Article

Design Principles for Considering the Participatory Relationship of Students, Teachers, Curriculum, and Place in Project-Based STEM Units

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Abstract: Historically, STEM learning spaces and curriculum have overlooked the strengths and agency of students, teachers, and their communities. Project-based STEM units about environmental issues like water quality offer the possibility to create more expansive, equitable learning experiences. These units can leverage local problems and resources while also including the global dimensions of the issue to provide meaningful opportunities for diverse student sensemaking. However, even project-based STEM learning requires explicit attention to the agency of teachers, students, and place. In order to identify a set of design principles for supporting equitable learning in a project-based STEM curriculum, this manuscript brings together a set of empirical and theoretical frameworks including teacher participatory relationship with the curriculum, culturally sustaining pedagogy, critical pedagogy of place, and equitable sensemaking. The authors use these frameworks to describe a conceptual model of Participatory Relationship of Students, Communities, Teachers, Curriculum and Place. Then, the manuscript outlines a set of seven design principles that connect to the theoretical frameworks to the conceptual model and provide implementation strategies with examples of how we apply these design principles to a project-based STEM unit for 4–8 grade students. The design principles have implications for design of future project-based units and learning opportunities for teachers and students.

Keywords: design principles; project-based; STEM learning; educative curricular materials; culturally sustaining pedagogy; critical pedagogy of place

1. Introduction/Problem

Historically, STEM units have overlooked the strengths and agency of students and teachers as well as the strength of the place where these investigations occur. Research has described how curriculum materials affect student identity change, engagement, and inclusion [1] particularly for students of color [2]. However, there are few opportunities within curricula to leverage student expertise and culture as a part of their STEM learning. Moreover, curricular materials often expect teachers to follow procedures with fidelity cf. [3] rather than recognizing teachers’ agency and resources as assets that work with teachers to support student learning. Although STEM education has been moving toward more expansive and inclusive curriculum and instruction, modifications to school STEM learning have been more additive [4,5] in nature, such that experiences and cultures of minoritized populations are added on top of the current content rather than inclusion of culture into content and activities. Moreover, STEM learning spaces and curriculum have stopped short of supporting participation and inclusion of diverse groups through representation, expansive activities, and culturally sensitive evaluations leading to hierarchies within STEM education [6].
Project-based STEM units about environmental issues offer a place to create more expansive, equitable learning experiences. Project-based learning incorporates five key features: (1) a driving question and/or problem to be solved, (2) students participate in inquiry and exploration of the problem, collaboration of students, (3) teacher(s), and community experts toward a solution, (4) learning supports for students provided throughout the process, and (5) tangible outcomes as a product of the inquiry [7]. These projects can leverage local problems and resources while also including the global dimensions of the issue to allow for an expansive consideration of a problem [8,9]. For example, when considering a curriculum centered around drinking water, where water resources are highly variable, water quality is hyper-local, and yet simultaneously a global concern. However, even project-based STEM learning requires explicit attention to the agency of teachers, students and place.

Recognizing that project-based STEM units may have historically overlooked opportunities to support student and teacher learning, we ask, what are design principles for project-based STEM units that recognize and support the agency of students, teachers, and place? As part of a larger design-based research project designing and studying a project-based STEM unit on water quality for 4th–8th grade students, this paper focuses on the identification and elaboration of the design principles for the curriculum materials. In this paper, we begin by discussing the theoretical underpinnings of our conceptual model that emphasizes the participatory relationship between the curriculum and students, communities, teachers, and place. Next, we describe a set of design principles and discuss each principles connections to our theory and research. For each design principle, we discuss examples of how we apply these design principles to a science-standard aligned curricular unit for 4th–8th grade students. We conclude by discussing future research and uses of the design principles for project-based STEM units.

1.1. Theoretical Frameworks

When considering a curriculum that incorporates teacher learning, sustains students’ culture within science learning, considers the location of inquiry, and expands sensemaking opportunities, we recognized that one framework would be significantly limiting and not reflective of the larger objectives of the curriculum. Therefore, we sought to incorporate several frameworks to best support the development of this curriculum: teacher participatory relationship with the curriculum, culturally sustaining pedagogy, equitable sensemaking, and critical pedagogy of place. In the below paragraphs, each framework has tenets outlined and how the curriculum engages with each one. To conclude this section, we offer a new consideration for curricular design called Participatory Relationship of Students, Communities, Teachers, Curriculum and Place Framework.

1.2. Teacher Participatory Relationship with Curriculum

Teachers regularly engage in the selection, evaluation, and interpretation of the curriculum materials as they consider how to use these materials within their local context [10]. Remillard theorized teachers interact with curriculum materials as a participatory relationship, shown in Figure 1, and others have built and expanded on this view [11–13]. Rather than expecting teachers to teach curriculum with fidelity cf. [3], this view considers resources that teachers bring when using curriculum materials in order to make decisions about how to adapt curriculum for use in their local classroom [11,14]. In this view, curriculum materials can work with teachers rather than serving means of talking to teachers [11]. Teachers’ knowledge, beliefs, experiences, perceptions, and identity (represented by the left circle in Figure 1) interact with resources of the curriculum (represented by the right circle in Figure 1) in a participatory relationship to create a planned curriculum which is then enacted within a classroom [11,15]. As teachers design their planned curriculum from selected materials, they might add new elements, omit others, use elements as written, and modify others [16,17]. These choices made by teachers as they plan a lesson are linked
to the resources of the teachers as well as the resources provided within the materials themselves [11,12]. For example, the voice used within the curricular materials can impact how teachers read and understand the material [18]. As seen in Remillard’s work, this participatory relationship is influenced by the context of the classroom, school, and community [19,20].

**Figure 1.** Participatory Relationship of Students, Communities, Teachers, Curriculum and Place Framework.

As teachers interact with the resources within curriculum materials in this participatory relationship, they can also develop new knowledge and pedagogy [15,21,22]. Educative curriculum materials are materials explicitly designed to support teacher learning along with student learning [15,23,24]. Empirical research suggests that consideration of teachers’ resources and learning in the design of educative curriculum materials can result in the improvement of both teacher and student learning [21,25]. For example, some curricular materials provide rationale for why certain elements of a lesson or a resource for the teachers to interact with and learn from when planning their lesson [26,27]. Research highlights using a variety of educative features to fit the varied needs, interests, and strengths of teachers, their students, and context [12,19,28]. Because teachers often come to curriculum materials at different locations within development of their pedagogical content knowledge and practices [29], they need varied support for their learning [12,13,19].

### 1.3. Culturally Sustaining Pedagogy

Participation in disciplinary practices of STEM require deep understanding through engagement of skills and content. By disciplinary practices, we mean the activities and processes that scientists, engineers, and mathematician engage in to make sense of phenomena and solve problem. Disciplinary practices include arguing from evidence, designing
solutions, and modeling with mathematics. Curriculum that focuses on active engagement of these science practices has been shifting toward more expansive and inclusive curriculum and instruction for marginalized and minoritized communities. Yet, some STEM curricular processes have been marginalizing and exclusionary [6,30,31] to peoples and communities who are not from Eurocentric, Westernized, and colonized perspectives and norms [32,33]. Along those lines, modifications to school science have not largely been transformative [4,5] in nature, such that experiences and cultures populations are deeply connected to the content of the curriculum and teacher instruction. By expanding curriculum and pedagogy to be inclusive of non-dominant and non-European perspectives, students’ culture is integrated into classroom norms and the curriculum being taught to support intellectual leaders and knowledge builders in the classroom [34]. This is part of a larger problem in science education that is increasingly important as settled hierarchies “can profoundly shape who and what is seen and heard as scientifically meaningful” [35], (p.1573); and, therefore, who is able to participate and, ultimately, persist in STEM learning spaces. As a result, there exists much educational research opportunity for exploring curricula within STEM learning environments and cultures of students who have been historically marginalized [36,37] through shifts in curriculum and instruction. These shifts in pedagogical approaches are situated to highlight cultural practices that impact learning and are revised and adapted in many conditions [38].

STEM learning reform that stops short of complete restructuring of experiences within the classroom through pedagogy [39], and curriculum [40,41] is insufficient. The inclusion and representation of students’ culture within STEM curriculum challenges settled hierarchies and representation within STEM experiences. We are utilizing culture as “the constellations of practices communities have historically developed and dynamically shaped...including tools they use, social networks with which they are connected ... ” [42] (p, 286). In order to further support students’ interest in the content and agency through discourse, collaboration, and choice options throughout the curriculum, we are incorporating tenets from a culturally sustaining framework [43] which is an expansion on culturally responsive pedagogy (CRP). The three tenets of CRP are (a) students must experience academic success; (b) students must develop and/or maintain cultural competence, and (c) students must develop a critical consciousness through which they challenge the status quo of the current social order [44] (p. 160). A goal of CRP is to encourage positive student relationships, recognition of racial identity development, and a place in the curriculum for students to find commonness [45–47]. Moving beyond CRP to a culturally sustaining framework, students are supported in having authority to make sense of content ideas and procedures as they engage with the curriculum. These sustaining curricula incorporate activities and assessments that “perpetuate and foster—to sustain—linguistic, literate, and cultural pluralism” [43] (p. 88). More specifically, we incorporate and leverage the expertise and funds of knowledge students bring from outside of the classroom [48] including ways of speaking and sharing information through a project-based learning model. A focus of culturally sustaining pedagogy is to perpetuate and continue youth culture through literacy and cultural expressions which we seek to support through conversation, collaboration, and project-based learning. Engaging with student cultures and background as part of the science classroom experience [49,50] provides space for a powerful learning experience that allows student criticality while engaging content in the classroom and social arenas [51]. Students are supported in having authority to make sense of content ideas and procedures as they participate with the curriculum.

1.4. Equitable Sensemaking in STEM

Building from the culturally sustaining pedagogy framework within the context of STEM education, we start with a view that children should be engaging in sensemaking through the engagement in the practices of scientists, engineers, and mathematicians to develop knowledge of the big ideas of the different disciplines [52,53]. Despite common conceptions that children cannot engage in abstract thinking, even young children won-
nder about their world, develop ideas about phenomena around them, and are able to reason with these ideas to explain natural phenomena and solve problems with proper support [54,55]. However, students are often not given the space and resources (e.g., science ideas for reasoning, opportunities to engage in investigation) needed to engage in this sensemaking [55,56]. However, cultural connections lend themselves to be integral in students’ learning since they can serve as instances of transfer for knowledge beyond the classroom. Connecting science learning to personal experiences gives students an opportunity to support ideas and interests that are contextual, rooted in the communities, cultures, and families [57].

Traditionally, students have been expected to conform and assimilate to privilege “ways of knowing, talking, seeing, and acting shaped by European American practices and values, without consideration of sense-making repertoires, constructions of nature–culture relations, and orientations . . . valued in other cultural historical communities and, significantly, in how they approach scientific phenomena” [35] (p. 1574). Along those lines, students who are not aligned with the normalized expressions of science have been expected to learn science content while simultaneously assimilating to a “culture of power” [6] (p. 564) within STEM learning environments and navigate spaces that do not celebrate, encourage, or affirm their ways of talking, seeing, and being in the world [37,58,59]. This is due to ways students construct meaning of science content and that expression of understanding can incorporate cultural signifiers and markers [60].

We suggest challenging these “cultures of power” and reimagining the ways curriculum, instruction, and assessment can engage student culture and STEM learning content [61]. To allow for student agency within their learning, equitable sensemaking in STEM requires authentic integration of science where engineering, technology, and mathematics disciplinary practices are embedded throughout curriculum, instruction, and assessment. Each individual discipline makes sense with and serves the other content areas [62]. For example, technology is not used to add “fun” to the curriculum rather that the technology is a tool for engagement in a scientific investigation or mathematical modeling to solve problems. By honoring how real-life problems often require interdisciplinary problem-solving, students also should use ideas and practices from across the disciplines for their sensemaking and problem-solving. In this way, students are provided with the tools they need from across the disciplines to answer their questions about the phenomenon and solve the problems they identify [9,53,62].

1.5. Critical Pedagogy of Place

When designing curriculum, particularly a curriculum that includes problem or project-based elements, how much consideration is given to the specific location in which the curriculum will be used? For small-scale projects, this may be seamlessly integrated, but when designing a large-scale project-based curriculum centered on water resources, place suddenly becomes a focal point in the design. For instance, questions arise such as: Where is surface water located nearby? How much rainfall does the area receive annually? What is the primary source for drinking water? Critical pedagogy of place provides a lens for centering place in this type of curriculum by acknowledging the power of place, the multidimensions of place, and the ecological nuances of place [63]. Taken together, critical pedagogy of place combines the theoretical frameworks from place-based education [64] and critical pedagogy [65–67] into the combined idea of centering ecology within a socioecological framework, while understanding and working to subvert power structures that maintain the status quo.

Ecological education has long held the importance of understanding and valuing the biotic and abiotic communities that support a local ecosystem, and from a scientific perspective, tends to ignore the human connections within that ecosystem [68,69]. If humans are discussed, it is in reference to ecological impacts of human activities, rather than the interconnectedness of humans and the environment, or the socioecological implications of this interaction, on both local and global scales. Using a place-based educational lens
in curriculum design allows us to consider the local community issues of a region, and to leverage those issues into problems or project-based units of instruction. However, how does one create a universal curriculum that acknowledges the local issues of a global problem with local consequences, like drinking water? This is where participatory teacher curriculum [11] supports this aim, by acknowledging the interactions between teachers, the curriculum, and ideas and resources that support teacher’s local places and communities.

If we stay with a place-based lens and participatory teacher curriculum, we neglect the third philosophy of our work which includes culturally sustaining pedagogy. By addressing local socioecological issues with the combination of place, educative teacher curriculum, and culturally sustaining pedagogy, we move closer towards critically examining power structures and systems within STEM education and providing students with opportunities to exercise their agency in authentic and meaningful ways.

In summary, our work is, in fact, what Greenwood suggests when he asks, “what are the opportunistic connections that we might discover between place-based educators, science educators, environmental educators, critical pedagogues, and those who embrace the commons?” [70] (p. 338). These opportunistic connections include a framework for participatory teacher curriculum, culturally sustaining pedagogy, and critical pedagogy of place, within a framework of equitable sensemaking in STEM education, focused on the global and local issue like drinking water.

1.6. Participatory Relationship of Students, Communities, Teachers, Curriculum and Place Framework

Drawing on research and theory in teachers’ use of curriculum, culturally sustaining pedagogy, critical pedagogy of place, and equitable sensemaking, we created the Participatory Relationship of Students, Communities, Teachers, Curriculum and Place Framework seen shown in Figure 1. This framework expands Remillard’s Framework describing the participatory relationship between teachers and curriculum materials from Figure 1 [11]. The framework includes explicit consideration of (1) student and community resources; (2) place including socioecological contexts; and (3) the role of students’ prior sensemaking within the planning and enacting of curriculum materials.

In addition to highlighting how teachers bring their resources such as knowledge, beliefs, experiences, perceptions, and identity to interact in a participatory relationship with the resources of the curriculum such as voice, look, structures, and representations of the content [11], this framework expands curricular interactions to include students and community. The resources of the students and community include students’ funds of knowledge, prior learning within school, prior experiences in science, and sensemaking of phenomenon as well as the expertise and understandings of members of the community [9,57,71,72]. In our framework, we highlight the participatory relationship that occurs when the teacher considers the resources and agency of students and their community as well as when curricular materials value and speak with the resources and agency students/community. This participatory relationship between teacher, curricular materials, and students results in the development of a planned curriculum. The planned curriculum as well as the relationship between the teacher, curricular materials, and students within a particular moment becomes the enacted curriculum within the classroom.

Within a STEM project-based unit, with the support of teachers and curricular materials, the students engage in sensemaking of phenomena or problem during the enacted curriculum. The students’ sensemaking results in the brainstorming of new solutions for solving the problem or the identification of new ideas and evidence for explanations of the phenomena [9,73]. The solutions, ideas, and evidence that emerge during the enactment inform the future interaction of students, teachers, and curriculum materials in order to develop the future planned curriculum. Thus, in addition to the enacted curriculum impacting future planned curriculum [11], the solution and ideas expressed from one day of an enacted curriculum feed into the participatory relationship as the next lesson is planned and then, enacted.
In creating a place-based, project-based STEM unit that draws on local community resources, including socioecological dimensions of place, this allows the participatory relationship between curriculum, teacher resources, and student and community resources to be leveraged further to include the experiences and particularities of many different communities. As students investigate local issues and problems related to STEM content, the content ceases to be decontextualized and arbitrary, as the content has an anchor in their community [64,74]. As students seek answers to their questions, or solutions to their problems, their experiences and funds of knowledge contribute to their learning and understanding of the content. Similarly, as teachers engage in this sensemaking with both students and the curriculum, teachers are also able to increase their knowledge and understanding of local socioecological communities and socioscientific issues.

2. Context of the Design-Based Research Project

We used the Participatory Relationship of Students, Communities, Teachers, Curriculum, and Place to identify a set of principles. We use these design principles in a larger design-based STEM research project that focused on human uses of water, the role of water in the environment, and the problems related to water quality for grades 4–8. The larger project includes both the initial design of a curricular unit using 5E Learning Cycles [75], implementation in various classrooms, research of the implementation, and revision of the curriculum based on the research and input from teachers. In using a design-based research methodology, we enter in multiple iterations of design, study, and improvement while attending to our theoretical frameworks in order to recognize the agency of students, teachers, and place. In order to identify design principles, we looked at existing research on the design of STEM learning environments and curriculum materials for elementary and middle grade students. We also draw on a set of theoretical perspectives on learning and teaching to re-imagine how the STEM curriculum could expand toward more equitable sensemaking for students and teachers. The combination of the theoretical perspectives of teachers’ participatory relationship with the curriculum, culturally sustaining pedagogy, critical pedagogy of place, and equitable sensemaking into a larger conceptual model offer a more robust approach to curricular design and implementation. Thus, our use our conceptual model, Participatory Relationship of Students, Communities, Teachers, Curriculum, and Place, enables us to identify both principles and implementation strategies that expand opportunities for equitable sensemaking. The design principles inform both the design of our curriculum as well as how we study and improve it over time. In this paper, we focus on outlining the design principles and how we use them to create the curricular resources for a project-based STEM unit for water. In the next section, we provide a description of the context of the STEM unit.

3. Context of the Water Curriculum

The STEM water unit for students in grades 5–8 has six modules. As a project-based unit, the STEM water unit includes: (1) a driving question and/or problem to be solved, (2) students participate in inquiry and exploration of the problem, collaboration of students, (3) teacher(s), and community experts toward a solution, (4) learning supports for students provided throughout the process, and (5) tangible outcomes as a product of the inquiry [7]. The unit is tied to NGSS and Mathematics common core standards as well as connection to the local state standards for ease of use (Table 1). The units center on performance expectations from the NGSS as well as incorporating mathematics concepts and practices.
Table 1. Related Standards from the Next Generation Science Standards and Mathematics Common Core.

<table>
<thead>
<tr>
<th>Related NGSS Performance Expectations</th>
<th>Related Mathematics Common Core Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop a model to describe the cycling of water through Earth’s systems driven by energy from the sun and the force of gravity. MS-ESS2-4</td>
<td>Display numerical data in plots on a number line, including dot plots, histograms, and box plots. CCSS.MATH.CONTENT.6.SP.B.4</td>
</tr>
<tr>
<td>Apply scientific principles to design a method for monitoring and minimizing a human impact on the environment. MS-ESS3-3</td>
<td>Use proportional relationships to solve multistep ratio and percent problems. Examples: simple interest, tax, markups and markdowns, gratuities and commissions, fees, percent increase and decrease, percent error. CCSS.MATH.CONTENT.7.RP.A.3</td>
</tr>
<tr>
<td>Construct a scientific explanation based on evidence for how the uneven distributions of Earth’s mineral, energy, and groundwater resources are the result of past and current geoscience processes. MS-ESS3-1</td>
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<td>Describe and graph the amounts and percentages of water and fresh water in various reservoirs to provide evidence about the distribution of water on Earth. 5-ESS2-2</td>
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<td>Use argument supported by evidence for how the body is a system of interacting subsystems composed of groups of cells. MS-LS1-3</td>
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<tr>
<td>Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions. MS-ETS1-1</td>
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<tr>
<td>Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved. MS-ETS1-4</td>
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<tr>
<td>Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem. MS-ETS1-2</td>
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<tr>
<td>Convert among different-sized standard measurement units within a given measurement system (e.g., convert 5 cm to 0.05 m), and use these conversions in solving multi-step, real world problems.</td>
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<tr>
<td>Summarize and describe distributions. CCSS.MATH.CONTENT.5.MD.A.1</td>
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</table>

Each of the six modules include a 5E Learning Cycle [75]. An empirically tested model for designing and planning STEM learning opportunities, the 5E model includes 5 elements: Engage, Explore, Explain, Elaborate, and Evaluate (See [75,76]. For example, the Engage Element of Lesson 1 starts with students engaging in a water walk, where they ask how and why they use water in their community. In the Explore Element, students conduct investigations of how they use water, where water is located, and the movement of water into aquifers. Then, students analyze and draw conclusions about their uses of water in the Explain Element. In the Elaborate Element, students extend their investigations by examining how their family can conserve water. In the Evaluate Element, students write about the solutions they found about conserving water and as well as what new questions they have about water use in their community. By using this 5E structure, students are situated as active knowledge builders. Each lesson supports students with opportunities to engage in disciplinary practices throughout. These practices support the ways students investigate and make sense of the natural world through questioning and solve meaning problems through the engineering design [53,77]. Regardless of order, each lesson leads to a solution that can be compounded toward a larger solution at the end of the curriculum. Table 2 outlines each module with its objectives as well as the related disciplinary practices.
<table>
<thead>
<tr>
<th>Lesson Title</th>
<th>Objectives</th>
<th>Focal Disciplinary Practices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Where’s our water?</td>
<td>1. Identify the locations of water in their local community.</td>
<td>Analyzing data</td>
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<td></td>
<td>2. Explain with evidence how humans use water and what changes can be made to conserve fresh water.</td>
<td>Asking questions and defining problems</td>
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<td>3. Compare the percentage of water in different locations on the Earth to explain why freshwater is limited.</td>
<td>Solving problems, Reason abstractly and quantitatively.</td>
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<tr>
<td></td>
<td>Focal Disciplinary Practices:</td>
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<td></td>
<td>Analyzing data</td>
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<td>Asking questions and defining problems</td>
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<td></td>
<td>Solving problems</td>
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<td></td>
<td>Reason abstractly and quantitatively.</td>
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<tr>
<td>Where does our water come from?</td>
<td>1. Identify local drinking water sources and communicate their importance to the local community</td>
<td>Developing and Using Models, Obtaining, Evaluating, and Communicating Information</td>
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<td></td>
<td>2. Develop models to explain how local drinking water is treated and distributed to the community, and what happens after humans have used the water</td>
<td>Attend to precision.</td>
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<td>3. Identify and explain how local drinking water supplies are affected by the water cycle, and how humans fit into the water cycle</td>
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<td>4. Pose questions about drinking water sources and supply possible solutions to water treatment issues</td>
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<td></td>
<td>Focal Disciplinary Practices:</td>
<td></td>
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<td></td>
<td>Developing and Using Models, Obtaining, Evaluating, and Communicating Information</td>
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<tr>
<td></td>
<td>Attend to precision.</td>
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<tr>
<td>What’s in my water from the faucet?</td>
<td>1. Analyze the quality of the water in their area by creating a graph to compare their community with one of another community.</td>
<td>Analyzing data</td>
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<td></td>
<td>2. Define the problem of contaminated water in communities by making connections to the flow of water through the water cycle and water cleaning systems in the area.</td>
<td>Defining problems, Reason abstractly and quantitatively.</td>
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<tr>
<td></td>
<td>Focal Disciplinary Practices:</td>
<td></td>
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<tr>
<td></td>
<td>Analyzing data</td>
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<td></td>
<td>Defining problems</td>
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<td></td>
<td>Reason abstractly and quantitatively.</td>
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<tr>
<td>What are our sources of pollution?</td>
<td>1. Identify local drinking water contaminants and determine their general origins</td>
<td>Developing and Using Models, Obtaining, Evaluating, and Communicating Information</td>
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<td>2. Develop models to explain how point source and non-point source pollution can be identified</td>
<td>Model with mathematics.</td>
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<td>3. Identify and explain how local drinking water supplies are affected by contaminants, and how humans fit into the water cycle</td>
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<td>4. Pose questions about drinking water sources and supply possible solutions to water treatment issues</td>
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<td></td>
<td>Developing and Using Models, Obtaining, Evaluating, and Communicating Information</td>
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<td></td>
<td>Model with mathematics.</td>
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<tr>
<td>What are contaminants? Why do they matter?</td>
<td>1. Describe how cell structures, cells, tissues, organs, and organ systems interact to maintain the basic needs of organisms.</td>
<td>Ask questions</td>
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<td>2. Develop a model and construct an explanation of how cell structures contribute to the function of the cell as a system in obtaining nutrients in order to grow, reproduce, make needed materials, and process waste.</td>
<td>Develop and use models, Analyze and interpret data</td>
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<td>3. Develop and use a conceptual model of how cells are organized into tissues, tissues into organs, organs into systems, and systems into organisms.</td>
<td>Construct explanations</td>
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<td>4. Construct an argument that systems of the body (Cardiovascular, Excretory, Digestive, Respiratory, Muscular, Nervous, and Immune) interact with one another to carry out life processes</td>
<td>Construct viable arguments and critique the reasoning of others.</td>
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<td>Focal Disciplinary Practices:</td>
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<tr>
<td></td>
<td>Ask questions</td>
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<td>Develop and use models</td>
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<td>Analyze and interpret data</td>
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<td>Construct explanations</td>
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<td></td>
<td>Construct viable arguments and critique the reasoning of others.</td>
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<tr>
<td>Our Solution</td>
<td>1. Identify the criteria and constraints for the water problems.</td>
<td>Designing solutions</td>
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<td></td>
<td>2. Design solutions to the water problems they identify.</td>
<td>Planning and conducting investigations</td>
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<td></td>
<td>3. Evaluate solutions to water problems</td>
<td>Make sense of problems and persevere in solving them.</td>
</tr>
<tr>
<td></td>
<td>4. Revise and re-test based on data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Share solutions with community stakeholders</td>
<td></td>
</tr>
</tbody>
</table>
Although the six modules are listed in a particular order in the table, teachers and students can decide to move through the modules in different orders based on the goals for the students, as well as issues that surface from discussions about the role of water in students’ lives and the problem of water quality. Additionally, we are designing the curriculum to be non-linear in an effort to encourage teachers to center and follow students’ interests and questioning. We have prepared curricular modules that can follow a sequential order or allow for multidirectional movement through the unit based on students’ questions and answers. The unit ends with students engaging in an engineering design project based on the problems they identified in the unit, leading to a variety of different possible solution ideas. By supporting the students themselves to identify the problem, including the constraints and criteria based on their learning through the unit, this engineering design project has several possible problems and solutions; from designing appropriate water filtration for their area, designing water collection systems, or designing information systems to share with the community. Through the section of the results, we present examples of the design principles in action based on this STEM water unit as well as other examples from the existing literature.

4. Design Principles

Using the participatory relationship of students, communities, teachers, curriculum, and place framework, we answer the question: What are design principles for project-based STEM units that recognize and support the agency of students, teachers, and place? with seven design principles (see Table 3). We identified these principles by considering the participatory relationship of these frameworks and context of our particular project. In the following sections, we enumerate each design principle, provide a rationale for the principle through describing connections to the theoretical frameworks and empirical research. Next, we outline implementation strategies connected to each principle. We conclude each design principle section with examples from the project-based STEM curricular unit for water.

Table 3. Seven design principles with broad implementation strategies.

<table>
<thead>
<tr>
<th>Design Principles</th>
<th>Broad Implementation Strategies</th>
</tr>
</thead>
</table>
| 1. **Questions and problems identified through the curriculum should be driven by the students and their interests lead to student generated solutions** | • Tracking students’ questions and ideas publicly  
• Allowing for multidirectional movement through the lessons based on students’ ideas  
• Use of 5E model  
• Each lesson leads to a small solution that can be compounded toward a larger solution  
• Culturally sustaining frameworks used for activity and evaluation development |
| 2. **Multiple expressions of community/local knowledge and expertise** | • Water stories and narratives as a part of science learning experiences  
• Recognition/use of local expertise and knowledge |
| 3. **Disciplinary practices, content ideas and crosscutting concepts as tools for students’ inquiry and problem-solving** | • Purposeful integration of content and practices  
• Intentionally using cross-cutting concepts for sense-making  
• Multiple opportunities engage in authentic disciplinary practices  
• Discussion of the how and why of the practices and cross-cutting concepts |
| 4. **Include educative features to support teachers’ knowledge and practice that recognizes their participatory relationship with the curriculum materials** | • Embedding content and pedagogical content knowledge supports throughout the lessons  
• Providing rationales for choices  
• Embedding disciplinary practices support for the teachers through the lessons  
• Use variety of support structures |
4.1. Design Principle 1

**Design principle 1:** Questions and problems identified through the curriculum should be driven by the students and their interest lead to student generated solutions.

**Rationale for design principle:** In order to attend to the strengths and agency of students, teachers, and places, we have included curricular support for a wonderwall (Figure 2) within each lesson. The wonderwall is intended to be a space that encourages students to collaboratively and continuously engage in the disciplinary practice of asking questions as they build science knowledge through the curriculum. Following Driscoll and Lownds [78], we intentionally highlight the natural curiosity and wonder of students as they interact with science phenomenon and systems. A suggested template for the wonderwall includes curricular support for a wonderwall based on the students, teachers, and places, we have included curricular support for a wonderwall and lesson planning.

<table>
<thead>
<tr>
<th>Current Lesson</th>
<th>Problems identified</th>
<th>Questions about this problem</th>
<th>Answers to our questions with evidence</th>
<th>Potential questions and solutions based on these answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lesson 2</td>
<td>Limited water for drinking and use</td>
<td>Where does our water come from?</td>
<td>The water cycle - water on Earth – lakes, rivers, groundwater, snow/ice, oceans, atmosphere</td>
<td>Using and filtering rain water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where does our water go?</td>
<td>Water treatment plants clean our water through filtration and disinfection</td>
<td>More filters for tap water systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>What’s inside of our water?</td>
<td>Contaminants - biological and chemical</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>How do we clean our water?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lesson 3</td>
<td>There are contaminants in the water The contaminants affect body systems</td>
<td>What contaminants are a problem?</td>
<td>They can impact body systems such as cardiovascular, excretory, digestive, and respiratory.</td>
<td>Testing water at home – can we test the water at the tap?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Why are they a problem?</td>
<td>Contaminants by-products of water treatment</td>
<td>Tests at the doctor’s office – How do we know if we have water contaminants affecting our body?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where do the contaminants come from?</td>
<td>Point-source pollution</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>What do contaminants do in the body?</td>
<td></td>
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</tbody>
</table>

Figure 2. Example Wonderwall.
Through the wonderwall, students can experience the various ways to demonstrate learning and express understanding through questions and solutions generated for each lesson. Additionally, teachers engage in a participatory relationship with the curriculum by guiding the choice for the next module used in investigation. Further, we want to situate the wonderwall as an opportunity for students to engage power in the classroom such that their interests and solutions are important to the curriculum [79].

**Implementation Strategies:** Through the utilization of a wonderwall, we amplify the strengths and agency of students, teachers, and place. Students have the choice to use or not use scientific vocabulary [43] on the wonderwall in an effort to identify solutions or generate additional questions. Additionally, the solutions are intended to be generated based on student-led, community-informed, place-based problems and solutions. Using the wonderwall as an opportunity for students to engage in collaborative conversation, we intend for students to have intentional participation with STEM content that incorporates “identities, cultures, and discourses that students bring with them into the classroom are not always valued as legitimate mechanisms or resources to help them participate in science or engineering” [80] (p. 442). The wonderwall will serve as a focal point for investigation questions; however, the solutions and projects are countless. As more solutions and questions are generated, students are able to use content and solutions that has been addressed in content across the lessons. This multidirectional movement through the curriculum provides teachers and students with agency so that the interests of the class guide the order of lessons rather than predetermined investigation questions or a lesson order.

**Curricular Example:** Through the wonderwall, we follow students’ interests and sense-making toward various solutions. For example, as students choose to explore a lesson about how contaminants affect the body, they may develop questions about where these pollutants arise from. Therefore, to support the students in their sense-making, the next lesson would be focused on point-source pollution. Each lesson in the curriculum is developed such that there is an opportunity in each lesson that encourages questioning and solution generation through the wonderwall.

Based on the questions on the wonderwall, the teacher has the agency to identify which lesson best follows students’ interests. Along those lines, students will be able to continue to engage in conversation and collaboration through disciplinary practices as part of their sense-making [81]. Through these student-generated questions, there are multimodal lesson products in the culminating modules. The lesson activities build on themselves in a way that each lesson has several solutions, and the overall curriculum leads to a project-based solution. Students are also able to identify various outcomes per lesson based on their initial questions and areas of interest. The curriculum supports non-linear investigations that lead to broad, diverse, and community-informed solutions.

4.2. **Design Principle 2**

**Design principle 2:** Multiple expressions of community/local knowledge and expertise.

**Rationale for design principle:** In order to attend to the strengths and agency of students, teachers, and places, this curriculum relies on multiple expressions of community/local knowledge and expertise. Traditionally, curricular materials identify specific questions that guide investigations for students and teachers. These pre-determined areas of investigation give power to curriculum and assessment such that the agency of students, teachers, and place are attended to in the curricular materials. Historically, STEM learning spaces operate within existing rules, expectations, and power structures that further marginalize students who may already be having difficulty finding their space and place in science [82]. For example, how students understand what counts as science by utilizing scientific thinking and beliefs could look differently for each student based on their cultural expressions through makers and signifiers; however, these cultural misunderstandings can result in penalization for students’ expression of science understanding based on cultural markers and signifiers [35]. Cultural misunderstandings can result in students being
improperly penalized for expressions of science understanding and participation that are based on normalized cultural makers and signifiers [31]. This is part of a larger problem in STEM education that is increasingly important as settled hierarchies “can profoundly shape who and what is seen and heard as scientifically meaningful” [35] (p.1573); and, therefore, who is able to participate and persist in STEM learning spaces. These types of classroom interactions sustain societal hierarchies by what is considered science content and how it is or is not explored within educational spaces [35,36,42]. By situating the agency of students, teachers, and place, this curriculum uplifts the local and communal knowledge and expertise of the students, teachers, and place.

Implementation Strategies: We highlight the participatory relationship of students, teachers, and place by restructuring power dynamics [79,83] such that local knowledge of place as informed by the community, inclusive of students and teachers, guides the curriculum. By creating a relationship between the curricular content to things outside of the classroom within the community, a student is more likely to consider the information relevant as real-world settings further assign value to the science knowledge. As problems are identified by students, we support students continued engagement with their community as a resource and base of information such that students are able to leverage their personal connections and experiences to inform their science learning. Additionally, as students utilize their own networks, they are positioning other community members as information sources and experts on a scientific topic. Alongside the curricular content, students are able to collaborate with their community to inform scientific solutions.

Curricular Example: Throughout the curriculum, students will share narratives about how water impacts their families and greater local communities. Students will lead the development of these narratives based on conversations with family and community members. These water stories provide students with the opportunity to participate with the content as an authority which moves knowledge as capital from beyond the teacher and curriculum to be inclusive of students and community members through sharing their personal experiences through narratives. “Following the natural curiosity and wonder of students, we recognize the intersecting roles of families, communities, organizations, and institutions in nurturing young learners makes the opportunity to leverage local forms of expertise and to attend to how histories of structural inequalities, economic circumstances, and discrimination can constrain or expand access to learning opportunities” [38] (p. 324). Situating community and local expertise alongside the curriculum and classroom teacher rather than secondary or not considered at all is another way this curriculum seeks to reorder power dynamics in a STEM learning space [6,84]. These water stories reposition the students as experts with experience informed by their communities and the place they are located. Through water stories, students will be able to share their own experiences with water as well as delve deeper into their family and broader community’s engagement with water. Through expanding expressions of community knowledge and expertise, water stories incorporate expertise on local water amongst students, teacher, curriculum, and place.

4.3. Design Principle 3

Design principle 3: Disciplinary practices, content ideas and crosscutting concepts serve as tools for students’ sensemaking and problem-solving.

Rationale for Design Principle: Students can engage in meaningful sensemaking of natural phenomena and problem solving through use of disciplinary practices, content ideas, and crosscutting concepts [9,85,86]. Crosscutting concepts are the ideas that “unify the study of science and engineering [and mathematics] through their common application across fields” [53] (p. 2), such as cause & effect and systems & system models. Rather than restricting the content to items to be memorized as required by the standards, students should draw on their abilities and engagement in the disciplinary practices along with their understanding of the content ideas and crosscutting concepts to help figure out more about a pressing question, phenomena, or problem [53]. The use of the disciplinary practices with
the content ideas as tools for students’ sensemaking and problem-solving in project-based units have shown to improve student learning and allow for diverse sensemaking [9,86,87].

Beginning each unit of study with student-generated investigation questions seeks to engage students in authentic investigation to support explanations of phenomena and solving of problems [88]. These student-driven projects make use of the practices of each discipline, including science practices and mathematical practices. As active knowledge builders, students are able to convey understanding through explanations of difficult science content [89,90] using disciplinary practices. These disciplinary practices emphasize the skills and support practices such as investigation, analysis, argumentation, and communication that are useful in answering real-world problems [91]. For example, students need active engagement to promote the development of argumentation skills which results in deeper content knowledge [92]. However, teacher education has previously focused on preparing students for standardized assessment through memorization rather than cultivating spaces of scientific investigation using inquiry and discourse [93]. The disciplinary practices require adaptations in pedagogy and curriculum to include, support and empower all student voices in discourse [90].

By framing the disciplinary practices, content ideas, and cross-cutting concepts in support of student sensemaking and problem-solving, curricular materials can allow for coherence from the students’ perspective and allow for student agency [73]. By discussing central question, problem, or phenomena of interest to their lives and communities, students have the agency to use their own sensemaking resources to decide what questions need to be asked, what additional research they need to explore, what investigations and evidence they need [37,58,73]. In this process, students will use disciplinary practices such as asking questions, investigation, argumentation, and modeling although these may not match traditional “western” science versions of doing science. Likewise, in their continual work on making sense of the world students bring with them science ideas related to big ideas of the discipline as well as reasoning abilities related to the crosscutting concepts that they draw on in their sensemaking [58,94–96]. As they explore a question, problem, or phenomena further, students will seek out disciplinary core ideas to support their explanations and draw on crosscutting concepts to frame their reasoning and understanding. As seen in our conceptual framework (Figure 2), students’ ideas and solutions from this sensemaking can feed back into the planning process.

We continue to push against oppressive norms in STEM education by positioning students as experts within the curriculum. By recognizing the role of students and community resources in the planning of the lesson in our conceptual framework, we position students’ agency as an asset within the curriculum to be leveraged for learning. Student agency is defined as “an individual’s ability to shape the world around them both in their everyday actions and in their broader goals” [80] (p. 442). We consider students’ cultural ways of knowing and expertise as an asset to any STEM curriculum which should be leveraged to support learning opportunities and expanded assessments. Supporting student agency in STEM also includes developing and practicing habits of mind and allowing students to engage in the culture of science and science education [30]. Part of this engagement is being involved in creating a road map for learning and being able to see where the final destination is located. By using a coherent curriculum framework that logically and sequentially builds skills, knowledge, and understanding, using student-driven questions, students can see how each lesson connects to the others, and to the end goal. Student agency allows for the collaboration and co-creation of a curricular experience that follows students’ identities, cultures, and discourses [74].

Use of the disciplinary practices, disciplinary core ideas, and crosscutting concepts for engagement in sensemaking and problem-solving is authentic and complex [52,53,97]. Students need explicit support in understanding how and why to use the disciplinary practices, crosscutting concepts, and content ideas in their learning [53,98]. This support includes tools embedded within the curriculum materials themselves as well as scaffolding from teachers and others within the classroom [99,100] (For example, in supporting students’
arguments, scaffolding within the curricular materials such as hints about the elements of arguments (e.g., what data to consider or the importance of evidence) along with instructional support from the teachers (e.g., questions and prompt) provided synergistic support for students in this disciplinary practice. Likewise, Fick [86] describes how explicit class discussion of the links between the features of scientific models, the crosscutting concept of systems, and the disciplinary core ideas related to watersheds enabled students to make sense of phenomenon. In the STEM units with a focus on engineering design, teachers created purposeful community spaces for students to engage in the practices of argumentation about their designs [101].

In using the disciplinary practices, content ideas, and CCCs as tools for student learning, the STEM units model the interdisciplinary nature of solving complex human problems in the real worlds; however, integration of disciplines also brings possible challenges [52]. Carefully supporting students to see both the similarities and differences in practices from different disciplines can allow for students to have a deeper understanding of the nature of these disciplines and how to engage in the practices [52,62]. Cunningham and Carlsen [102] argue that teachers need to understand the nuanced differences between science practices and engineering practices to engage students in both sets of practices in meaningful ways. Likewise, Lee [103] highlighted the similarities and differences in expectations for the common practice of argumentation from evidence across the NGSS and Common Core standards. Therefore, curricular materials need to carefully scaffold student in the work of integration in a way that honors the complexity of each discipline.

**Implementation Strategies:** This design principle and rationale suggest that curriculum design needs to ensure that STEM content and practices are integrated through the unit to allow for student learning. Rather than a lecture on content followed by a drill for a particular skill, students should be learning through engaging in disciplinary practices to develop understanding of the content. Moreover, students need multiple opportunities to engage in the disciplinary practice in authentic ways with careful scaffolding that is leveled over time. The crosscutting concepts such as cause and effect should be included intentionally to support student reasoning. Students also need opportunities to develop understanding of how and why scientists, engineers, and mathematicians engage in the disciplinary practices and use the crosscutting concepts. Thus, explicit discussion of what the practices and crosscutting concepts are and why they are used in making sense of phenomena or solving problems is needed within the curriculum [53,96].

**Curricular Example:** Each 5E cycle within the curriculum purposefully draws on a set of disciplinary practices, disciplinary core ideas, and crosscutting concepts and leaves space for students to bring in additional content ideas, practices, and concepts as resources for their learning. In the lesson entitled, “Why do contaminants matter?”, students consider how different contaminants they identified in their drinking water can affect the different systems of the body and designers explicitly identified particular disciplinary practices, crosscutting concepts, and content ideas as tools to help students make sense of the role of contaminants within their bodies. For example, the lesson uses a variety of scientific and mathematical models. These models include a game analogy for thinking about contaminants interact with human body system; a conceptual scientific model created by students to example how the system works; and graphs showing the amount of contamination in the water. By selecting a particular contaminant to examine the effect of on a human body system, students are also likely to construct or use other models such diagrams they find in their personal research or graphs outlining the relationship between the amount of contamination and its effect on a body student. Each of these models allows for students to engage in deeper sensemaking of the phenomena of the role of contaminants in human body systems. To support use of the disciplinary practice of modeling in science and mathematics, the curricular materials provide suggest scaffolding for students such as explicit discussion of how interpret the axis on a graph or consideration of strengths and limitations of the human body game model.
Along with disciplinary practices like modeling, the students use the CCCs and content ideas to engage in reasoning about the impact of contaminants in their body. The modules build up students understanding of the content idea that “the body is a system of interacting subsystems that allows for survival, growth, behavior, and reproduction,” which is needed for making sense of how contamination plays a role in this system. Likewise, the human game model highlights the crosscutting concept of a system and system models with a system that students are familiar with a common game. The class engages in a discussion about the different parts of the game system and how they interact. Then, students can transfer this knowledge of a system to engage in sensemaking around how contaminants interact with the system of the human body. By clearly discussing the common features of these systems, students are able to explicitly use the CCC of system and systems models along with the content ideas and disciplinary practices, e.g., [86].

Another example of how the curriculum materials have students use the disciplinary practices, CCCs, and content ideas as tools for sensemaking and solving problems is the final module. The final module allows students to identify a problem they see related to water quality and design a solution to solve this problem. Through this module, the students use their new understanding of the content ideas and CCCs from through the unit as well as their knowledge of their local community to engage in the engineering practice of designing solutions to problems. Through the use of the wonderwall that tracked learning of ideas and questions from throughout the unit, the students can easily reference key ideas they need to solve their identified problem.

4.4. Design Principle 4

**Design Principle 4:** Include educative features to support teachers’ knowledge and practice that recognizes their participatory relationship with the curriculum materials.

**Rationale for design principle:** As discussed in the section above, educative features are elements of the curriculum materials that intentionally focus on developing teachers’ knowledge and practice [15,24]. When these features are designed to consider the resources teachers bring to their participatory relationship with the curriculum materials, students, and place [11], the teachers are able to develop their knowledge and teaching practices through their interactions with and enactment of the curriculum [21,27,104,105]. In particular, research has shown positive effects of educative features focused on (1) the alignment goals and activities to the standards [105] (2) science content knowledge [15,106], (3) developing teachers’ understanding of the instructional strategies and why to include them [28,104], (4) the how and why of supporting science practices [25,27], and (5) pedagogical content knowledge, especially around students’ ideas [105].

Based on the research on educative curriculum materials, educative features should include a rationale for the choices made in the curriculum materials and, therefore, acknowledge the knowledge and expertise that teachers bring in adapting the materials to their classroom setting [26]. Because research points to the need to use varying different formats of educative features to align with teachers’ resources as well as where and when they need additional support [12,105]. Therefore, the educative features should take a variety of formats such as (1) expository text to explain particular topics in support of teachers’ science content knowledge and pedagogical content knowledge, (2) concept maps to show connections of ideas to goals and standards, (3) vignettes to illustrate choices teachers can make in teaching the curriculum, and (4) rubrics with examples of student work [27,28,107].

Discussing how and why to engage students in science practices and crosscutting concepts in support of student sensemaking are particularly important area given that teachers may not have had opportunities to engage with these practices or concepts as learners [25,27,108]. For example, in a science unit focused on electric circuits, Arias and colleagues [21] included rubrics with examples of student work to show how the rubric could be used to support students in science practices of argumentation and asking questions. When using the curricular materials, the teachers embedded the rubrics into the
students’ assignments and supported student reflection on use of these rubrics. Finally, use of hyperlinks to multimedia content such as videos exemplars of students’ engagement in science practices or sensemaking of science ideas can enable teachers to envision new strategies for supporting student learning [109].

**Implementation Strategies:** Based on the design principle and rationale, project-based STEM curricular materials should embed content and pedagogical content knowledge supports throughout the lessons, such as information on how the content works, as well as key ideas about how to connect content to students and assessments. The materials should also include disciplinary practices support for teachers through the lesson, such as how to engage students in argumentation from evidence. Teachers also need explicit rationale shared for choices throughout the unit. Finally, the use of varied supports (e.g., narratives, explicative texts, etc.) for teachers is included to model teacher agency within the curriculum.

**Curricular Example:** Within the project-based STEM unit on water, we intentionally have included educative features that use a variety of formats to provide support for alignment with standards, science content knowledge, instructional strategies, supporting science practices, and pedagogical content knowledge of students’ ideas. One type of educative feature included in the curriculum materials to support teachers’ pedagogical content knowledge are examples of students’ likely funds of knowledge, prior knowledge and prior experiences that can be leveraged within a lesson. For example, the lesson entitled, “What’s in my water?” focused on investigating contamination in the local tap water discusses that students may already have experiences with mixing items with water such as sugar or salt. We suggest teachers can use these prior experiences to help students think about the visible and invisible contaminants within a glass of tap water. Although considering students’ prior experiences with mixing items with water may be a simple example, we hypothesize that by making the connections between the content of the lesson and students’ prior experiences more explicit, teachers are prompted to reflect on the assets that students bring to the classroom and build on these assets within the co-construction of the lesson.

In another example of applying this design principle, we intentionally provide rationales for different elements of the lesson. Figure 1 provides an example of how we provide the rationale for why we start with having students share their thinking about the big question of the lesson. These types of rationales are embedded throughout the materials to highlight the reasoning the curriculum designers made to help support teachers’ pedagogical content knowledge around supporting science learning as well as provide teachers more information as they make decisions about how to enact the curriculum [12,26,28]. Moreover, to support teachers’ content knowledge and pedagogical content knowledge of how and why to support students sensemaking of the disciplinary practices and content, we have included links to additional background knowledge, exemplars of supporting students’ engagement in disciplinary practices, and potential questions and scaffolds for student sensemaking.

4.5. Design Principle 5

**Design Principle 5:** Questions, problems, evidence and solutions are based on the data for the local context.

**Rationale for design principle:** The emphasis on using a local context for curriculum development is grounded in Place-Based Education [64]. With a Place-Based approach to curriculum writing and development, this allows for local issues to lead the content development, explicitly connecting students to science concepts in their own communities. Smith and Sobel [64] note that the term “place-based education” first appears in 1998, with numerous examples of research in both urban [74,110] and rural settings [111,112] since.

Context matters in how students and teachers experience the phenomenon. For example, the Learning in Places curriculum [113] offers the activity of a “family wonder walk” in which the participants take a purposeful walk around their neighborhood and
collect questions about the experience. Because neighborhoods are very different, this experience will vary greatly between students in rural and urban contexts, between students living in arid deserts and in temperate deciduous forests, or between students living along the coast and along a river, yet similar questions can still be posed. Where does water flow here? What kind of plants grow here? What sorts of animals or living things do we see? What relationships do we notice?

However, place is a tricky concept, and as van Eijck and Roth note, “whose (account of the) place is recounted here?”. Indeed, “people make places, and places make people” [63] (p. 621), which incorporates the human component of place and connects to Culturally Sustaining Pedagogy. During the Learning in Places Wonder Walk [113] students are encouraged to think about their personal connections to places. How do they use this place? What resources come from it? What other connections might we have to this place? Conversely, students are also encouraged to think about non-human connections within this place—what other living things need this place? How do other living things use this place and the resources that come from it? How might this place have looked in the past? Helping students shift their perspectives about place from human-centered to eco-centered allows students to begin investigating the ethics behind making decisions about environmental issues. This shifting of perspectives relates back to Critical Pedagogy of Place, as we interrogate the complex interactions between people and places through both sociocultural and ecological lenses.

**Implementation Strategies:** To use local questions, problems, and issues as the learning context for a project-based STEM unit allows the teacher and students to utilize and leverage local community resources. This includes people who work in fields related to the issue, people who study the issue, and people who have direct experience with the issue. For a project about water, local resources can include local water quality boards, municipal water treatment and sewage treatment facilities, agriculture, storm runoff management, and student experience. By utilizing specialized water testing resources, students can follow up on published water quality reports by testing their own tap water and looking at different parameters for drinking water cleanliness.

**Curricular Example:** Where does your water come from? Ask yourself about what you currently know about your own water distribution system, its source, how it’s delivered to your home, how it’s treated or handled along the way, and then ask a friend or relative in a different state or country the same question. Water management and treatment for drinking is a highly variable process, and even within a single town or city, there can be multiple distribution networks, or a number of citizens with wells and septic systems, in addition to the citizens with public water. To illustrate this idea of local context related to water issues, we highlight two areas, one rural, and one urban, as we walk through the activity of tracing our water delivery.

In Warm Springs, Virginia, an unincorporated small town in the western part of the Alleghany Mountains, the underlying geology is Karst—this means there are frequent sinkholes, springs, gaining streams, losing streams, caves, and other features common with limestone bedrock. As its name suggests, Warm Springs does indeed have a geothermal spring (as does the neighboring Hot Springs), although the chemical signature of the water is different from the surface waters surrounding the springs, suggesting that this particular spring comes from a deep fissure, instead of the more surficial geologic spring. The town of Warm Springs has a public water supply system that is spring and gravity fed [114]. The source of the spring is near the top of Warm Springs Mountain, and gravity feeds it to the surrounding homes. As it is spring water, it is minimally treated at the source with chlorine, prior to distribution. Because it is a public water source, it is routinely monitored by the water board and the State Health authority. However, just to the west of Warm Springs, water is provided to homes through private wells. Because of the nature of Karst topography, groundwater flow in the area can be difficult to map—in one case, geologists found trace dye in a well they considered to be upstream of a losing stream, and in another case, could not locate their trace dye at all [115]. Karst is best described as Swiss cheese...
bedrock. For water quality in private wells, this poses a problem as there is no monitoring for bacterial or chemical contamination. Because the groundwater is connected through somewhat unknown routes, this makes protecting well water a challenge, compared to a public water distribution system.

In sharp contrast, the City of Atlanta, along the banks of the Chattahoochee, receives roughly 70% of its water from Lake Lanier, which lies about 50 miles north of the city, and was formed from a dam on the Chattahoochee River in the 1950’s. The headwaters of the Chattahoochee are in the northeast corner of Georgia, in the toe-end of the Blue Ridge Mountains, near the state line of Tennessee, North Carolina, and Georgia. As the river rolls south, towards the Georgia Alabama border, it pulls along with it the light industrial pollution from North Georgia, as well as agricultural runoff. Unlike the geology of Warm Springs, Virginia, the Atlanta, Georgia area is underlain by a thick and impermeable granite layer that prevents greater access to groundwater. Without groundwater access, the Atlanta metro area relies on surface water for its supplies. While the majority comes from the Chattahoochee River via Lake Lanier, other lakes like Allatoona and smaller lake systems, are used as raw water reservoirs for the city. Once water enters one of the reservoirs, it is released to one of two large Water Treatment Plants which uses a contemporary water filtration process including steps of mixing, flocculation, sedimentation, filtration, disinfection, and clean water storage for distribution to residential customers.

Students in each location trace their water supply, from source to treatment to consumers, then as wastewater back into the water systems, and they see vastly different problems and issues inherent in each. While drought is certainly a concern in both contexts, the spring water in Virginia is more drought resistant than the surface waters in Georgia. Similarly, while students may have wells in Virginia, they are not likely to have the same issues of a tri-state-water war with North Carolina and Tennessee that Georgia is currently litigating. Students in the Atlanta area will not likely see issues with fecal contamination of their treated drinking water, while students in Virginia with unprotected wellheads may.

The context in both instances matters—the problem a student might identify in one place is not the same as a student in another, for good reason! Why should a curriculum only focus on one context, when there is an option to leverage local knowledge, experience, understanding, and socioecological resources? By using the local context as a framework for identifying problems and issues, using local data to investigate the issue, and creating solutions based on local resources, students have an authentic opportunity to investigate scientific concepts and share their learning with their community.

4.6. Design Principle 6

**Rationale for design principle:** John Muir is famously remembered for penning “When we try to pick out anything by itself, we find it hitched to everything else in the universe.” [116]. This is a sound scientific concept, as we see across food webs, habitats, and ecosystem interactions. However, this idea of connection also applies in our increasingly globalized society, from international supply chain delays to empty grocery shelves in a rural supermarket. When considering a STEM-based curriculum investigating socioecological issues, it is important to highlight how global issues have local implications, and vice versa. This is not immediately apparent in Western-centered science curriculum, which often posits global issues like climate change in abstract and decontextualized ways [112], and traditional place-based education tends to foreground local issues in absence of global context [69]. However, the reality is certainly somewhere in-between. As we see increases in severe weather across the United States, from intense heat domes in the traditionally cool Pacific Northwest, to cluster tornado outbreaks in the Southeast, and 1000-year flooding events in Appalachia, the Desert Southwest, and the Rockies, we witness local and regional evidence of climate change [117].

However, global issues like climate change are challenging to teach, simply because of their enormity and feelings of a hopeless narrative surrounding the problem [118]. This
is because the issue feels too big, and indeed, it is, for just one person. Instead of framing the issue as a global concern, if we provide students with a framework or tools to break down a large issue into smaller, local problems, with manageable local solutions, this same tool can be used to build up to consideration of global issues. An example of a framework for exploring local issues is the “Should we” activity framework [113], in which students pose a socioecological question for investigation, related to their neighborhood, for which data can be collected. Should we add worms to our garden compost? Should we plant more native plants in our garden? Should we plant a rain garden on the wet side of the playground? The Learning in Places framework provides students with a structure for investigating their question and providing evidence and reasoning for their answer to their “should we” question.

By recognizing problems and solutions to socioecological problems as both local and global, this connects back to the theoretical framework of Critical Pedagogy of Place. As we provide opportunities for students and teachers to engage in equitable sensemaking with authentic assessments to support culturally sustaining pedagogy, a critical pedagogy of place framework allows students and teachers the opportunity to interrogate the complexities of social, cultural, historical, ecological, and geological contexts that are meaningful and important to their own community.

**Implementation Strategies:** Global problems may seem too big, or too abstract, for students to feel as if they are able to have a meaningful impact. By providing students with tools to break large problems down into smaller, more manageable, local problems, we provide opportunity for students to develop agency and problem-solving skills within a framework that simultaneously allows us to scale up local issues to make connections to global problems. Once students are able to connect local issues to global issues around one topic, like safe drinking water, they have a framework for making these connections between other topics, the disciplinary content, and problem-solving skills.

**Curricular Example:** Drinking water contamination, scarcity, and quality are global issues, yet how these issues appear locally can vary greatly by context. In the curriculum, teachers and students are offered several options for considering local drinking water contamination, by starting with their local water authority and the water quality reports that are shared annually as Customer Confidence Reports [119], or with a Case Study about the ongoing water quality crisis in Flint, Michigan [120]. This choice allows for the teacher to use a framework that best suits their students’ questions about the topic—particularly if students have heard about the drinking water contamination in Flint, and they have questions about what, how, and why the water was contaminated. Similarly, if students live near a large point-source industrial pollutant, like a paper mill, oil refinery, or other heavy-industry, their water quality questions may stem from what they know, or do not know, about these facilities and their water use/discharge.

Once students examine water quality issues for their local areas, they can start to wonder about what issues students in other parts of the world might face. A student in West Virginia, with little experience with drought but with a large coal ash site nearby, might wonder what a student in Nevada might face during a drought. The student in Nevada might wonder about how drinking water is kept safe from coal mining overburden in West Virginia. A student in California whose city water is processed by desalination might wonder how a student’s water is processed in the United Arab Emirates, and if they have similar water quality issues. A student in Mississippi might wonder about microbial contaminants in well water, and how other parts of the world might address this by local wellhead filtration options, or by using the humidity in the air to create drinkable water through condensation.

By creating a framework for understanding a local issue, students can extend their knowledge about drinking water issues to other parts of the US and world. Once students begin making connections between local water quality issues and global water quality issues, it becomes easier to see the global and local connections between other issues, like climate change.
4.7. Design Principle 7

**Design Principle 7:** Assessments authentically support student learning and evaluate students’ engagement in the disciplinary practices, crosscutting concepts, and content ideas as part of sense-making and problem-solving.

**Rationale for design principle:** Authentic assessments play a key role in students’ learning across the STEM fields. The role of assessments is to provide information for teachers and students in supporting further learning (formative assessments) and show the learning that occurred within the classroom (summative assessment). With the goal of developing students’ abilities to engage in disciplinary practice as well as develop conceptual knowledge in science, mathematics, and engineering, the assessment allows students to show their learning in ways that integrate practices with concepts [53]. Rather than traditional multiple-choice tests that emphasize memorization, assessments that require integration of disciplinary practice, crosscutting concepts, and content ideas allow students to show they can engage in reasoning and sensemaking.

Research has highlighted the importance of formative assessment as a way for feedback for teachers and students that can lead to shifts in students’ conceptual understanding and engagement in disciplinary practices [98,121]. Collecting this information on student learning allows teachers to recognize the resources of students, which allows for a participatory relationship with the students, teachers, curriculum materials, and place to create a planned curriculum (Figure 2). Teachers also can adapt and adjust the planned curriculum as needed based on their knowledge of students [10,122]. Moreover, regular use of formative assessment with clear feedback provided to students rather than a focus on grades can increase student learning significantly [123]. These assessments should be embedded regularly within the learning activities to allow for regular cycles of feedback for teachers and students [53].

To continue to interrogate existing measures of science evaluation, assessment instruments can be part of larger systems of oppression due to the ways they support, perpetuate, and uphold Whiteness as property [124] through biases and deficit-based approaches to curriculum, instruction, and assessment [125,126]. Although students’ engagement with science disciplinary skills is important for development of deeper content knowledge [92], the tools used for assessment can be exclusionary to who is seen and labeled as a participant in science [127]. With there being a very narrow expression of science thinking and doing, the assessments for sense-making have reflected assimilation and lack of cultural diversity necessary to be recognized as thinking or behaving like a scientist [128]. Therefore, the assessment should allow for identification of students’ identities, resources, and prior experience. The assessment should be authentic opportunities for students to express their learning in ways that show their sensemaking and problem and share these with their communities [9]. For instance, Nasir [42] utilized the game of dominoes to provide support for learning opportunities through complex mathematics exercises, strategy building, and complex reasoning that can be transferred to the classroom. One method for expanding assessment practices is engaging students in the co-design of rubrics and criteria for success for their projects. For example, Kilgour and colleagues [129] researched the co-design of rubrics with students and teachers toward expanding teachers’ understanding of assessments and student learning. Along those lines, a model for co-construction of project rubrics supports collaboration between students, teachers, and curriculum before, during, and after the completion of the project [79].

**Implementation Strategies:** The implications of this design principle and rationale include the need of the assessment to integrate disciplinary practices with crosscutting concepts and content ideas. Therefore, students should use a disciplinary practice to show their developing understanding of the content. For example, students construct an argument with evidence (a disciplinary practice) that there is a limited quantity (crosscutting concept of scale, quantity, and proportion) of freshwater available for use on earth (a content idea). Moreover, the formative assessment should be included and embedded throughout the unit in order to support students’ learning and to inform planning of future lessons. Likewise,
the collection of evidence of student learning should be authentic to students’ sensemaking and problem-solving, where the assessments match and expand students’ learning rather than focus on memorization or multiple-choice tests separated from learning objectives. Students should have agency and voice in how they are assessed through inclusion of assessment that allow for students’ voice and identity as well as the co-development of criteria and rubrics for activities.

Examples of using the design principle: The first module entitled “Where is our water?” includes a variety of formative assessments that integrate disciplinary practices with science and mathematics content. At the beginning of the lesson, students are encouraged to think about where they find water in the community and how the community uses through a water walk of their neighbor (Figure 3). The students share their initial ideas through a discussion and posing of their ideas and questions on the wonderwall, which is returned throughout the lesson. Seeing this first activity as a formative “pre-assessment” allows the teachers to find out about the resources the students bring into the classroom about the topics of the STEM unit as well as the resources within the community to consider. Next, students engage in an integrated mathematics and science activity where they calculate how to model the amount of water on Earth as a bucket in the classroom. In the formative assessment worksheet that accompanies the activity, students show their understanding of the content by calculating the percentage of a whole as well as their ability to engage in the mathematics practice of reasoning abstractly and quantitatively about real-world problems. The students continue by mapping the locations of water, modeling aquifers, and calculating their water footprint. In each of these activities, the lesson guide includes possible informal formative assessments such as discussion questions or prompts for the students. The guide also includes more formal formative assessments such as writing an argument with evidence about how they can conserve water using data they calculated (Figure 4). The final part of the module includes an “exit ticket” where students reflect on their learning through a set of prompts as well as add additional ideas to their Wonderwall.

**Water Walk**

For this activity, you and your family will take a walk around your neighbor to notice where you can find water and how water is used in your neighborhood. You might think about locations of water in your neighborhood such as creeks and where water goes when it rains. You can look for examples of plants, animals, and people using water. You can use this chart to keep track of your observations and wonderings.

<table>
<thead>
<tr>
<th>What we saw and noticed.....</th>
<th>What we thought and wondered.....</th>
</tr>
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<tbody>
<tr>
<td></td>
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Figure 3. Water Walk Activity.
Figure 4. Example Formative Assessment.

The final module where students work to solve a problem that they identified allows for summative assessment of student learning throughout the unit. Because the students identify the problem that they want to solve, they are required to decide on the criteria and constraints of the problem as a class. This discussion of criteria and constraints leads into a discussion of how the solutions will be graded as a class through creation of a rubrics or checklist as a class. As students engage in the design process, they show their knowledge of the disciplinary practices, content ideas, and crosscutting concepts from the unit. Their final solution can take a variety of forms as the students seem fit for the problem they identified, from a type of water filtration system to a public service announcement on a social media platform. In this way, the summative assessment enables students to use their agency and resources to provide evidence of what they have learned.

5. Discussion: Interlocking Nature of the Principles

Our goal is to design project-based STEM units that recognize and engage the participatory relationship of students, teachers, curriculum, and place (See Figure 5). The use of the seven design principles for project-based STEM unit has the potential to expand how curricular materials and assessments recognize the agency of student, teacher, and place. To do this work, these principles should be used alongside one another rather than stand-alone strategies for curriculum design, since these interlocking design principles support and strengthen each other. For example, the design principles begin with student-driven instruction, as students formulate the questions based on their interests. Features in the curriculum support teacher learning, while recognizing and honoring their practice and expertise. All questions, problems, evidence, and solutions are based on the local socioecological context, which allows for multiple expressions of local and community knowledge and expertise. As we recognize that problems are both local and global in scope, we move into content-based ideas about STEM practices and supporting student learning. Solving one problem generates more questions and more investigations, which continue to be student-driven. Therefore, the assessments for the curriculum must be expansive, such that students’ agency and culture are incorporated and sustained as assets for learning.
and evaluation. As the design principles work together in concert, they support student sense-making about their world, while providing opportunities for student and teacher agency, and an equitable voice in science classrooms.

Figure 5. Interlocking Design Principles.

Another consideration of this curricular unit is that the principles and curriculum need to be consistently modified based on enactment and feedback. Considering the intentional, non-linear nature of the curriculum and assessments, we anticipate various dynamic modifications based on the teacher, students, and location of implementation. Although we have developed a curriculum that centers students’ interests and questions, we recognize that some lessons may follow and support other lessons naturally such that questions and problems that arise in one configuration may not in another. Over time, many of the gaps in how the framework does or does not lead to equitable sensemaking will be fully exampled. As such, identifying gaps in the principles after each iteration of the curriculum would lead to increased opportunities to support teacher learning, center in student and community expert knowledge, and engage in appropriate learning assessment of student sensemaking in various learning spaces. The wonderwall, project rubrics, and other lesson artifacts will lead to the development of modified lessons and learning for strategies to improve the curriculum and support student sensemaking regardless of grade level, teacher experience, and physical location.

By bringing the theoretical frameworks of teachers’ participatory relationship with the curriculum, culturally sustaining pedagogy, critical pedagogy of place, and equitable sensemaking as well as empirical research on learning and teaching in STEM, we identified several key design principles for STEM units. Yet, we recognize that these design principles are not exhaustive of the items to consider when designing STEM project-based unit that examine local-global problems like water. For example, we did not explicitly address research and theoretical frameworks related to the strengths and needs of emergent bilinguals. For example, teachers were able to develop new understandings of how to
support English Language Learners through their interaction with curriculum materials that included explicit supports for this work [104]. Although we suspect some of the design principles would be similar, additional design principles related to discourse and language are likely needed given the growing linguistic diversity within U.S. schools [130]. Another area to consider is supporting teachers in differentiating instruction and making adaptations based on the strengths and needs of their students. How to support the modification and extension of learning goals and activities is certainly a key part of the curricular materials design and implementation. As we continue interactive cycles of investigation and revision of the curriculum in this design-based research project, we imagine that new design principles will emerge from our work with teachers and students.

6. Conclusions

In conclusion, curriculum designers, educators, and researchers need to consider the strengths and agency of students, teachers, and places when designing learning opportunities. By connecting multiple lines of research and theory in curricular materials, e.g., [24], project-based design, e.g., [7], critical pedagogy of place, e.g., [63,64], and culturally sustaining pedagogy, e.g., [43], into conceptual model of the Participatory Relationship of Students, Communities, Teachers, Curriculum and Place Framework, this work extends the research on supporting student and teacher learning through curriculum materials. Drawing on this conceptual model, we have outlined seven design principles to provide useful implementation strategies that can expand how teachers and students interact with curricular materials and the places in which they live. Our future research intends to examine how these principles can be seen in the teaching and learning that take place when teachers enact this STEM unit using these design principles in classrooms. We also intend to apply the seven design principles and the conceptual model to the creation of professional development to support teachers in their adaptations and enactment of the curriculum materials. These design principles likely apply to the design of project-based STEM units for other “local-global” issues beyond water use and pollution, such as health epidemics and climate change. We can explore how the design principles need to be refined to extend to other areas of study.

By bringing together diverse theoretical perspectives, these design principles provide a new approach to designing project-based STEM units. By using these design principles, our water unit as well as other units would honor the agency of students, teachers, and place in ways that have been previously ignored. Specifically, we highlight how to use disciplinary practices to support student sensemaking and questioning while also acknowledging the complexities of socioecological issues in STEM. This work also highlights how to leverage the expertise of teachers to create meaningful learning opportunities within context of their local communities. The project-based STEM units that draw on these principles have the potential to give students and teachers the agency and voice in learning to address problems facing their communities, their countries, and their world, by drawing on the tools of science, technology, engineering, and mathematics.


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