the ability to connect one's own actions with water quality is still often lacking. In Nevada, USA, the majority of respondents said their personal actions affected water quality either only a little bit or not at all [36]. Similarly, residents in Colorado, USA, were mostly aware that their actions would impact water quality of nearby streams, but also often chose to leave grass clippings and dog waste on lawns as fertilizer, despite the risk of nutrient pollution [96].

Hydrosocial knowledge also extends beyond water quality. The connections between human water withdrawals, drought, and watershed health are well understood by scientific communities. Many adults are able to associate drought with increased water and food prices, increased fire risks, and increased water conflicts [10]. Yet, the more complex and less visible connections are far less understood, like how drought impacts water quality, or what the causes of water shortages are beyond meteorological drought [10,95]. Still, the ability to tie a climatic event like drought to societal costs and conflicts is promising. It implies that perhaps it is easiest for people to recognize the aspects of hydrosocial relationships that most directly impact them. Indeed, other surveys have documented a growing recognition among the public of the key role water plays within economic systems and our public health [90,94,97].

4.2.4. Adult Functional Knowledge

Around the world, the public is increasingly recognizing burgeoning water crises. Adults tend to harbor a significant level of concern for water issues, which is often higher than the level of concern for many other environmental issues [10,96]. Two international surveys of adults indicated that the public places water quality and water shortages as the top two current problems [98,99]. Newer research indicates even more growth in this public concern [96,99,100]. However, recognizing an issue and understanding how to fix that issue are two very different sets of knowledge.

That is not to say that adults know nothing about how to use water. In Alberta, Canada, more than 80% of survey respondents are aware that they can protect their watershed by reducing or eliminating lawn chemicals, or by using a certified carwash rather than washing a car themselves [81]. Across the USA, surveys indicate awareness of household-level water conservation, like installing water saving fixtures or operating sprinklers in cooler hours to limit loss from evaporation [36,82,83]. However, much of adult functional knowledge appears to be contextually dependent. For example, He [45] found that survey participants living in drought-prone regions of China had better conservation knowledge than those living in more water-rich regions. Similarly, well owners in Kansas, USA, knew more about sustainability of groundwater than those on municipal supply [47]. Experience plays a critical role

within functional knowledge, because understanding how to better manage water resources tends to follow after times of water crises.

Still, there is an acknowledged gap among adult populations in understanding how best to utilize and protect water resources. In addition, it is not just scholars and water managers emphasizing this gap; the public themselves are among the first to admit they need more information. Surveys indicate that people are aware that they could be doing more to protect water resources, but simultaneously feel as though they do not know enough to do so [98,101]. Some survey data indicate that the public perceives a lack of easily available information regarding water resources [36,81]. Time and time again, survey participants express a desire to learn more about how to use water sustainably, whether it is about water conservation [82] or the “true cost of water” [95] (p. 15). Adults in Iran expressed the need for more educational programs about conservation and the cultural barriers of reuse and gray water [100]. Thus, it is clear that functional knowledge could most definitely be improved for students and adults alike.

4.2.5. Adult Attitudes, Values, and Actions

Within adult populations, the attitudes, values and actions categories of water literacy are a stronger focus than with students, who are not yet the primary decision makers in their households. In contrast to students, adults represent an age group that is not only capable of making many water-related decisions, but also expected to do just that. Their behaviors directly influence the success of initiatives like water conservation, pollution prevention, and the funding of large infrastructural projects. Thus, the translation of water knowledge to attitudes, values and actions is a very important process to understand.

Given the high levels of concern for water issues, it is no surprise that attitudes about water are emotional. Surveys indicate a reoccurring fear among adult populations about the ability of current water systems to meet the needs of the future [6,92,93,97]. Only one survey indicated a substantial amount of optimism about future water supplies, but then went on to say that participants worry that urban centers will struggle more with water supplies than rural areas [86]. Furthermore, while many believe that conservation is the responsibility of everyone [81,102], an even larger number indicate that some level of government ultimately needs to take charge [6,10,98]. Even so, Cooper and Cockerill [6] found that adults strongly prefer that water resources are controlled and managed by local governments rather than state governments.

Adult public opinions regarding the efficiency and success of current systems are fairly mixed. Some surveys demonstrate an even split between critique of and support for current water management strategies [81,92], while several others document dissatisfaction and a desire to see changes to water laws and practices [91]. Such division is evident in the public’s concern surrounding the quality of tap water. One survey demonstrates that more than one third of American participants believe tap water is unsafe to drink [93]. Other surveys indicate that although tap water is perceived as safe, respondents still choose to filter or boil before drinking, or even choose to purchase bottled water instead [83,103]. Water managers and local government are not the only targets of such distrust. Surveys reveal that members of the public also tend to blame each other. For example, one survey indicates people think that that new residents are to blame for increased water demand and subsequent water shortages [104]. Additionally, while the public often shows willingness to conserve and get involved, surveys often find that there is also a preference for mandatory conservation through government restrictions [10,91], revealing a lack of trust in one’s neighbors’ ability or willingness to conserve.

In terms of behaviors, adult surveys mirror what is found in student surveys with a strong preference for individual actions over collective actions, especially those that require the least costs or lifestyle changes. For example, 90% of surveyed Americans [82] and Australians [105], as well as 70% of surveyed adults across the world [97], turned off their taps while brushing their teeth or doing dishes. Another 85% of surveyed Americans [82], 89% of surveyed Australians [105], and 64% of surveyed adults worldwide [97] only ran full loads of laundry and dishes. These are small changes with no price

tags, that actually can save households money. Meanwhile, actions that are more pertinent to adults and homeowners, like installing water saving fixtures indoors or eliminating lawn chemicals are much less common [36,81,83,105]. The price tags of water saving fixtures can be hundreds to thousands of dollars including installation, not to mention that eliminating lawn chemicals may mean a less green lawn with more maintenance.

Collective actions, however, are by far the least common applications of water literacy. While 40% of survey participants in Alberta, Canada, had discussed water issues with their friends at some point, less than 13% had extended that conversation to include municipalities, government officials, or watershed groups [81]. A survey across the USA found that 32% of participants were involved with watershed conservation or protection groups [82].

4.2.6. Adult Water Literacy Summary

The water-related research and surveys conducted on adult populations provide a clear contrast to those conducted among student populations. Perhaps because science and systems knowledge is often the primary focus within conventional school programs, it is assumed (or at least hoped) that such knowledge will be retained through adulthood. The adult surveys suggest, however, that student misconceptions or knowledge gaps, like those surrounding groundwater, are carried through to adulthood [81,83]. However, systems knowledge may also emerge more prominently out of contextual and experiential learning moments [38,47,84]. Along those lines, local knowledge is a much stronger focal point for adult populations, likely because it is the category of knowledge that most directly applies to household decision-making and local voting initiatives.

As suggested for student populations, there is also a need among adults for a greater focus on hydrosocial knowledge. While adults indicate some awareness of the economic and social importance of water, they clearly show room for improvement. There is also a lack of surveys that emphasize culturally indigenous water knowledge as opposed to western knowledge, upon which most modern water management systems are based [13]. Additionally, the gap in students' functional knowledge extends into adult populations. This is acknowledged not just by surveyors, scholars and water managers, but also by the public themselves. There is a desire to learn how to become more engaged with water-conscious behaviors and governance processes [82,95]. Interestingly though, this is paired with an apparent disregard for one's water bill, which often includes educational articles, helpful information, or answers to frequently asked questions. Perhaps such passive attempts to enhance functional knowledge among adults should be more active and engaging.

Finally, it is clear that water knowledge among students is vastly different from that among adults. These two populations are typically educated and engaged in isolation from one another. This creates substantial gaps in water literacy knowledge sets. Achieving sustainable water governance may require more reflective and iterative approaches to water literacy, such that acknowledging gaps in water knowledge among adults results in a shift in educational programs among youth, and vice versa.

5. Approaches to Improving Water Literacy

A goal in identifying water knowledge and gaps is to find ways to improve and develop a more complete water literacy among the populace. Our review of water knowledge studies of students and adults reveals several key areas in need of improvement. These include the generation of misconceptions and misunderstandings among students that carry through to adulthood; the uneven emphasis of local knowledge; the widespread lack of hydrosocial and functional knowledge; the treatment of student and adult education as isolated and separate. Drawing on the published literature, a suite of approaches that have been suggested or put into practice could be appropriate to address these particular gaps. While this is not an exhaustive list, using a combination of enhanced visual tools, place-based learning initiatives, interdisciplinary approaches, and a more reflective and iterative process between student and adult water education programs can help move the needle toward an improved and balanced water literacy.

Conceptual change around water and water systems is one of the greatest challenges to improve water literacy. Incomplete and incorrect conceptions abound, persist and may be exacerbated by the very tools we use to educate, such as the ubiquitous water cycle diagram. Thus, improved visual tools and messaging have been targeted as an important approach to improve water literacy. Studies demonstrate that depictions of the water cycle used in school curriculum, textbooks, online sources and even published academic and government documents are largely the same image of water moving through mountainous settings, devoid of groundwater movement and human interactions [2,60]. Instead, more inclusive and complete mental models can result from the depiction of more diverse settings, including urban and rural locations [60,106], varied biomes and different seasons [2]. Interactive computer simulations are another visual tool that can capture the dynamic and complex nature of water systems and are adaptable to a range of learners. Research has shown that such tools improved the systems-thinking skills of elementary students [107], corrected misconceptions about groundwater among secondary students [73], increased groundwater knowledge among university students [73,108], and increased water knowledge of primary and secondary teachers [108]. Additionally, visual tools can tie local knowledge to actionable functional knowledge. For example, in Colorado, USA, Denver Water's award-winning "Use Only What You Need" drought campaign utilized visuals ranging from slogans on billboards to three-dimensional sculptures that demonstrated differences between current water use volumes and actual need volumes [109]. The information conveyed in these visuals that tailor actionable information to the Denver population corrects misconceptions that water is renewable, while pairing science and systems knowledge with local knowledge in visually stimulating and relatable ways. Ultimately, this can help learners to understand and hopefully retain information from childhood to adulthood.

The suggestion of emphasizing place-based learning requires that all lessons are situated in place and space. In terms of water literacy, this entails connecting typical science and systems curricula to the physical, social and political context of water resources. Indeed, attempts to increase water literacy that embrace place-based learning are often found to be more successful. For example, a 5th-grade place-based curriculum on watersheds led to improved identification of links between urban land-use, runoff, water quality and the concept of watershed drainage [110]. Additionally, place attachment to a rural lake region in Wisconsin led to adults not just understanding water quality better, but also expressing greater intentions to preserve water quality by voting for laws or joining a group [96]. Both of these examples involve a stronger focus on local water knowledge, while the latter also weaves in functional knowledge and water literacy attitudes.

Place-based approaches also offer opportunities to address significant gaps in hydrosocial knowledge. Within Linton and Budd's [50] hydrosocial cycle, the physical environment of one's water system helps to shape one's narrative of water. Thus, it follows that water literacy would be tied to one's geographic place. However, places can have different meanings to different people, which impacts how knowledge is internalized and understood. Assaraf et al. [65], for example, highlighted how indigenous Bedouin 4th graders in Israel have "richer mental models of water cycle phenomena" (p. 451) than their small-town Jewish counterparts because they incorporate elements of their theology into the water cycle. Similarly, Swentzell [111] showed how U.S. Indigenous Pueblo culture provides a deeper connection to the water cycle and watershed, which does not always fit within a traditional positivist scientific literacy perspective. Thus, attempts to teach social, cultural, and political water relationships must be contextualized within place. An example of such an attempt can be found in Australia, where a local water authority partners with the Widjabul/Bundajalung peoples to provide local Water Walks. Participants of all ages meet at a creek and dam location to experience oral history, bilingual interpretive signage and worksheets as "a walking, listening, breathing, discovery project that requires conscious and embodied participation" [13] (p. 240). The program offers an interactive, engaging lesson that ties our water knowledge not just to the local geographic context, but also to the cultural and social context of the region.

Gaps in hydrosocial and functional knowledge can also be minimized through greater valuation and development of interdisciplinary education. The future of water management and water justice needs citizens and leaders who firmly understand the numerous and complicated connections between water resources, human activities, and culture. As such, several new curricular models in post-secondary education have emerged that frame water education within interdisciplinary structures. These include efforts from Emory University, Atlanta, GA [112], Fresno State University, CA [40] and University of Nebraska-Lincoln [62,113]. In addition to student learning, these interdisciplinary efforts resulted in powerful faculty development through cross-pollination of ideas and perspectives on water. Graduate programs are also embracing this approach in training future water resource managers, citing that not only water knowledge, but “soft skills” are important [114]. Further, the United Nations touts a “Multiple-Perspective Tool” as an important framework for sustainable development and freshwater issue education [115].

Finally, this review highlights a major disconnect between how we approach water literacy in student and adult populations. Specifically, we tend to survey, study and address their knowledge separately. While numerous studies have addressed student conceptions of the water cycle and scientific knowledge, less is known about their attitudes and values regarding water. The opposite is true regarding adult water knowledge. As such, the approaches used to educate these populations are disconnected. Such disconnects and inconsistencies between populations also make direct comparisons of survey results difficult. Thus, a more reflective and iterative approach linking student and adult water literacy initiatives is proposed, such that knowledge gaps in one population inform educational initiatives for the other population and vice versa. One such example of this exists in a research study by Thompson et al. [89], who surveyed 1000 adults in North Central Texas’ Upper Trinity River Watershed, and then used the results to design a set of educational programs for each school year between kindergarten and 5th grade. Their results showed increased awareness and commitment by students to conserve water based on the new water programs. Such innovative studies and approaches should be more commonplace, as they address recognized knowledge gaps that prevent a more holistic water literacy.

Such reflective approaches should go in both directions. Indeed, there are several studies that highlight the important potential of intergenerational learning [116–118]. What children learn in school they often share with their parents, creating an opportunity to share water knowledge. One Project WET program delivered in Arizona, USA, taught students how to audit household water usage, resulting in many of them showing their parents how to conserve water and install water-efficient faucet aerators [119]. Programs that engage youth and parents at the same time also show promise at increasing water literacy. Water festivals, which interface experiential education with classroom education, are a prime example. Studies have revealed statistically significant gains in student knowledge, conservation behaviors, and enthusiasm for water [120] while also engaging parents and guardians with the same educational information and opportunities to speak with scientists and water experts [121]. It should be noted that many studies indicate the success of intergenerational learning is context-specific and can never replace adult education entirely [118]. However, given the increasing complexity of modern water issues, and the revealed water knowledge gaps that span age groups, any and all tactics that can increase awareness and generate action should be employed.

6. Discussion and Conclusions

Through the review of existing definitions and descriptions of water literacy, we highlight what other scholars have also found, which is that current water literacy definitions, understandings, and applications vary substantially [7,22]. However, by coding and collating current definitions, we have also identified several commonalities. Our emergent knowledge set framework (see Figure 1) can be used as a guide for future work towards a more inclusive and relevant use of the water literacy concept. It bolsters the efforts of previous frameworks, like the AWC’s water literacy ladder [22], Project WET’s water literacy principles [31], and the UN’s ESDG framework [20], to analyze their

strengths and weaknesses and identify specific elements of water literacy. The emergent framework highlights an uneven emphasis on cognitive domains compared to affective and behavioral learning domains, as well as a bias towards anthropocentric water needs. It also suggests new ways to view the interconnected nature of water knowledge with our identification of unique knowledge sets. The diversity of definition sources also makes clear that the development of common language and goals around what constitutes water literacy will require enhanced engagement, collaborations and communication among the diverse groups working in the field.

We applied the emergent framework to review existing surveys and studies of water knowledge, attitudes and behaviors among student and adult populations to highlight the current standings and broad knowledge gaps that exist around the world. There are limitations to this application, including the fact that most of the literature we analyzed studied relatively small populations in primarily westernized countries and typically addressed only a subset of all the knowledge sets identified in Figure 1. Additionally, our review has identified areas that are in need of additional research, such as in the values and attitudes and the action knowledge sets of students, or within the affective and behavioral domains of water literacy more broadly. However, the data that emerge from our analysis reveal several reoccurring knowledge gaps and inconsistencies in current water literacy initiatives, including the generation of misconceptions and misunderstandings among students that carry through to adulthood; the uneven emphasis of local knowledge; the widespread lack of hydrosocial and functional knowledge; the treatment of student and adult education as isolated and separate. If the goal is to work towards water sustainability by increasing water literacy among the public, these issues must be addressed in future efforts.

Indeed, the literature suggests a varied number of approaches for improving water literacy. In order to best address the knowledge gaps we identified, we have highlighted a select few approaches for future work. These include: creating and utilizing enhanced visual tools to correct student misconceptions while tying local and functional knowledge to current science and systems knowledge curricula; emphasizing place-based learning initiatives to convey local and hydrosocial knowledge; increasing the interdisciplinarity of educational curricula to shape future generations of water leaders that are well versed in hydrosocial and functional water knowledge; shaping future initiatives through more reflective and iterative processes between student and adult water programs.

However, as we consider water literacy and developing water literate populations, we would benefit to keep in mind several ideas suggested by Koballa, Kemp and Evans [122] in their exploration of science literacy. First, the complexity and breadth of water literacy suggest that there will be different levels of literacies across multiple domains and that these will change over time in an individual based on personal and external motivations, experiences and values. Additionally, we must view the development of water literacy as a lifelong pursuit, supported at first by schooling to develop knowledge base, skills and motivation, but then supported and valued by society as a whole, (including government, industry, municipal water providers, resource managers, the media, etc.) [122]. Attempts to address misconceptions, knowledge gaps, and overall water literacy should occur at all ages, from “K to gray”.

Finally, as scholars, managers and global citizens, we may also benefit from a reminder that the majority of views and surveys reviewed here about water literacy privilege a western science view of knowledge. Indeed, the vast majority of reviewed water literacy definitions emerge out of the Global North, with particular emphasis on Australia, Canada, and the USA. We were able to find more diverse literature when expanding the search beyond “water literacy” to surveys about water knowledge, attitudes and behaviors, but there is still a strong bias towards western cultures. However, as numerous scholars note, deep cultural and eco-cosmological literacies about water are equally important as an understanding of a concepts like drought index [13,46]. Thus, future research on water literacy should seek greater exploration of non-western water knowledge across a much broader range of settings, with specific attention on developing countries.

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