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Towards water literacy: an interdisciplinary analysis of standards for teaching and learning about humans and Water

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Abstract

Water is critical to sustain human existence. Water literacy involves understanding the interactions within and between natural and human dimensions of water systems to support informed decision-making, an important outcome for learners of all ages. It is therefore critical to foster water literacy in today's global citizens, particularly through formal education. The purpose of this study, in tandem with a parallel study focusing on natural dimensions of water systems (Mostacedo-Marasovic et al., in press), is to examine water-related K-12 standards for teaching and learning about human dimensions of water systems to develop a comprehensive and transdisciplinary perspective on water education. Our overarching question is, *"What do disciplinary standards specify as outcomes for students' learning about water and humans?"*. Our research questions are: i) *"To what extent do these water-related standards address recognized domains of learning?"* and ii) *"What thematic outcomes for students' learning are apparent across grades in these water-related standards?"*. We use chi-square statistics and a conventional qualitative content analysis method complemented by processes from grounded theory to analyze water-related education standards ($N = 341$) from 12 education-oriented, governmental and non-governmental organizations based in the United States. Our results indicate that first, water-related standards emphasize the cognitive domain, including declarative and procedural knowledge. The affective domain and its social and emotional components are much less prevalent. Second, the water-related standards illustrate five categories which encompass human dimensions of water spanning K-12 grade bands, including human settlements; the nexus between water, food, and energy; public health; impacts of human activities on water quality and quantity; and water resources management. Overall, the study contributes to a more holistic and comprehensive perspective of water and human systems that can help inform teaching and learning to cultivate water literacy, including curriculum development and classroom pedagogy.

Keywords: Water literacy, Education standards, Socio-hydrologic systems, Curriculum

Introduction

Water is critical for human systems. Humans have historically implemented water management strategies to utilize water resources to support diverse human activities. Nevertheless, ever-evolving water use patterns have brought about major changes in natural water flows,

storages, and quality (Savenije et al., 2014; UNESCO & UN Water, 2020; United Nations World Water Assessment Programme (WWAP), 2017; World Health Organization & UNICEF, 2015). These changes pose risks to human health, habitats, ecosystems and their ecosystem services (UNESCO & UN Water, 2020; UN WWAP, 2017). Furthermore, climate change and its associated impacts on water distribution and availability, especially in water-stressed regions, compound these through extreme weather events, the spread of water-borne diseases, and changes in crop production yields, impacting

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communities disproportionately (UNESCO & UN Water, 2020). With increasing threats to water resources, water management decisions have and will become more complex, needing to account for both natural and human components of 'socio-hydrologic systems' (Sivapalan et al., 2012).

Water education will play a critical role in preparing the next generation of water experts, policy-makers, and informed citizens, each of which will contribute to water-related decision-making in social, cultural, and economic spheres of human activity. As such, water education is fundamentally interdisciplinary and of interest to many different organizations. Water is a core component of all scientific disciplines (geo-, life, agricultural, physical, and chemical sciences), as well as for engineering, economics, business, public policy, public health, and many others. Each of these disciplines has its own unique perspectives and priorities in respect to water as a disciplinary topic. And, because much curricular and instructional decision-making in formal education remains discipline-specific, whether at the K-12 or postsecondary level, it is perhaps not surprising that standards for teaching and learning, which remain broadly influential on curricular and instructional decision-making, reflect these disciplinary perspectives and priorities. However, given the many documented challenges cultivating students' learning about water, it is critical to afford them water-focused learning opportunities that span disciplines, particularly as water relates to human activities. Doing so requires, among others, a transdisciplinary account of water-related standards that provide a comprehensive account of water-related knowledge, skills, and practices that can guide teaching and learning about water across K-12 grades. However, thus far, no effort has sought to account for water-related standards, originating from a diverse array of sources, as a comprehensive blueprint for water education outcomes. The purpose of this study is to address the overarching question, "*What do disciplinary standards specify as outcomes for students' learning about water and humans?*" To do so, we post two research questions that guide the study: 1) "*To what extent do these water-related standards address recognized domains of learning?*", and 2) "*What thematic outcomes for students' learning are apparent across grades in these water-related standards?*" This study is part of a larger study of water-related standards, including those that foreground the natural dimensions of water (Mostacedo-Marasovic et al., *in press*).

A standards-based perspective on Water literacy

Water literacy, like other 'literacies' (science, climate, environmental, etc.), provides a generalized construct that can serve as an overarching aim of water education.

Like these other literacies, however, it is a complex construct defined in many ways. We draw upon McCarroll and Hamann's (2020) definition of water literacy as the "culmination of water-related knowledge, attitudes, and behaviors" (p.2), which builds upon other definitions of water literacy that also foreground the importance of water-related knowledge, attitudes, and behaviors as part of water literacy (Amahmid et al., 2019; Çoban et al., 2011; Johnson & Courter, 2020; Martínez-Borreguero et al., 2020; Sammel, 2014; Simonds et al., 2018). The discrete knowledge, skills, and behaviors that comprise water literacy can be defined by water-related standards for teaching and learning. Standards can provide guidelines that can orient water-related curriculum, instruction, and assessment. In addition, definitions of water literacy and water standards provide a more global perspective on outcomes associated with teaching and learning about water. Both finer-grained definitions of water literacy, as well as implementation and translation of standards, are context-specific, reflecting local social, economic, and geographic characteristics, and the accessibility and features of formal and non-formal water-related programs (Barab et al., 2007; Ben-zvi-Assarf & Orion, 2005; Dean et al., 2016; Johnson & Courter, 2020; McCarroll & Hamann, 2020; Otaki et al., 2015; Simonds et al., 2018). For many, formal education will constitute their primary opportunity to learn about socio-hydrological systems, especially in K-12 education. In this sense, the coordination between standards and practice needs to be both malleable and inclusive of localized settings in which this coordination may occur.

The knowledge, skills, and behaviors reflected in these standards can be accounted for through a learning domains perspective. These are taxonomies of learning processes which help classify learning outcomes (Bloom et al., 1956; Brunning et al., 2010; Krathwohl et al., 1964; Rieckman et al., 2017). Here we focus on the cognitive and affective domains. Both domains focus on helping students develop conceptual understanding and skills conducive to responsible attitudes and behaviors towards the environment (Ballantyne & Packer, 1996; Chen & Liu, 2020; Dean et al., 2016; Littledyke, 2008). Within the cognitive domain, knowledge can be declarative, procedural, or conditional. Declarative knowledge refers to factual or conceptual knowledge. Procedural knowledge refers to knowing how to do something. Conditional knowledge refers to knowing when, why, and how to apply declarative and procedural knowledge. The affective domain focuses on emotional components, such as people's interests, attitudes, motivations, self-reflection, and values; and attitudinal or social components that focus on social skills like collaboration, negotiation, and communication. Within the scope of the study, knowledge about human

and natural systems is represented within the cognitive domain and its declarative and procedural components, and attitudes are represented within the affective domain and its emotional and social components. Embedded within these constructs, behaviors are observable actions and responses to different conditions linked within socio-hydrologic issues (SHIs). Conditional knowledge is considered as part of behaviors.

Literature review

Education about natural and human dimensions of Earth's water systems is critical to help students develop knowledge, skills, and values that promote sustainable water resource use (Barab et al., 2007; Bodzin, 2008; Çoban et al., 2011; Covitt et al., 2009; Davis, 2005; Endreny, 2009; Halvorson & Westcoat, 2002; Havu-Nuutinen et al., 2011; King et al., 2012; McCarroll & Hammann, 2020; Moreno-Guerrero et al., 2020; Pan & Liu, 2018; Roth & Lee, 2004; Sammel, 2014; Simonds et al., 2018; Spellerberg et al., 2004). Prior research has investigated teaching and learning about water and its relationship with human systems in very young children (Davis, 2005), the elementary grades (Bodzin, 2008; Endreny, 2009; Gunckel et al., 2012; Havu-Nuutinen et al., 2011; Shepardson et al., 2007; Simonds et al., 2018), middle school (Amahmid et al., 2019; Belland et al., 2015; Çoban et al., 2011; Gunckel et al., 2012; Pan & Liu, 2018; Shepardson et al., 2007; Simonds et al., 2018; Spellerberg et al., 2004; White et al., 2022), secondary levels (Amahmid et al., 2019; Ben-zvi-Assarf & Orion, 2005; Fremerey et al., 2014; Gunckel et al., 2012; Pan & Liu, 2018; Shepardson et al., 2007; Spellerberg et al., 2004), and undergraduate classrooms (Halvorson & Westcoat, 2002; Owens et al., 2020; Petitt & Forbes, 2019; Sabel et al., 2017; White & Forbes, 2021). These studies provide collective evidence for approaches to teaching and learning through which students can develop a better understanding about coupled human-natural water systems, including incorporation of sustainability topics about water (Çoban et al., 2011; Davis, 2005), use of visualizations and representations (Havu-Nuutinen et al., 2011; Pan & Liu, 2018), place-based inquiry (Endreny, 2009; Halvorson & Westcoat, 2002; Roth & Lee, 2004; Spellerberg et al., 2004), technology such as Google Earth (Bodzin, 2008), computer and modeling-based tools (Belland et al., 2015; White et al., 2022), and SHIs (Barab et al., 2007; Havu-Nuutinen et al., 2011; Owens et al., 2020). They also highlight the need to cultivate these opportunities across the PK-16 continuum in formal, informal, and nonformal settings.

However, this same research also documents and highlights challenging aspects of socio-hydrologic systems for students, as well as teachers. Although water-focused

teaching and learning can help students develop a more comprehensive understanding of water systems (Çoban et al., 2011; Davis, 2005; Havu-Nuutinen et al., 2011; McCarroll & Hamann, 2020), research indicates that students exhibit fragmented or incomplete understanding about socio-hydrologic systems posing them difficulties for making connections between water and its natural and human components (Çoban et al., 2011; Covitt et al., 2009; Gunckel et al., 2012; Havu-Nuutinen et al., 2011; Martínez-Borreguero et al., 2020; McCarroll & Hamann, 2020; Pan & Liu, 2018; Sadler et al., 2017; Shepardson et al., 2007; White et al., 2022), including those that are most pertinent to them (Fremerey et al., 2014; Gunkel et al., 2012; Shepardson et al., 2007). Water education experiences may not provide students sufficient opportunities to build upon prior knowledge and consider the location and social environment, nor their inherent values and ethical dimensions (Amahmid et al., 2019; Belland et al., 2015; Ben-zvi-Assarf & Orion, 2005; Covitt et al., 2009; Dean et al., 2016; Havu-Nuutinen et al., 2011; Littledyke, 2008; McCarroll & Hamann, 2020; Martínez-Borreguero et al., 2020; Shepardson et al., 2007). When students investigate these relations, they seem to over-emphasize the human components with which they are most familiar (Ben-zvi-Assarf & Orion, 2005; White et al., 2022), or have difficulties linking different concepts of water systems with practical aspects occurring within their own context (Shepardson et al., 2007). These gaps can also be reflected at the undergraduate level (Petitt & Forbes, 2019; Halvorson & Westcoat, 2002; Johnson & Courter, 2020).

Research indicates that teachers, like students, may also struggle with certain aspects of coupled water-human systems. They articulate dynamic and varied understanding of water, natural water systems, and interrelationships between water and humans (Çakır Yıldırım & Karaarslan Semiz, 2019; Lee et al., 2019). A number of studies have described programmatic elements and research findings from water-focused professional learning programs for teachers. These studies have shown that these workshops and programs can have a positive impact on teachers' personal and individual characteristics, including their awareness of challenges associated with water resource use, their knowledge about water and water systems, abilities to identify, learn about, and implement sustainable water behaviors, and increase their self-efficacy and confidence teaching about water-related phenomena (Cankaya & Iscen, 2015; Gruver & Luloff, 2008; Gruver et al., 2009; Shepardson et al., 2002). Evidence also suggests these experiences can positively impact their classroom practices, including using more student-centered, project-based, and authentic instructional approaches to support student learning about water and human

interactions within the environment (Hale et al., 2017; McKim et al., 2018).

One of the primary challenges for teaching and learning about water and humans is the curriculum and disciplinary structure of K-12 subjects and courses (Çoban et al., 2011; Covitt et al., 2009; Dean et al., 2016; Martínez-Borreguero et al., 2020; Pan & Liu, 2018; Sadler et al., 2017). Overall, teaching and learning about water and humans is relatively limited in formal school settings and, when these topics are addressed, they are done so in a disconnected, discipline-specific, distributed manner (Brody, 1995; Covitt et al., 2009; Gunckel et al., 2012; Sadler et al., 2017; UNESCO, 2015). Similar challenges have been identified in international settings (Ben-zvi-Assarf & Orion, 2005; Havu-Nuutinen et al., 2011; Martínez-Borreguero et al., 2020). Different frameworks to help improve water science curriculum have been developed. While the *Next Generation Science Standards* includes several objectives related to water and social, behavioral, and economic sciences, its main emphasis is on STEM (NRC, 2012). Brody and colleagues (1995) developed a water-related curriculum framework that included conceptual, skill, and affective areas encompassing both science and social sciences related to water. They identified that participants had diverse perspectives about these different concepts depending on their roles and geographical areas. Gunckel et al. (2012) identified four levels of achievement to explain students' change of ideas over time about water in environmental systems for K-12 levels in which students need to be able to develop model-based accounts of water to be able to engage in decision-making. However, overall, although human systems and their relationship with water resources are addressed to some extent within these and other education frameworks, none of these existing resources have sought to bring together water-related standards from diverse sources. More work is therefore needed to bring together disparate guidance on water-related teaching and learning to inform comprehensive efforts to cultivate water literacy in students across K-12 grades.

Methods

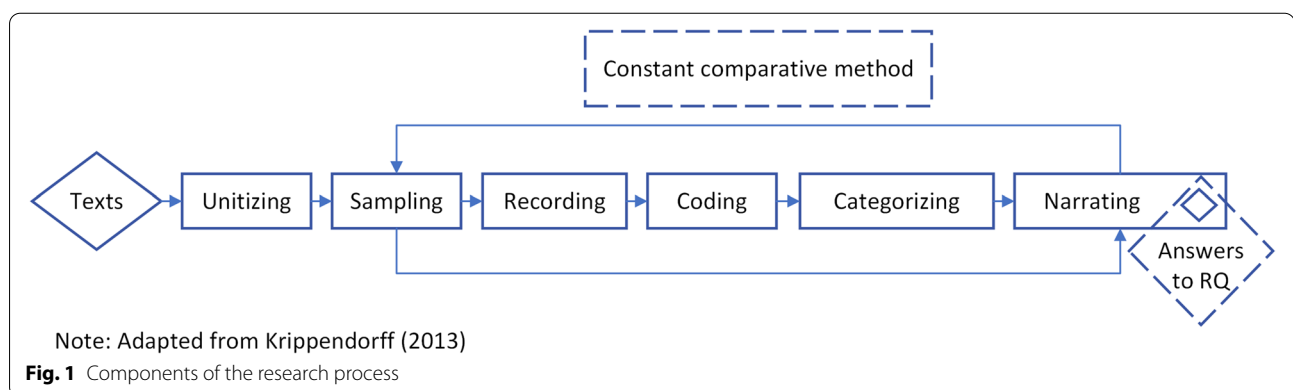
Study design

This study is part of a larger study of water-related standards, including those that foreground the natural dimensions of water (Mostacedo-Marasovic et al., *in press*). The study is based on a mixed-methods approach. The qualitative component utilizes a conventional qualitative content analysis, complemented by processes from systematic grounded theory, to construct an emergent empirical narrative that responds to the overarching question and research questions. Figure 1 presents the core components of the research process. The content analysis methodology used adheres to procedures described by Krippendorff (2013), which include the unitizing, sampling, recording, coding, and narrating processes to answer the research question “*What thematic outcomes for students' learning are apparent across grades in these water-related standards?*”. Based on the grounded theory methodology (Cresswell & Guetterman, 2019; Creswell & Poth, 2018), we embedded theoretical sampling and the constant comparative method to support the data collection and data analysis using open, axial, and selective coding to develop labels and categories, until we found the main categories and subcategories that served as basis for our narrative.

The quantitative component of the study is based on a nonparametric analysis of the cognitive and affective domains and their corresponding components represented in the water-related standards to help respond to the research question “*To what extent do these water-related standards address recognized domains of learning?*”. The quantitative analysis was guided by Gravetter & Wallnau (2017).

Data collection

We used existing standards documents as our main data source. Our unit of analysis is standards for teaching and learning. To define our dataset, we used *purposeful sampling* to collect the water-related education standards from publicly-available sources. We identified



12 governmental and non-governmental organizations, mostly based in the United States (US), that have generated education standards and guidelines (Table 1). The selection of these organizations was based on two criteria: the geographical scope and the thematic scope. The geographical scope concerns whether the organization defines education standards with broad reach beyond individual regions or countries. The thematic scope criterion concerns whether the organization defines education standards focused on water, water systems, and/or water resources. In a first pass, we searched for standards that explicitly focus (water-specific) on water, water systems, and/or water resources (i.e., “water”, “hydrology”, “hydraulic”, “water resources”, and related terms). In a second pass, we used *theoretical sampling* guided by the emerging results to identify additional standards that further develop the results. These standards addressed water indirectly and represented emergent categories (water-related), (i.e., “environmental health”, “renewable energy”, “agriculture practices”, “infrastructure”, “climate change”, “human settlements”, “management”, and related terms). Overall, throughout the document, all the collected standards are referred to as water-related standards. Table 1 summarizes the sources of the water-related education standards collected and used in the analysis.

Recording

To ensure traceability of the water-related education standards to their sources, we *recorded* the standards on an Excel matrix using four digits that represented their characteristics. The first digit indicated the name of the organization from which the standard was extracted

based on the order in which the organization was identified. The second digit indicated the order in which the standard was included in the database. The third digit indicated the academic level to which the standard belongs. Number “1” was assigned to standards belonging to the K-5th grade band; “2” to the 6-8th grade band; “3” to the 9-12th grade band; and “4” to standards without a specific grade band (unspecified). When a standard overlapped two of the grade bands, they were registered to the upper level they represented. The fourth digit indicated if the content of the standard was water-specific (number 1), or water-related (number 2). By the end of the recording process, we identified $N=341$ water-related education standards; out of which 29%, 23%, 28%, and 20% represented the K-5, 6–8, 9–12, and unspecified grade bands, respectively. From all water-related standards identified, 42% were water-specific, and 58% were water-related standards.

Data analysis

Learning domains coding

We identified the characteristics of each water-related standard based on the learning domains. The standards that described an action were coded as behavioral; whereas those that presented a concept were coded as non-behavioral. The standards representing scientific principles of water resources and the natural systems with which they interact were coded as cognitive. Further, these were also coded as declarative knowledge and/or procedural knowledge. The standards focused on social and emotional aspects an individual or group

Table 1 Summary of water-related education standards

| Organization | Identifier used in the results | # Water-specific standards | # Water-related standards |
|--|--------------------------------|----------------------------|---------------------------|
| 1 American Association for the Advancement of Science (1993) | AAAS | 15 | 24 |
| 2 American Farm Bureau Foundation for Agriculture (2012) | Pillars | 6 | 9 |
| 3 Earth Science Literacy Initiative (2010) | ESLI | 11 | 14 |
| 4 Geography Education National Implementation Project (n.d.) | NatGeo | 64 | 19 |
| 5 International Society for Technology in Education (2016) | ISTE | 0 | 6 |
| 6 Joint Committee on National Health Education Standards (2007) | CDC | 0 | 38 |
| 7 National Agriculture in the Classroom Organization & National Institute of Food and Agriculture (Spielmaker & Leising, 2013) | NALO | 11 | 13 |
| 8 Next Generation Science Standards (2013) | NGSS | 13 | 7 |
| 9 North American Association for Environmental Education (2019) | NAAEE | 2 | 58 |
| 10 U.S. Department of Energy (2017) | ELP | 2 | 7 |
| 11 U.S. Global Change Research Program (2009) | Climate Literacy | 5 | 3 |
| 12 United Nations Educational, Scientific and Cultural Organization (Rieckmann et al., 2017) | UNESCO | 13 | 1 |
| Total | | 142 | 199 |

of people has towards water were coded as affective, and social and emotional.

We evaluated the inter-rater reliability between two coders for the learning domains and their sub-categories. Two rounds of coding included 16.4% of the data. We attained 86.6% agreement and after review and discussion following each round of coding, we reached 100% agreement. Cohen's kappa ($k=0.72$) was calculated after the final round of coding.

Nonparametric tests

To address our first research sub-question, we obtained frequency counts to identify the number of standards representing each domain. Since we classified the water-related standards in different nominal categories, and they do not produce numerical values that can be used to calculate means and variances, we used nonparametric tests to evaluate the proportions or relationships between the different learning domains. We used R to perform these analyses. First, we used Tests for Goodness of Fit using Chi-square statistics to evaluate the proportion of each learning domain in each grade band from K-12. The null hypothesis states that each learning domain is represented equally among each grade band. In the case in which we found statistically significant differences, we calculated Cohen's w to evaluate the size effect. Second, we performed Tests for Independence using Chi-square statistics to do pairwise comparisons between learning domains to determine if the distributions of the different learning domains across grade bands from K-12 are significantly different from each other. The null hypothesis states that the proportions in the distribution of one domain are not different from the proportions in the distribution of grade bands of another domain. In this sense, they both have the same proportions. In the cases in which we found statistically significant differences, we calculated Cramer's V to evaluate the size effect.

Qualitative content analysis and systematic grounded theory

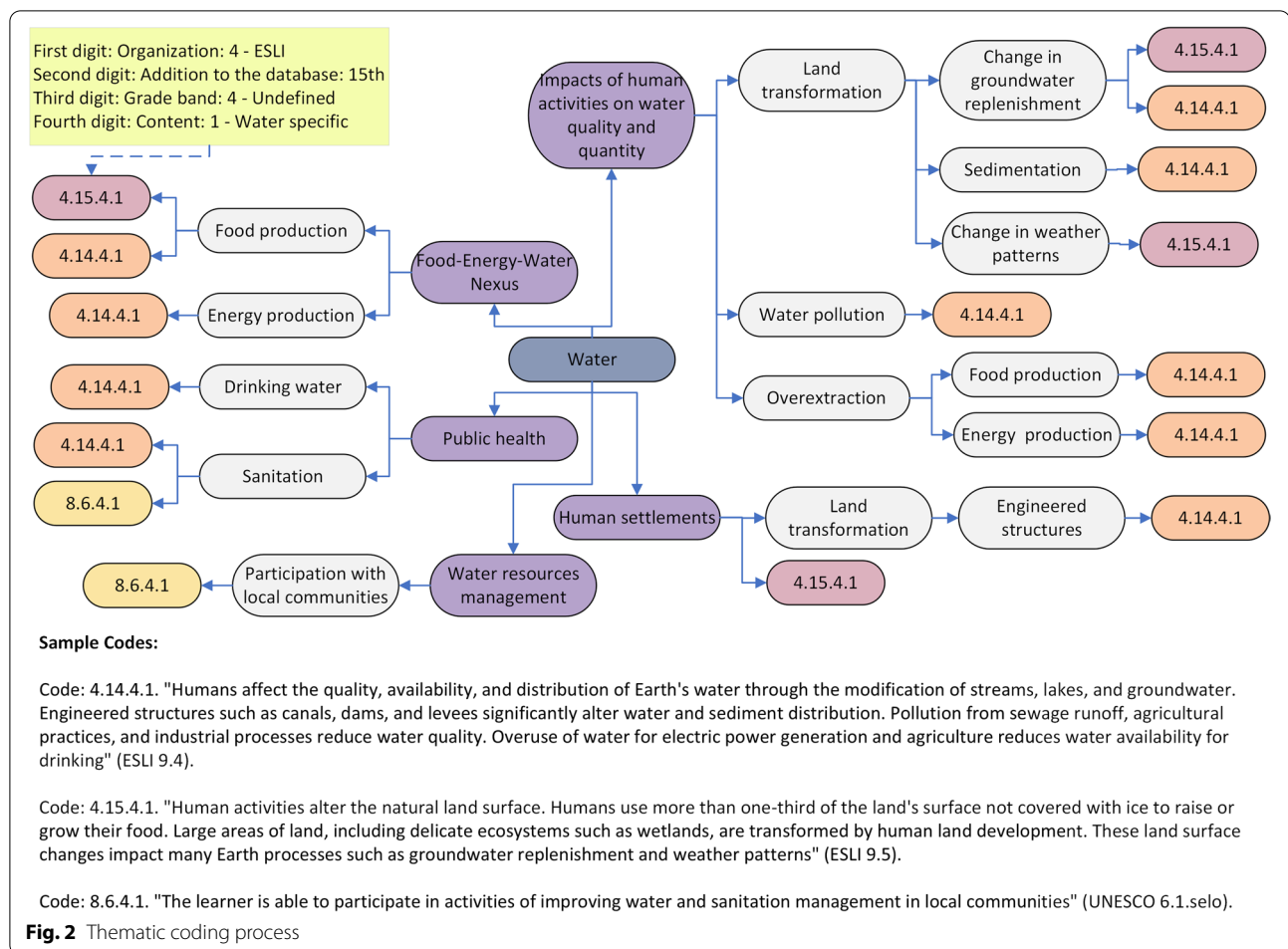
To address our second research sub-question, we used the constant comparative method to continue with the coding, categorizing, inferring and narrating processes presented in Fig. 1 (Krippendorff, 2013), following an inductive approach. To support the coding process, we created a concept map using the MindMup software that enabled us to organize the conceptual labels and categories and compare them continuously. At the center we used the word "water" as the nuclear topic. First, we used open coding to segment the information and begin forming categories analyzing each water-related standard and coding it based on the concept it represented. Many standards received different labels because they represented different concepts. To ensure traceability, we

added a note indicating the standard's four-digit identification number at the end of each label.

Second, we used axial coding to re-organize and group and re-group the initial codes based on categories and sub-categories with similar and recurring thematic attributes around the nuclear topic. This coding process allowed us to avoid overlooking important categories and their attributes and facilitated identifying the location of each of the components along a continuum of all the standards for a more in-depth analysis of their relationships.

Third, we continued re-organizing the codes and identifying the core categories using the criteria described by Merriam & Tisdell (2016) and used selective coding to develop a narrative describing the interrelationship between different categories. The categories needed to be i) exhaustive or sufficient to include all the relevant data; ii) mutually exclusive or be capable to be located only in one core category; iii) their naming needed to be as sensitive as possible to the contents of all data; and iv) conceptually congruent in which all categories had the same level of abstraction. The resulting core categories were the closest to the center of our nuclear word "water", and linked all the categories together and served as a basis for the construction of the narrative. Figure 2 shows a view of the coding process for three water-related standards, where it is possible to observe the nuclear word "water" from which the ramifications related to each core category extends depending on the concepts the standards are addressing. At the end of the branch, the four-digit code was included to support its traceability. The codes identified during the open coding were re-organized multiple times using axial to identify the core categories. A similar process was applied to the $N=341$ water-related standards. These core categories were informed by more standards than the ones presented in Fig. 2. Table 2 shows a description of each core category as well as water-related standard as a representative example of each.

The *narrating* process provided the response to the second research question which includes a comprehensive perspective of what students could learn about water and human systems. This process followed a deductive approach. We used Word during the narrating process. We first introduced each category with support from the unspecified water-related education standards. Second, we described the learning outcomes for each grade band within each sub-category. We performed several rounds of revision of the standards within the text to ensure the inclusion and representativeness of all the data within each category and sub-category. We reached saturation once we identified that the standards, the categories and subcategories, and the standards within each grade band

**Table 2** Examples of water-related standards across thematic outcomes

| Core category | Example |
|---|---|
| Water and Human Settlements | "Describe and compare distributions of people, places, and environments to examine spatial patterns, sequences, regularities, and irregularities, as exemplified by being able to: Describe and compare the natural features and human factors using geographic representations that may influence where people live (e.g., access to water, climatic conditions, rivers, and bridges)" (NatGeo 3.4.2.A). |
| Food-Energy-Water Nexus | "Human use of energy is subject to limits and constraints. Industry, transportation, urban development, agriculture, and most other human activities are closely tied to the amount and kind of energy available. The availability of energy resources [including water] is constrained by the distribution of natural resources, availability of affordable technologies, socioeconomic policies, and socioeconomic status" (ELP 4.2). |
| Water and Public Health | "The environment may contain dangerous levels of substances that are harmful to human beings. Therefore, the good health of individuals requires monitoring the soil, air, and water and taking steps to make them safe" (AAAS 6E/M5). |
| Impacts of Human Activities on Water Quality and Quantity | "Human activities alter the natural land surface. Humans use more than one-third of the land's surface not covered with ice to raise or grow their food. Large areas of land, including delicate ecosystems such as wetlands, are transformed by human land development. These land surface changes impact many Earth processes such as groundwater replenishment and weather patterns" (ESLI 9.5). |
| Water Resources Management | "Describe benefits and challenges of using conservation practices for natural resources (e.g., soil, water, and forests), in agricultural systems which impact water, air, and soil quality" (NALO T1.6–8.b). |

were well-represented and stopped with this continuous process. To ensure traceability within the narrating process, we included the nomenclatures of each standard as they were presented in the original documents.

Results

Categorization of Water-related standards in learning domains

In research question #1, we asked, “to what extent do water-related standards address recognized domains of learning?” The water-related standards identified in the study are diverse, as each can represent one or more domains of learning. Their distribution within learning domain categories is shown in Fig. 3.

First, across all standards and grade bands (including the unspecified grade band), $n = 259$ (76%) were behavioral while $n = 82$ (24%) were non-behavioral. From all the standards, $n = 295$ (87%) pertained to the cognitive domain; $n = 223$ (65%) were declarative; and $n = 108$ (32%) were procedural. Also, $n = 84$ (25%) belong to the affective domain; $n = 49$ (14%) to the social, and $n = 39$ (11%) to the emotional components across all standards.

When we consider the standards across the K-12 levels only (without the unspecified standards), $n = 236$ (70%) belong to the cognitive domain; $n = 177$ (52%) to the declarative; and $n = 90$ (26%) to the procedural

components. Also, $n = 67$ (20%) belong to the affective; $n = 36$ (11%) to the social; and $n = 35$ (10%) to the emotional domains across the K-12 levels.

We also analyzed the frequencies and distributions of standards in the various learning domains by K-12 grade bands, as shown in Fig. 4.

Results from the Tests for Goodness of Fit (Table 3) showed significant differences and a large effect among the three grade bands for the emotional domain $\chi^2(2, N=35)=8.46, p<.0146, \text{Cohen's } w=.5137$. Standards representing the emotional domain were lower in the K-5 grade band ($n=5$), increased in the 6–8 grade band level ($n=11$), and were the highest in the 9–12 grade band level ($n=19$). These findings suggest that the proportion of standards reflecting the emotional domain is lower than expected in the K-5 level, but higher than expected in the 9–12 grade band (Table 4). No other differences were found in the analysis of the other learning domains across grade bands. These results suggest that other standards are relatively equally distributed among grade bands.

Results from the Test for Independence (Table 5) showed significant differences with small effects in the distributions across grade bands between the emotional and declarative domains, $\chi^2(2, n=212)=7.92, p<.0191, \phi=0.18$. These findings suggest that the proportions in

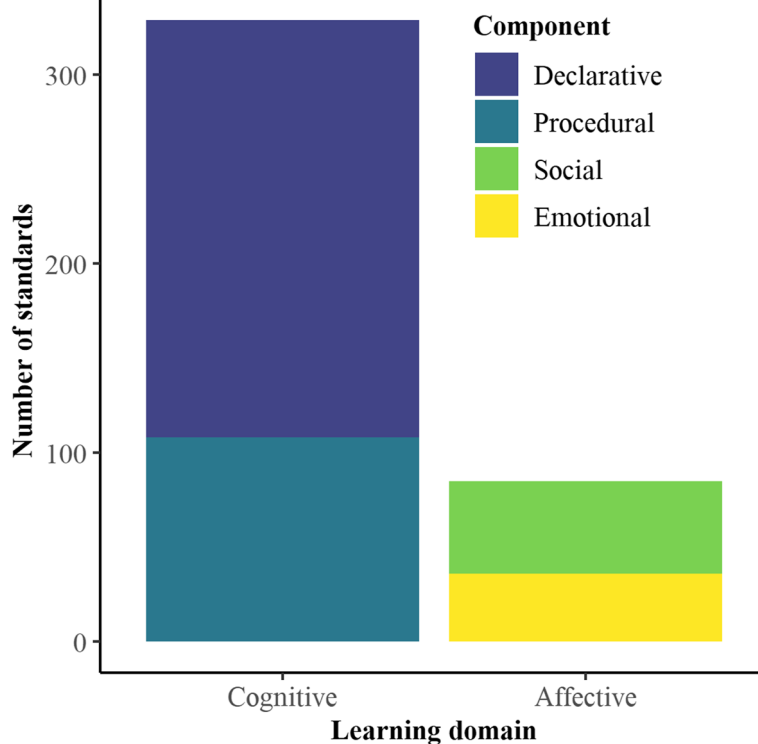


Fig. 3 Learning domains of water standards

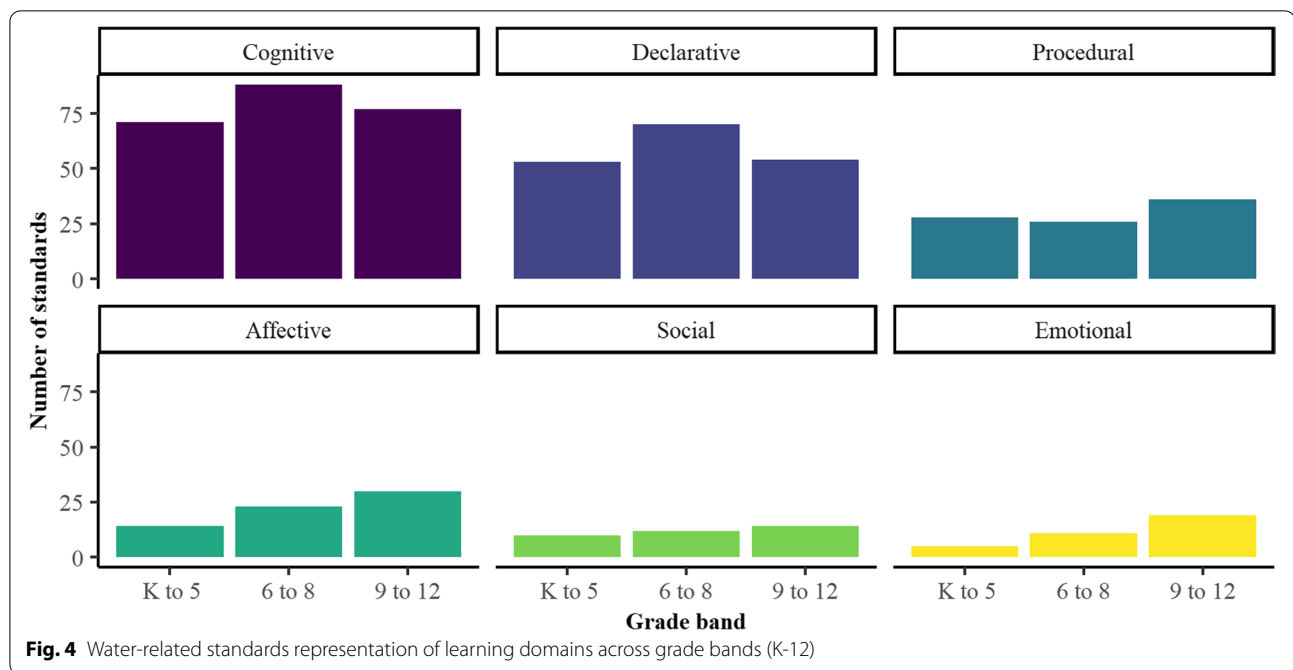


Table 3 Proportion of learning domains and grade bands: chi-square statistics (χ^2) test for goodness of fit

| Learning domain | df | N | χ^2 | p value |
|-----------------|----|-----|----------|---------|
| Cognitive | 2 | 236 | 1.89 | .3887 |
| Declarative | 2 | 177 | 3.08 | .2139 |
| Procedural | 2 | 90 | 1.87 | .3932 |
| Affective | 2 | 67 | 5.76 | .0561 |
| Social | 2 | 36 | 0.67 | .7165 |
| Emotional | 2 | 35 | 8.46 | .0146 |

Table 4 Observed and expected frequencies of the emotional domain across grade bands

| Frequency / Contribution | K to 5 | 6 to 8 | 9 to 12 |
|--------------------------|--------|--------|---------|
| Observed | 5 | 11 | 19 |
| Expected | 11.67 | 11.67 | 11.67 |
| Contribution to χ^2 | 3.81 | 0.04 | 4.61 |

the distribution of standards across grade bands of the declarative domain is different from the distribution of the emotional domain. No other significant differences were found. Results from the observed and expected frequencies (Table 6) indicate that the distribution of standards within the emotional domain across grade bands is disproportional, particularly as it compares to the declarative domain.

Table 5 Differences between learning domains and grade bands: chi-square statistics (χ^2) test for independence

| Learning domain | df | N | χ^2 | p value |
|--------------------------|----|-----|----------|---------|
| Cognitive - Affective | 2 | 303 | 3.88 | .1439 |
| Declarative - Procedural | 2 | 267 | 3.51 | .1732 |
| Social - Emotional | 2 | 71 | 2.45 | .2932 |
| Declarative - Social | 2 | 213 | 1.10 | .5759 |
| Declarative - Emotional | 2 | 212 | 7.92 | .0191 |
| Procedural - Social | 2 | 126 | 0.27 | .8732 |
| Procedural - Emotional | 2 | 125 | 3.93 | .1404 |

Table 6 Observed and expected frequencies between the emotional and the declarative and procedural domains

| Frequency / Contribution to χ^2 | Learning domains | K to 5 | 6 to 8 | 9 to 12 |
|--------------------------------------|------------------|--------|--------|---------|
| Observed | Emotional | 5 | 11 | 19 |
| | Declarative | 53 | 70 | 54 |
| Expected | Emotional | 10 | 13 | 12 |
| | Declarative | 48 | 68 | 61 |
| Contribution to χ^2 | Emotional | 2.19 | 0.42 | 4.01 |
| | Declarative | 0.43 | 0.08 | 0.79 |

A transdisciplinary matrix for Water-related standards

In research question #2, we asked, “*what thematic outcomes for students’ learning are apparent across grades in water-related standards?*”. In the sections that follow, we

outline core themes resulting from analysis and organization of water-related standards for teaching and learning focused on the interactions between water and human systems.

Water and human settlements

Intersection between the thematic outcome and learning domains Additional file 1 shows the representation of the $N=341$ water-related standards and their corresponding learning domains within each thematic outcome. The thematic outcome on water and human settlements accounted for 30% of the standards. The representation of the cognitive domain was larger than the affective domain; the declarative component was larger than the procedural component; and the social component was lower than the emotional component. The number of behavioral standards was larger than non-behavioral standards.

Description Water has historically influenced human settlements, especially in areas with access to water resources that are favorable to satisfying human needs (ESLI 7.2–4). The unevenness of water distribution has also shaped the social, economic, and political characteristics of each region (ESLI 7.4). To ensure a continuous supply of water resources, infrastructure was developed to support different human activities (ESLI 9.4). These transformations have enabled the development of different civilizations in areas with and without an abundance of water resources, as human's relationship with water has influenced culture, the development of arts and literature, scientific inquiry, values, and spirituality (ESLI 1.1, 7.1). Nevertheless, these transformations have altered water-related ecosystem services, transformed the land, and changed the distribution of surface and groundwater resources (ESLI 7.5, 9.4–5). Furthermore, climate change is an important factor compromising the distribution and availability of water resources for humans, as can be evidenced with the impacts of the decline of freshwater resources in regions that depend on glaciers, rising sea levels, changes in precipitation patterns and ocean circulation, increased forest fires, extreme weather events, and changes in the distribution of global systems (Climate Literacy 7.A-C, 7.F; ESLI 8.3, 9.1–3). Water-related hazards can increase risks to humans, affect populations' size, and drive migrations, particularly in vulnerable and highly populated areas (ESLI 8.1–5, 9.6).

Grade specific standards In grades K-5, students could be able to conceptualize that water is a natural resource (NALO T1.K-2.c; NatGeo 16.4.1.A; Pillars EC-3.1.D) that sustains humans' basic needs (AAAS 6A/P2). They could

be able to understand that water availability, distribution, and accessibility is variable as a result of different natural features, influencing the ways humans have historically adapted and transformed the physical environment to have access to water enabling them to settle in different territories (AAAS 7E/E3; NAAEE K-4.2.1.B, K-4.2.3.A; NatGeo 12.4.3.A, 14.4.1.A, 14.4.3.A, 17.4.2.A, 18.4.2.A; NGSS K-ESS2-2), where technology has played an important role (AAAS 3A/E4; NatGeo 14.4.2.A). In this sense, students could be able to use geographic representations to reason, describe and compare how access to reliable freshwater supply, presence of different weather patterns, access to a river or sea, natural harbors, and use of water for transportation and recreation, among other factors, influence the distribution of people as they provide opportunities and constraints for human settlements (NAAEE K-4.2.1.B, K-4.2.3.A, C; NatGeo 3.4.2.A, 3.4.3.A, 9.4.2.B, 12.4.2.A, 12.4.3.A, 15.4.1.A-B, 18.4.1.A). Furthermore, students could also identify and describe the locations and types of natural hazards and how humans might be affected by them, and how humans act in response (NatGeo 15.4.2.A-B). In this sense, students could understand that these adaptations also influence human behaviors (NAAEE K-4.2.1.B, K-4.2.3.A; NatGeo 15.4.3.A), perceptions, and responses in relation to the overall availability of natural resources, including water, and the presence of natural hazards (NatGeo 15.4.2.A-B, 17.4.3.A).

In grades 6–8, students build upon what they learned in elementary grades about the influence of physical conditions and the environment, including natural hazards, on humans' distribution to develop evidence-based explanations and representations of these phenomena from a local to a national and global scale (AAAS 5D/M1b; NAAEE 5–8.2.1.A-B; NatGeo 1.8.2.B, 2.8.2.A, 3.8.2.A, 9.8.2.B; 12.8.3.A, 15.8.1.A-B, 15.8.2.A-B), and the role of technology to adapt to different locations (AAAS 3C/M4; NatGeo 15.8.2.A, 15.8.3.A). They could also be able to analyze both positive and negative consequences that human-induced changes have on the environment and can bring changes to other locations (NatGeo 14.8.1.A, 14.8.3.A). Furthermore, students could be able to integrate the influence of water on social, political, economic and cultural phenomena. For example, they could understand the influence that the presence of coasts has shaped human activities as the presence of ports influenced commerce, trade, and transportation, enabling the development of large centers of human settlements (NatGeo 2.8.3.A, 9.8.2.B, 12.8.2.A, 17.8.1.A). They could expand their understanding about how identities, cultures, philosophies, and perceptions can form based on the places where people live, and how they use the natural resources

that are available (AAAS 10F/M1b; NAAEE 5–8.2.2.B, 5–8.2.3.B, 5–8.2.3.C; NatGeo 4.8.1.A, 16.8.1.A), including water. They could also be able to explain how water features play a role in establishing political boundaries (NatGeo 13.8.1.A).

In grades 9–12 students could use spatial concepts, geographic representations, and models to identify and describe these patterns (NatGeo 1.12.4.A, 2.12.1.A, 3.12.1.A, 3.12.3.A, 15.12.1.A, 16.12.2.A; NGSS HS-ESS3–1, 3). Students could be able to develop a more complex understanding about the interactions between water patterns and the overall environment with socio, cultural, economic, political, economic, and technological factors that influence human settlements differently (NAAEE 9–12.2.2.B, 9–12.2.3.B–C; NatGeo 3.12.2.A, 4.12.2.A, 4.12.2.B, 6.12.2.A, 10.12.1.B, 10.12.2.B, 16.12.1.B, 17.12.3.A). They could be able to understand the concept of “limits to growth” (NatGeo 15.12.3.B) and identify that water use patterns and environmental changes, and natural disasters can influence the growth or decline of different regions (NatGeo 3.12.1.A, 6.12.2.A, 9.12.2.A, 12.12.1.A, 12.12.2.A, 12.12.3.B), and how these can impact human migration patterns and transform human settlements (NatGeo 9.12.2.B, 9.12.3.B; NGSS HS-ESS3–1). Students could understand that different policies around water, and other natural resources, also influence urbanization, and upstream and downstream locations (NatGeo 14.12.3.A; NGSS HS-LS2–7), and they could compare the adoption of policies, adaptation strategies, and technologies to respond to water-related natural hazards (NatGeo 15.12.2.A, 15.12.2.B, 15.12.3.A, 15.12.3.B).

Food-energy-Water Nexus (FEW-Nexus)

Intersection between the thematic outcome and learning domains The thematic outcome on the nexus between food, energy, and water accounted for 30% of the standards. The representation of the cognitive domain was larger than the affective domain; the declarative component was larger than the procedural component; and the social component was lower than the emotional component. The number of behavioral standards was larger than non-behavioral standards.

Description Societies rely on water resources to produce energy and food (ELP 7.3; ESLI 7.5; UNESCO 6.4.clo). Moving water is a primary source from which humans transfer and transform energy (ELP 4.1; ESLI 7.10). Land surface is also transformed to satisfy agriculture needs (ESLI 9.5). Although gravity is the major

force that helps to transport water, additional water-related infrastructure, like canals, dams, and levees are needed to divert water to other areas and to transform this movement into energy, and as reservoirs for future uses of water, including irrigation. These reservoirs help to store a stable source of energy for future use, which are necessary for national security, access, and equity (ELP 4.6–7). The transformation of the land influences climate change, which repercuss on water systems (Climate Literacy 6.C; ESLI 9.3), as well as the capabilities to produce energy and food, as important sources of water, such as winter snowpack and mountain glaciers, are declining (Climate Literacy 7.B, 7.F). Furthermore, as a result of population growth, industrialization, and socioeconomic development, food and energy demand are increasing, adding stress to water systems (ELP 6.3–4), impacting water quality, availability, and distribution, as well as the balance of different ecosystems, such as wetlands, and different natural processes, including groundwater replenishment, weather patterns, and ecosystems’ energy balance (ELP 3.6, 7.3, 9.1; ESLI 9.4–5). In this sense, the availability of water resources, technological aspects, social, economic, political factors (ELP 4.2), and environmental impacts (ESLI 7.10) pose limits and constraints to the use of water for energy and agriculture production (ELP 4.2), influencing decision-making processes (ELP 4.6–7, 5.6–7).

Grade-specific standards In grades K–5, students could identify and explain that water is used for agriculture and energy production (NALO T2.K–2.e, T1.3–5.e; NatGeo 16.4.2.A; NGSS 4-ESS3–1; Pillars EC-3.1.C), which are limited by water’s availability and proximity (NAAEE K-4.2.3.A; NatGeo 15.4.1.B, 16.4.2.A). Students could be able to use observations to identify that animals and plants need water to grow (NGSS K-LS1–1, 2-LS2–1), and that water and weather patterns delineate the types of crops and livestock produced in different regions (AAAS 8A/E5, 8A/P1bc; NAAEE K-4.2.3.B; NALO T1.K-2.b, T1.K-2.d, T1.3–5.b; NatGeo 11.4.2.B). They could understand the role of stewardship of these resources (NALO T2.3–5.e). Learners could also be able to identify, describe, and construct an argument supported by evidence for ways in which humans adapt to the affordances and constraints of the environment and modify the environment to gain access to water resource to produce food and energy (NAAEE K-4.2.3.A, K-4.2.3.B; NatGeo 14.4.1.A; NGSS K-ESS2–2). In this sense, elementary students could recognize the present and historical role of technology to facilitate food production (i.e., irrigation) (AAAS 3A/E4, 8A/E4, 8A/E1c; NALO T4.3–5.b; NatGeo 14.4.2.A), energy generation (AAAS 3A/E4, 8C/E1), and water movement (AAAS 10J/E1).

In grades 6–8, students are expected to build upon their learning about how geologic and environmental patterns (AAAS 4B/M10ab; NatGeo 15.8.1.A-B, 16.8.2.A; NGSS MS-ESS3–1), and technologies (AAAS 3C/M4; NatGeo 14.8.2.A, 15.8.1.B, 15.8.3.A) can influence water distribution and availability for energy and agricultural production. Learners could develop explanations about how technologies help obtain water (AAAS 10J/M2). Also, they could understand the influence of water availability and distribution as an energy source, and how this influences the global distribution of energy and amounts of energy produced by it once it is collected, concentrated, and transported for its use for different purposes (AAAS 8C/M4–6, 8C/M9–10; NALO T2.6–8.d; NatGeo 16.8.2.A, 16.8.3.B; Pillars 4–8.2.C). They consider many drivers of increasing water resource use, including a growing human population (NGSS MS-ESS3–4), agricultural production (NALO T1.6–8.c; T1.6–8.d), and energy production. They begin to elaborate more complex explanations that include social, economic, and political factors (AAAS 8C/M10; NAAEE 5–8.2.3.D; NALO T3.6–8.f; NatGeo 16.8.1.A; NGSS MS-ESS3–4) that provide different opportunities and constraints to respond to higher demands of food and energy (NatGeo 15.8.1.A-B, 18.8.1.B, 18.8.2.A; NGSS MS-ESS3–4). In relation to water use for food production, students also continue developing an understanding of the influence resulting from weather patterns on the availability of water to produce food (NALO T1.6–8.g), and how importation of food can help reduce the dependence on weather but augment the reliance on transportation and communication with distant markets (AAAS 8A/M3b). They can evaluate the trade-offs associated with the use of different technologies to use water for agriculture and energy production (AAAS 3C/M9, 8A/M3acd), and how the different uses of water can compete with other human and non-human uses (AAAS 5D/M1a, 4B/M8; NALO T1.6–8.a).

In grades 9–12, students build upon their understanding about the social, economic, political, and environmental complexities around the use of water and technology for energy generation and agriculture production to increase emphasis on complex systems and notions of sustainability (NALO T5.9–12.e-f, T1.9–12.f; NatGeo 14.12.1.A, 14.12.2.A, 14.12.3.A, 16.12.2.A; NGSS HS-ESS2–2). They could analyze the historical and potential impacts that changes on climate patterns bring to water resources, and how these can affect agriculture and energy production (NALO T1.9–12.e; NatGeo 3.12.2.A). Students could be able to use models to describe the impacts that changes in water systems to satisfy increasing demands for food, energy and water in both developed and developing countries (AAAS 8C/H4, 8B/H7, 4B/H8; NatGeo

9.12.3.B), can bring changes to human systems (NatGeo 3.12.3.A, 5.12.2.A, 15.12.3.B), including changes in migration patterns (NatGeo 9.12.3.B). They could identify the role the state has in determining the types of policies and their impacts on water, food and energy systems (AAAS 8A/H2; NatGeo 16.12.3.B). Some of these changes result from the adoption of different technological changes to improve food and energy production, bringing changes to the use of water inputs and humans' ways of living (AAAS 8A/H3b; NALO T4.9–12.b; NatGeo 10.12.2.B; Pillars 9–12.5.A, 9–12.5.D). Students also need to explain that technology presents trade-offs regarding between the use of water to improve food (AAAS 8A/H3a; NALO T5.9–12.b) and energy production (NatGeo 14.12.3.A, 16.12.3.A).

Water and public health

Intersection between the thematic outcome and learning domains The thematic outcome on water and public health accounted for 15% of the standards. The representation of the cognitive domain was larger than the affective domain, but with a short difference; the declarative component was lower than the procedural component; and the social component was larger than the emotional component. The number of behavioral standards was larger than non-behavioral standards, but more emphasized than in other thematic outcomes.

Description The availability and quality of water resources is fundamental for public health. The availability of clean water is essential for drinking water, sanitation, and hygiene, and for the prevention of the transmission of diseases that can increase people's morbidity and mortality. Learners could be able to comprehend, put into practice, and communicate the importance of sanitation and hygiene as means to prevent diseases and enhance personal, family, and community health (CDC 1, 7, 8; UNESCO 6.1.selo, 6.2.selo, 6.4.selo). They could understand that there is a "global unequal distribution of access to safe drinking water and sanitation facilities" (UNESCO 6.3.clo), not only in terms of spatial distribution, but also in terms of socio-economic and gender dimensions (UNESCO 6.5.selo). Furthermore, the impacts of climate change on water resources can pose challenges for public health (Climate Literacy standard 7.F). Organisms, including disease vectors like mosquitoes, need to adapt to changing conditions or migrate to more favorable areas to survive (Climate Literacy 3.A, 7.E), resulting in increased incidence and geographical range of climate-sensitive infectious diseases (Climate Literacy 7.F). Other water-related impacts of climate change "will contribute

to unhealthy conditions, particularly for the most vulnerable populations” (Climate Literacy 7.F).

Grade-specific standards Students in grades K-5, could recognize the importance of healthy behaviors and identify and demonstrate practices that help them prevent diseases (CDC 1.2.1, 1.2.3, 1.5.1, 7.2.1–2, 7.5.1–3) that can result from direct or indirect acquisition of contaminated water that can function as a disease reservoir. As standard AAAS 6E/P3 states, “Some diseases are caused by germs, some are not. Diseases caused by germs may be spread by people who have them. Washing one’s hands with soap and water reduces the number of germs that can get into the body or that can be passed on to other people”. Learners could also be able to make requests to promote, express opinions, and encourage peers and others to implement healthy practices (CDC 8.2.1–2, 8.5.1–2).

Students in grades 6–8 could be able to identify that water resources may contain different substances or carry bacteria and virus which can affect people’s health (AAAS 6E/M5, 8F/M5) and that sanitation and safe handling of food and water are among health practices that help prevent germs from entering the body (AAAS 10I/M7). They could recognize various sanitation measures, the need to monitor the environment for health hazards, and the historical importance of sanitation in enhancing human existence (AAAS 6E/M5; 8F/M1). In this sense, students could be able to assume responsibility of personal practices and behaviors that reduce health risks for themselves and others (CDC 1.8.1, 1.8.3, 1.8.7, 1.8.8–9, 7.8.1–3). They could also be able to present their position, influence and support, communicate, and work cooperatively (CDC 8.8.1–4) to promote a healthy use of water.

Students in grades 9–12 could expand on their understanding, attitudes, and behaviors they started building during elementary and middle school about water and public health. They could be able to analyze how the environment and their own health are connected, predict how healthy behaviors can have different impacts on health for themselves and others, analyze and propose alternatives; and communicate, and cooperate to and with others (CDC 1.12.1, 1.12.3, 1.12.5, 1.12.7, 7.12.1–3, 8.12.1–4) to reduce, prevent, or mitigate water-related diseases. Students could be able to explain causes that affect sanitation services (NatGeo 9.12.3.B).

Impacts of human activities on Water quality and quantity

Intersection between the thematic outcome and learning domains The thematic outcome on impacts of human

activities on water quality and quantity accounted for 11% of the standards. The representation of the cognitive domain was larger than the affective domain; the declarative component was larger than the procedural component; and the social component was lower than the emotional component. The number of behavioral standards was larger than non-behavioral standards.

Description While human activities are reliant on water as a resource, in turn, they impact water and water systems (ESLI 7.5, 9.4–8; UNESCO 6.1.clo). These impacts are multifaceted. On the one hand, human activities structurally reshape the landscape and naturally occurring water systems while, on the other, they often degrade them through erosion, pollution and overuse. Human impacts on water systems can be seen over the short and long term, and some of these impacts are not reversible (ESLI 7.3, 9.8). For example, in response to increasing water demands (ESLI 9.1), the withdrawal of surface and groundwater is often higher than their replenishment, and the restoration is often difficult (ESLI 7.5). Land use change affects the biosphere (ESLI 9.7), watershed and groundwater processes (ESLI 9.5), the hydrological cycle (ESLI 9.3), and the climate system (Climate Literacy 6.B-C, 7.F; ESLI 9.5).

Grade-specific standards In grades K-5, standards foreground specific ways in which humans impact natural water systems through their use of water as a resource (NAAEE K-4.2.3.A, K-4.3.1.B; Nat Geo 14.4.1.A, 14.4.3.A; NGSS 4-ESS3–1). In general, students could identify, describe, and construct an argument supported by evidence for ways in which humans modify the physical environment to meet their needs (NatGeo, 14.4.1.A; NGSS K-ESS2–2). Early learners could identify and describe impacts of humans’ use of water on the natural environment, particularly through concrete and localized examples (NAAEE K-4.3.1.A).

Grades 6 to 8 students could build upon their recognition and description of human impacts on water in elementary grades to investigate these relationships in more substantial ways. Students recognize that “the physical environment can both accommodate and be endangered by human activities” (NatGeo 14.8.3.A). First, students could explore not only direct impacts of water resource use in a localized area, but also how these impacts reverberate beyond the immediate phenomena to broader systems and other geographical areas (NAAEE 5–8.2.3.A; NatGeo 14.8.1.A). Second, they could recognize that these changes can have impacts over the short- and long-term (NAAEE 5–8.3.1.B). Third, students could go beyond identifying and describing specific examples of water

use consequences to be explaining these phenomena (NatGeo 14.8.1.A), comparing various related scenarios representing these relationships (NALO T1.6–8.a), and construct evidence-based arguments about these relationships (NGSS MS-ESS3–4). The consequences that students consider may be varied and diverse. For example, middle school students may consider how ineffective resource use limits the availability of water for other purposes (AAAS 4B/M11a) and that water “can be depleted or polluted, making it unavailable or unsuitable for life” (AAAS 4B/M8).

Grades 9–12 could analyze how humans and their environment interact with each other; how those interactions can change with technology, such as dams, channels, reservoirs, or irrigation; and how these can bring different costs, benefits, and unintended consequences to different groups of people, the economy, and the environment itself (NAAEE 9–12.2.3.A; NALO T5.9–12.b, T5.9–12.e; NatGeo 14.12.2.A). As students expand their consideration of impacts of water resource use, they may consider temporal dimensions of water resource use, such as describing “how agricultural practices have contributed to changes in societies and environments over time” (NALO T4.9–12.b). There is also increasing emphasis on understanding regional and global scales of these impacts rather than local examples alone (NALO T5.9–12.e; NatGeo 3.12.2.A; 14.12.1.A). As students recognize how human activities influence water resources (NAAEE 9–12.2.1.A), they integrate a more sophisticated reasoning supported by the use of technology, through which students both create and use computational tools (NAAEE 9–12.1.F) to “illustrate the relationships among Earth systems and how those relationships are being modified due to human activity” (NGSS HS-ESS3–6) that would help them “describe and evaluate scenarios for mitigating and/or adapting to environmental changes caused by human modifications” (NatGeo 14.12.3.A).

Water resources management

Intersection between the thematic outcome and learning domains The thematic outcome on water resources management accounted for 33% of the standards. The representation of the cognitive domain was larger than the affective domain, but with a short difference; the declarative component was lower than the procedural component; and the social component was larger than the emotional component. The number of behavioral standards was larger than non-behavioral standards, but more emphasized than in other thematic outcomes.

Description It is essential for water resources to be effectively managed to mitigate the impacts of natural hazards to reduce vulnerability (ESLI 8.7–8, UNESCO 6.5.clo) and ensure availability and access to water (UNESCO 6.5.clo). These practices encompass science and human-based approaches to support problem-solving and decision making (ESLI 7.10, 8.8, 9.8.). Science-based approaches include optimization of water use for agriculture (Pillars 1.B, 1.E, 1.F), the development and use of models to evaluate water-related hazards, such as floods and droughts (ESLI 8.6), model-based projections of the impacts of climate change on water systems (Climate Literacy 5.E) to improve preparedness (ESLI 8.7) and overall decisions (Climate Literacy 5.E). Managing water resources involves navigating priorities of diverse stakeholders and interest groups. Science-based awareness, engagement, communication, public policy and cooperation at different levels are key to support water management (ESLI 7.10, 8.8, 9.8–9; UNESCO 6.1–2.blo, 6.1–2.selo, 6.5.blo). Overall, students are expected to develop the skills that allow them to obtain, evaluate, analyze, and represent information about water resources that help them understand and explain the complexities of different decisions (ISTE 3a-b, 3d, 5b-c, 6c). These different kinds of knowledge are pertinent not only for individuals, but for society in general, as well as for daily and long-term activities (UNESCO 6.3–4.blo, 6.3.selo).

Grade-specific standards Students in grades K-5 begin to recognize their own rights and responsibilities with regards to the use of natural resources, including water (NAAEE K-4.4.A). They could be able to identify whose role it is to provide water-related services, and that many uses of water depend on the economy of the place (NAAEE K-4.2.2.C, D). They are able to identify water-related issues that take place within their closest environment (NAAEE K-4.3.2.A; NGSS 3-LS4–4), and develop an initial understanding of environmental, social, and economic issues that may accompany them (NAAEE K-4.3.1.B). Elementary students can express about these issues (NAAEE K-4.3.2.A) and their potential solutions (NALO T1.3–5.c; NatGeo 16.4.3.A; NGSS 2-ESS2–1, K-ESS3–3) in which they can contribute and start developing plans to address them (NAAEE K-4.4.B; K-4.3.1.C, K-4.3.2.B-D), with support of scientific information (NGSS 5-ESS3–1). For example, they can implement water conservation practices to improve the use of water in their own homes (NatGeo 16.4.3.A). They could be able to identify that different groups of people have differing perspectives about the use of water (NAAEE K-4.2.2.A-B), and that these views can lead to both cooperation and conflict in relation to proposed solutions (AAAS 7E/E3; NatGeo 13.4.2.A, 13.4.3.A).

Students in grades 6–8 recognize the importance of a sustainable use of natural resources, including water, defined as a balance between use and replenishment of the resource itself (NALO T1.6–8.h; NatGeo 16.8.3.A). Students continue exploring the role of economic, social, and political factors influencing the management of natural resources (NAAEE 5–8.2.2.C–D), including water. They recognize that as stakeholders, their decisions can influence the use of water (NAAEE 5–8.2.2.A). Middle-school students could also examine the consequences, both positive and negative, of different water allocation approaches that reflect existing practices and stakeholder priorities (NAAEE 5–8.2.3.D, 5–8.3.3.A–C; NALO T1.6–8.d; NatGeo 18.8.1.A; Pillars 4–8.1.F). They recognize and explain that differing viewpoints about use of rivers, water sources, and access to water can lead to conflict and/or present synergistic opportunities for collaboration and collective action at local, national, national, and global levels (AAAS 7F/M3; NAAEE 5–8.2.3.D; NatGeo 13.8.2.A, 13.8.3.A, 16.8.3.A). Based upon their understanding about the scientific and socio-economic components of water-related challenges, students could be afforded opportunities to design solutions to these challenges (NAAEE 5–8.3.1.C, 5–8.3.2.A–D; NGSS MS-LS2–5). As with elementary standards, middle school students could first be afforded opportunities to learn about and develop understanding of methods and strategies currently used to manage water resources in a variety of settings (NALO T1.6–8.b–d; NatGeo 16.8.3.A, 18.8.1.B, 18.8.2.A; Pillars 4–8.1.A, 4–8.1.C, 4–8.1.E–F), including the use of technology (NatGeo 16.8.3.B). They could be able to apply scientific principles and research skills to understand, monitor, and minimize environmental issues within their community and region (NAAEE 5–8.3.1.A; NGSS MS-ESS3–3). Also, they can compare the various challenges associated with the implementation of different strategies (AAAS 4B/M11bc*; NGSS MS-LS2–5).

Standards for grades 9–12 students focus on many of the same dimensions related to water management as in earlier grades. They are expected to continue developing understanding of specific water conservation practices in a variety of domains (NALO T1.9–12.b; Pillars 9–12.1.B), and their trade-offs (AAAS 8A/H3a, 8C/H5). Furthermore, they could develop more complex reasoning about sustainability (NAAEE 9–12.4.A–C; NALO T1.9–12.f), including the different drivers of water-related issues and the implications of different management decisions. In this sense, students go beyond a focus on their community to consider global challenges and ways in which local water-related issues and responses are embedded in broader contexts, including economics (NAAEE 9–12.2.2.D), stakeholders' perspectives

(NAAEE 9–12.2.2.B; Pillars 9–12.1.E–F), politics (NAAEE 9–12.2.2.C), and geography (NatGeo 18.12.1.A). They are expected to explain how access and control over natural resources, including water, have led to different social and political events (NatGeo 13.12.3.B). However, they are also able to observe and describe how different kinds of groups and institutions can organize and promote sustainable options to manage environmental issues (NAAEE 9–12.2.2.A, 9–12.2.3.D; NatGeo 16.12.3.B, 17.12.3.A). Within this framework, high school students continue developing critical thinking and advanced research skills that allow them to understand, investigate, and evaluate the accuracy of information related to water-related issues from local to regional and global scales (NAAEE 9–12.1.A–B, 9–12.1.E–F, 9–12.3.1.A; NGSS HS-ESS3–3). They are also expected to continue developing comprehensive analysis of solutions that can be implemented to reduce human impacts on natural systems, where they can understand contextual, cost-benefit, and technological factors that bring different kinds of constraints and consequences associated with their implementation (NAAEE 9–12.3.1.B–C, 9–12.3.2.C–D; NGSS HS-ESS3–2, 4, HS-ETS1–1, HS-LS2–7). They also recognize their own roles, rights, and responsibilities towards water resources conservation and can evaluate the plausibility of their own participation in these strategies (NAAEE 9–12.3.2.A–B, 9–12.4.A–C).

Discussion

Water is critical for human activities, so much so that most water systems today are socio-hydrological systems. Water literacy is key to support understanding and sustainable management of these systems. Research has shown the importance of water education in developing awareness and promoting behaviors which are consistent with water conservation efforts across PK–12 education (Amahmid et al., 2019; Ben-zvi-Assarf & Orion, 2005; Bodzin, 2008; Çoban et al., 2011; Davis, 2005; Endreny, 2009; Fremerey et al., 2014; Gunckel et al., 2012; Havu-Nuutinen et al., 2011; Pan & Liu, 2018; Simonds et al., 2018; Spellerberg et al., 2004; White et al., 2022), as well as undergraduate education (Halvorson & Westcoat, 2002; Owens et al., 2020; Pettitt & Forbes, 2019; Sabel et al., 2017; White & Forbes, 2021). Nevertheless, the disparate and discipline-specificity of standards and their translation across the curriculum present challenges for students and teachers alike (Çoban et al., 2011; Covitt et al., 2009; Dean et al., 2016; Martínez-Borreguero et al., 2020; NRC, 2012; Pan & Liu, 2018; Sadler et al., 2017; Shepardson et al., 2007; UNESCO, 2015). This study aims to contribute to the literature by providing a robust account, grounded in a learning domains perspective, of

standards focused on the human dimensions of water systems.

The cognitive, affective, and behavioral domains are each important components of water literacy (Amahmid et al., 2019; Ballantyne & Packer, 1996; Bodzin, 2008; Brody, 1995; Cankaya & Iscen, 2015; Çoban et al., 2011; Covitt et al., 2009; Davis, 2005; Dean et al., 2016; Havu-Nuutinen et al., 2011; Johnson & Courter, 2020; Martínez-Borreguero et al., 2020; McCarroll & Hamann, 2020; Pan & Liu, 2018; Roth & Lee, 2004; Sammel, 2014; Simonds et al., 2018; Spellerberg et al., 2004). Learners must not only develop understanding of water-related concepts, but also develop skills, behaviors, values, and ethics that underlie sustainable water resource use. The integration of knowledge, attitudes, and behaviors is essential to help students develop the ability to navigate complex SHIs (Amahmid et al., 2019; Ballantyne & Packer, 1996; Çoban et al., 2011; Littledyke, 2008; McCarroll & Hamann, 2020; Roth & Lee, 2004; Spellerberg et al., 2004).

First, as shown in the results, the cognitive domain is most strongly represented in the standards analyzed, including its declarative and procedural components. Students need to develop understanding of the components and processes of socio-hydrologic systems to properly understand challenges and make evidence-based decisions about water resources, both locally and globally (Belland et al., 2015; Cankaya and Iscen, 2015; Covitt et al., 2009; Gunckel et al., 2012; King et al., 2012). In terms of declarative knowledge, this includes *knowledge about*, or understanding of components and processes underlying socio-hydrologic systems. Because the focus here is on human dimensions of water system, this involves students developing more sophisticated reasoning and understanding of the mechanisms behind the interrelationships between humans and water through an interdisciplinary lens. This includes interrelationships between concepts traditionally embedded in science, and those that relate to the economy, politics, geography, culture, and history (Covitt et al., 2009; Gunckel et al., 2012; King et al., 2012). Additionally, the standards grounded in procedural dimensions of the cognitive domain focus on *knowledge to*, or skills and abilities necessary to engage in particular relevant practices. These include monitoring, analyzing scenarios, developing predictions, producing and using data and digital tools, proposing prevention mechanisms and solutions, collaborating and communicating these to others. These procedurally-oriented standards touch on not only scientific practices, such as investigation and research, but also engineering design, problem-solving, communication, and evidence-based decision-making. Each of these is crucial to understanding how to put knowledge of socio-hydrologic systems into practice through sustainability-oriented behaviors

(Barab et al., 2007; Bodzin, 2008; Çoban et al., 2011; Covitt et al., 2009; Davis, 2005; Endreny, 2009; Havu-Nuutinen et al., 2011; Halvorson & Westcoat, 2002; King et al., 2012; McCarroll & Hamann, 2020; Moreno-Guerrero et al., 2020; Pan & Liu, 2018; Roth & Lee, 2004; Sammel, 2014; Simonds et al., 2018; Sivapalan et al., 2012; Spellerberg et al., 2004). Collectively, these findings about standards reflecting both declarative and procedural dimensions of the cognitive domain foreground the interdisciplinary opportunities afforded by existing water-related standards focused on human dimensions of water. This finding reinforces the transdisciplinary nature of water and its strong connections to other disciplinary domains. In order to adequately address these standards, water-related curriculum, instruction, and assessment must support this interdisciplinary understanding of the interactions between and within human and natural dimensions of water systems (Covitt et al., 2009; Lee et al., 2019; McCarroll & Hamann, 2020; NRC, 2012; Sadler et al., 2017).

However, second, in comparison to these cognitive dimensions, the affective domain and its social and emotional components are far less emphasized, where the emotional component are less represented across grade bands. This finding is consistent with research about the predominance of the cognitive domain in extant conceptions of water literacy definitions (McCarroll & Hamann, 2020). It is important to bring attention about the role of the different attributes represented within the affective domain and the social (i.e. collaboration, negotiation and communication) and emotional components (i.e. values, responsibility, social norms, ethics, morals, meaning and significance of places, perceptions, cultural backgrounds, and beliefs), as these correspond to the guiding principles that influence people's reasoning, and decisions that ultimately determine how they will engage with water resources and sustainability efforts, which include justice, equity and inclusion (Petitt & Forbes, 2019; Amahmid et al., 2019; Martínez-Borreguero, et al., 2020; McCarroll & Hamann, 2020). The breadth of these analyses highlights the importance of providing more emphasis on the development of the affective domain in earlier learning experiences (Çoban et al., 2011; Davis, 2005; Littledyke, 2008). To prepare learners to address SHIs effectively, water education should foreground how ethics, morals, emotions, and context play a differential and contextual role when evaluating and making decisions about SHIs (Amahmid et al., 2019; Petitt & Forbes, 2019; Barab et al., 2007; Belland et al., 2015; Ben-zvi-Assarf & Orion, 2005; Dean et al., 2016; Johnson & Courter, 2020; McCarroll & Hamann, 2020; Otaki et al., 2015; Simonds et al., 2018; UNESCO, 2015). Given that existing conceptions of water literacy include all these components, the

relative underrepresentation of non-cognitive dimensions of water literacy in the standards raises important questions as to the degree to which existing standards accurately reflect definitions of water literacy and, if they are to be influential on teaching and learning, the degree to which standards-based water education would likely help students fully develop water literacy across the K-12 continuum. These affective outcomes, both emotional and social, are essential for students to develop intrinsic motivation and agency to support and influence water management decisions (Barab et al., 2007; Bodzin, 2008; Çoban et al., 2011; Covitt et al., 2009; Davis, 2005; Endreny, 2009; Havu-Nuutinen et al., 2011; Halvorson & Westcoat, 2002; King et al., 2012; McCarroll & Hamman, 2020; Moreno-Guerrero et al., 2020; Pan & Liu, 2018; Roth & Lee, 2004; Sammel, 2014; Simonds et al., 2018).

While the cognitive domain is present across all thematic outcomes, the higher prevalence of the declarative domain within human settlements, the food-energy-water nexus, and impacts of human activities on water quality and quantity suggest that these themes have a higher emphasis on conceptual aspects of water literacy. On the other hand, the higher prevalence of the procedural domain within public health and water resources management suggests that these themes emphasize the skills conducive to actions that can support water management efforts. A similar shift can be observed in the case of the affective domain across thematic outcomes. While the food-energy-water nexus, and impacts of human activities on water quality and quantity have a higher prevalence of the emotional component, public health and water resources management emphasize the social component, putting emphasis on collaboration, negotiation and communication. This shift brings attention to the balance between the understanding of the interrelations between water and human systems, and the hard and soft skills that are important to support water resources management.

Implications

Consistent with our overall perspective on educational standards, we highlight that the ways in which standards may or may not influence localized teaching and learning practices will vary tremendously from one context to another. However, their primary value is to serve as one set of guidelines that help parameterize the space within which effective water education efforts can be designed and implemented. The implications we outline are reflective of this perspective.

Curriculum and instruction

Research indicates that opportunities for teaching and learning about water and humans in K-12 curriculum are

limited, and when they are introduced, they tend to be disconnected, presented according to specific disciplines, and distributed, which pose difficulties for students to develop a comprehensive view of socio-hydrologic systems (Brody, 1995; Çoban et al., 2011; Covitt et al., 2009; Dean et al., 2016; Gunckel et al., 2012; Havu-Nuutinen et al., 2011; Martínez-Borreguero et al., 2020; Pan & Liu, 2018; Sadler et al., 2017; UNESCO, 2015). The study aims to address these gaps by providing a comprehensive and transdisciplinary perspective of socio-hydrologic education across K-12. As water-related topics are usually taught in separate disciplines (Covitt et al., 2009; Gunckel et al., 2012; Sadler et al., 2017; UNESCO, 2015), it is important to develop interdisciplinary instructional efforts that help address different dimensions of water (Amahmid et al., 2019; Covitt et al., 2009; Fremerey et al., 2014; Havu-Nuutinen et al., 2011; McCarroll & Hamman, 2020; Moreno, 2019; Spellerberg et al., 2004), as well as the use of different approaches for instruction framed within constructivist, active-learning, student-centered, place-based, and model-based approaches, among others, that support students' learning about water and humans while promoting scientific inquiry across K-12 (Ballantyne & Packer, 1996; Barab et al., 2007; Belland et al., 2015; Bodzin, 2008; Endreny, 2009; Havu-Nuutinen et al., 2011; McCarroll & Hamman, 2020; Moreno-Guerrero et al., 2020; Shepardson et al., 2007; Simonds et al., 2018; Spellerberg et al., 2004; White et al., 2022). These experiences need to build on students' prior conceptions, context, cultural backgrounds, and sources of information at their disposition, as these are of important influence for their understanding and can support developing diverse meaningful teaching and learning experiences (Ben-zvi-Assarf & Orion, 2005; Dean et al., 2016; Fremerey et al., 2014; McCarroll & Hamann, 2020; Shepardson et al., 2007; Spellerberg et al., 2004). Curriculum and instruction that aims to provide these kinds of opportunities require institutional support. At different educational levels, water can be used as an element to foster education within the natural and social sciences, which might require complementary efforts between instructors.

Professional development

The water standards discussed in the study also point to knowledge, skills, and behaviors teachers could help students develop about socio-hydrologic systems. For teachers, in particular, as the most 'local' of instructional designers, these standards can serve as one of a multitude of resources to leverage in crafting water-focused learning opportunities for students. However, research shows that teachers may hold an array of ideas surrounding water and the impacts of humans on water systems

(Çakır Yıldırım & Karaarslan Semiz, 2019; Lee et al., 2019). The importance of teachers' access to comprehensive curricula (Brody et al., 1995; Gruver & Luloff, 2008; Hale et al., 2017) as well as professional learning opportunities that support their confidence and self-efficacy to teach about water-related topics (Gruver et al., 2009; Hale et al., 2017; Lee et al., 2019), engage in cross-departmental collaboration (Gruver et al., 2009), and develop skills, behaviors and attitudes to support water conservation (Çakır Yıldırım & Karaarslan Semiz, 2019; Cankaya & Iscen, 2015). Forms of teacher support, including professional development and teacher-educative curriculum materials, can help scaffold and enhance teachers' roles as localized instructional designers who translate and implement standards-based, water-focused educational experiences for students in ways that are both responsive to and reflective of the cultural, socio-economic, geographic, and organizational surround. Ongoing research about how to mostly ideally support and position teachers in this role is essential (McKim et al., 2018; Sammel, 2014).

Limitations and research opportunities

While the aim of this study is to conduct a comprehensive analysis of standards focused on human dimensions of water systems, it is important to acknowledge that the main sources of information for the study are standards from organizations in the United States, as well as the United Nations. These are not globally or locally inclusive, as most countries outside of the US non-US organizations, and local US organizations may also articulate standards for teaching and learning about water. Therefore, it perhaps does not reflect the full array of global and local standards for teaching and learning about water. Also, while the selected organizations represent a comprehensive set of disciplines, there might be other organizations or studies that include other standards as well that did not fit the selection criteria of the study. Furthermore, standards analyzed in this study only reflect those that relate to water and humans. It does not include other water-related standards that focus exclusively on natural water systems independent of human activities and, as such, does not fully encompass ALL standards related to water. For a full perspective on water related standards, please see the study's parallel publication (Mostacedo-Marasovic et al., *in press*). Finally, this study does not examine implementation or translation of these standards into tangible educational interventions, programs, pedagogies, and/or resources. No claims are made here regarding how these standards might be implemented, other than that our perspective on the utility of such standards, more generally, is that they should and likely would be implemented in unique context-specific ways

reflecting an array of localized factors, including characteristics of students, teachers, schools, and communities.

Conclusions

The water-related standards discussed in this study are represented across a variety K-12 education curriculum from diverse organizations representing STEM and FANH fields (AAAS, 1993; AgFoundation, 2012; ESL, 2010; GENIP, n.d.; ISTE, 2016; NAAEE, 2019; NGSS, 2013; JCNHES, 2007; Rieckman et al., 2017; Spielmaker & Leising, 2013; USDE, 2017; USGCRP, 2009). The study affords a comprehensive, holistic, and multidisciplinary account of themes related to water and its human dimensions across the K-12 levels that, collectively, speak to a more fully-articulated definition of water literacy. The diversity of the standards presented speaks to the fundamentally interdisciplinary nature of a comprehensive perspective on holistic water education. Results from this research support water education research and practice that can enhance learners' understanding and decision-making about water resources to help address the most pressing water-related challenges of today and tomorrow.

Abbreviations

AAAS: American Association for the Advancement of Science; CDC: Joint Committee on National Health Education Standards; Climate Literacy: U.S. Global Change Research Program; ELP: U.S. Department of Energy; ESL: Earth Science Literacy Initiative; ISTE: International Society for Technology in Education; NAAEE: North American Association for Environmental Education; NALO: National Agriculture in the Classroom Organization & National Institute of Food and Agriculture; NGSS: Next Generation Science Standards; NatGeo: Geography Education National Implementation Project; Pillars: American Farm Bureau Foundation for Agriculture; UNESCO: United Nations Educational, Scientific and Cultural Organization.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s43031-022-00065-y>.

Additional file 1. Representation of learning domains within the thematic outcomes.

Acknowledgements

We would like to thank Tess Foxall for her contributions to this research.

Authors' contributions

Silvia-Jessica Mostacedo-Marasovic. The author has made substantial contributions to the conception, and design of the work; the acquisition, analysis, and interpretation of data; the drafting and substantial review of the work; and has approved the submitted version (and any substantially modified version that involves the author's contribution to the study). The author has agreed both to be personally accountable for the author's own contributions and to ensure that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved, are appropriately investigated, resolved, and the resolution documented in the literature. Brooke Colleen Mott. The author has made substantial contributions to the conception and design of the work; the acquisition of data; the substantial review of the work; and has approved the submitted version (and any substantially modified version that involves the author's contribution

to the study). The author has agreed both to be personally accountable for the author's own contributions and to ensure that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved, are appropriately investigated, resolved, and the resolution documented in the literature. Holly White. The author has made substantial contributions to the conception, and design of the work; the analysis of data; the drafting and substantial review of the work; and has approved the submitted version (and any substantially modified version that involves the author's contribution to the study). The author has agreed both to be personally accountable for the author's own contributions and to ensure that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved, are appropriately investigated, resolved, and the resolution documented in the literature. Cory T. Forbes. The author has made substantial contributions to the conception, and design of the work; the acquisition, analysis, and interpretation of data; the drafting and substantial review of the work; and has approved the submitted version (and any substantially modified version that involves the author's contribution to the study). The author has agreed both to be personally accountable for the author's own contributions and to ensure that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved, are appropriately investigated, resolved, and the resolution documented in the literature.

Funding

This research was funded by the National Science Foundation (DUE-1609598) and USDA National Institute of Food and Agriculture HEC (grant no. 2017-70003-26387/project accession no. 1011948) and PD-STEP (grant no. 2017-68010-25953/project accession no. 1010949) programs. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture or National Science Foundation.

Availability of data and materials

The documents analyzed during the current study are publicly available online.

Declarations

Competing interests

The authors declare that they have no competing interests.

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Received: 21 December 2021 Accepted: 17 August 2022

Published online: 29 August 2022

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