Professional Differences in Green Infrastructure Implementation: A Case Study of Integrating Engineering and Ecological Knowledge Systems in the Water Sector

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Abstract
As water organizations adopt green infrastructure for stormwater management to increase sustainability, new types of professionals are needed that were not previously widespread in the industry. Ecologists and other ecologically-oriented employees are being brought into these organizations that have long been mostly oriented around an engineering knowledge system. This study examines how these two different knowledge systems interact within a water organization, outlining the differences in their underlying assumptions and orientations that can cause friction. The research used a case study approach to examine implementation of asset management within a water organization that has been building and managing green infrastructure for over thirty years. It found that integration around a common decision process can occur, but that it is a slow process filled with continuous negotiation. The research suggests that water organizations looking to establish green infrastructure programs should be more aware and intentional about discussing differences in professional knowledge systems when bringing new types of professions into an established organization.

Keywords
Asset Management
Ecologists
Engineers
Green Infrastructure
Knowledge Systems
Water

1 Introduction

1.1 Green Infrastructure in the water sector

The water industry is facing unprecedented challenges. Infrastructure that was designed for a stationary climate can no longer reliably meet the needs of the future. Climate change-related precipitation changes, deteriorating sewer infrastructure, and population growth are putting increasing pressure on water organizations. As water organizations try to negotiate these, green infrastructure (GI) has been elevated as a way to tackle problems in a more holistic and forward-looking way (Mell 2009; Abhold, Loken, and Grumbles 2011; Finewood, Matsler, and Zivkovich 2019). Interest in GI has been growing in the United States over the last several decades, with the U.S. Environmental Protection Agency (EPA) promoting it for stormwater management (McPhillips and Matsler 2018). The recent increase in federal funding for infrastructure opens up the possibility of significantly more investment in GI across the country in the next several years.

Definitions of GI vary greatly depending on location, context, and use. This flexible definition has enabled it to be applied to multiple scenarios from a landscape scale down to the scale of an individual planter box (Mell 2013; Grabowski et al. 2022). For this study, green infrastructure is defined as: vegetated facilities, either intentionally designed or not, that are used to manage the flow, volume, or quality of stormwater. This definition includes anything from large landscape features that are protected from development to small bioswales that are highly engineered. This is consistent with its meaning in the United States in relation to stormwater management. Implementation of GI requires the expertise of such professionals as landscape architects, biologists and ecologists (for brevity, in this paper the term ecologists will be used), who have a very different orientation than traditional water managers (Karvonen 2011; Mell and Clement 2020).

Despite being used for stormwater management in the US for over three decades, and increasing interest among water utilities, use of GI is not widespread (Abhold, Loken, and Grumbles 2011; Matsler 2017). Several organizations, including the EPA, promote its use, but adoption has been very slow. One reason is that the culture in the water sector is oriented toward traditional pipe and treatment plant solutions and decision processes (Brown, Ashley, and Farrelly 2011; Matsler, Miller, and Groffman 2021; Heiberg, Truffer, and Binz 2022). For example, the industry's use of cost-benefit and business case analysis for infrastructure decision-making has been shown to favor traditional highly-engineered solutions because those decision processes generally exclude qualitative environmental and societal benefits in their calculations (Espeland 1998; Sunstein 2005; Gunawardena, Iftekhar, and Fogarty 2020).

To examine this dynamic, several scholars have looked at water organizations with GI programs in case studies in Seattle (Karvonen 2010), Pittsburgh (Finewood 2016; Finewood, Matsler, and Zivkovich 2019), and Chicago (Cousins 2017). They have concluded that GI is being implemented under existing engineering decision structures. These earlier studies focused on public processes for designing and siting GI, looking at interactions between planning departments, infrastructure departments, and the public. They found that ecological practices have been added on top of existing engineering practices, and only in ways that are compatible with the engineering knowledge system. This paper approaches the question from a different angle than earlier studies by examining organizational culture and interdisciplinarity, focusing on how GI has influenced the culture and decision processes inside a single department implementing GI, using a case study in Portland, Oregon.

Matsler's (2019) examination of GI accounting practices in Portland references the need for engineering and ecological knowledge, but focused on accounting practices, not on the dynamics between ecologists and engineers. That work did include an examination of an eco-techno spectrum, with some GI falling more in line with the engineering-techno knowledge system and some falling more in line with the ecologist-eco knowledge system (Matsler 2019). Matsler et al. (2021) also examined GI knowledge systems in Portland with a focus on the differences between departments and their separate missions and regulatory environments. Neither of these two studies looked at what elements of the knowledge systems around GI in Portland were most important in preventing GI implementation or examined the internal dynamics within the department implementing GI for stormwater management. The research presented in this current paper builds on that work, providing a more in-depth view inside the organization as it struggles with integration of these two knowledge systems. This study also provides an analysis of what differences exist between the two knowledge systems, and how that causes friction and contestation.

1.2 Professional Knowledge Systems

Much of the work in the water sector is technical, requiring specialized professional skills. Professional training does not only involve learning the technical aspects of the field, it also includes learning acceptable ways of seeing and interpreting the world from a specific point of view (Bourdieu 1990; Orlikowski and Gash 1994; Lennon et al. 2016). Because of the way professional identities influence the thinking of individuals, the profession someone is trained into can have an impact on such things as how those individuals interpret problems, what questions can be asked, and what solutions they will be willing to implement (Bijker 1993; Lennon et al. 2016). The values and beliefs that sustain the technical aspects are highly influential over their decision processes. These are part of a person's socialization into the profession and this knowledge is often unconscious and taken for granted.

The concept of "knowledge systems" (KS) is used to encompass the social processes involved in the interpretation, communication, and use of knowledge, and each profession has their own KS, though KSs are not always tied to professions (Grabowski et al. 2017; C. A. Miller and Muñoz-Erickson 2018). Knowledge systems are defined as "the organizational practices and routines that make, validate, communicate, and apply knowledge" (C. A. Miller and Muñoz-Erickson 2018, 3). Cornell et al (2013) say that knowledge systems include the agents, practices, and institutions that form around the production, transfer, and use of knowledge. This is not necessarily a linear process, but can operate in any order as use of knowledge helps transfer and produce it (Lave 2012). Miller and Muñoz-Erickson (2018) divide knowledge systems into four aspects: the knowledge itself, the values involved with interpretation of the knowledge, the epistemologies used to create and interpret the knowledge, and the structures built to produce, circulate, and use the knowledge. An out-of-context fact is not knowledge until it is given some meaning through interpretation. Therefore, the socialization process noted above influences knowledge since experiences, values, context, and insight impact how a piece of information is interpreted and becomes knowledge (Omotayo 2015). In hiring people trained in certain professions, organizations can obtain employees who are pre-trained into the values and KS of that profession, though they will still need to teach the specific history, mission, and goals of the organization (Selznick 1957; Noble 1979; Anteby, Chan, and DiBenigno 2016). There is an active field of study of ways to integrate disciplines in research and between organizations (Johns 2019; Bammer et al. 2020; Zuniga-Teran et al. 2020), but this dynamic within infrastructure organizations is less thoroughly explored.

Training and knowledge systems are not the only things that influences how decisions are made within a profession, regulations and standards are examples of things that also play a role. Both regulations and standards get their legitimacy from experts (Vincenti 1990; Brunsson and Jacobsson 2010). But, because standards are based in the expertise and assumptions from the time and place they were designed, they are inherently backward-facing, which can lead to lock-in and obduracy, restricting the actions of current experts (Brunsson and Jacobsson 2010; Allenby and Sarewitz 2011; Carse and Lewis 2017; Matsler, Miller, and Groffman 2021). Standards are very hard to change and can prevent discussions about ethics or what ‘should’ be done; many believe that if they just rely on the standard that things will be done the ‘right’ way (Porter 1996; Brunsson and Jacobsson 2010). For this study, this means that the history of the water sector as engineering-oriented is important in understanding current standards and decision processes.

1.3 Differences between Engineering and Ecological Knowledge Systems

Water sector organizations, whether public or private, have a focus on building and maintaining large infrastructure systems. Within water organizations, civil engineering expertise has historically been the most important in managing the infrastructure (Herrick and Pratt 2012; Andersen 2018; Matsler, Miller, and Groffman 2021). Other industry professionals, such as financial and communications specialists, have generally deferred to engineers and engineering decision processes for major decisions (Gandy 2003; Karvonen 2011; Finewood, Matsler, and Zivkovich 2019). In the last several decades the balance of professions has started to change in organizations that are implementing GI for stormwater management (Karvonen 2011). Hired for their knowledge and experience with vegetation, ecologically oriented employees have been entering these engineering-dominated organizations.

The KSs of engineers and ecologists have been studied separately; the main differences in their KSs are outlined in this section. Both of these professions have many sub-disciplines. In this section, the common elements that are at the heart of each are highlighted. As explained below, this was fairly straightforward for engineering, as there are consistent standards across the profession. For ecology, there is greater variability, but the literature does highlight some common elements built into the foundations of the professions found in the water sector, such as ecology, landscape architecture, and environmental science.

Ecology, like other scientific disciplines, is primarily aimed at discovering underlying truths about the world (Shapin and Schaffer 1989; Ferguson 1992; McKeon et al. 2020). Ecologists are orientated toward better understanding the natural world; they study ecosystems. Engineering, on the other hand, is focused on changing the world. Engineers interfere with nature for the benefit of people (Vincenti 1990; Ferguson 1992; Teisch 2011; Mitsch 2012). This different foundational orientation – toward understanding versus altering – means that the two will see problems differently and design different solutions.

The question of whether humans are part of nature or separate from it has been debated for centuries (Worster 1994; Cronon 1996; Winner 2010). The scientific view of the world is founded in a separation between the two. By making humans a separate category from nature, scientists can study the world in a mechanistic way as though nature is a complicated machine that can be fully understood through studying the parts in isolation (Worster 1977; Knorr Cetina 1999; Trepl and Voigt 2011). Engineering is based in this view. Engineers focus on technologies used to control nature to benefit people (Noble 1979; Melosi 2008; Schönborn and Junge 2021). Although some individual engineers may not fully accept this premise, the profession, and engineering practice, are based in the separation of nature and people (Espeland 1998; Teisch 2011). This separation of nature and humanity is an essential part of any scientific mindset. However, out of all the scientific disciplines, ecology has been the strongest in challenging this view (Bocking 2004; Kingsland 2005; Trepl and Voigt 2011), focusing on the health of communities of plants, animals, people, and processes together within ecosystems (Bocking 2012; Schönborn and Junge 2021).

Engineering is oriented toward reducing risk, whether this is risks to the public, risks to the organization, or the risk of going over the project budget. Quantification in monetary terms is upheld as the most rigorous way to compare risks against each other and against the cost of ameliorating them (Porter 1996; Sunstein 2005). Money is considered to be a neutral metric to compare things that are otherwise incommensurate (Weaver 1980; Sunstein 2005). Ecology has a more variable relationship with monetization of risks and benefits. There is a tradition within ecology of putting human use value on nature for conservation purposes, but there is also a tradition of rejecting a narrow conception of nature by only its economic or utilitarian values (Kingsland 2005; Bocking 2012). Some ecologists elevate the aesthetic, spiritual and existence value of nature, and monetizing these is sometimes seen as amoral (Bocking 2004; 2012).

Engineers try to increase predictability in their designs (Vincenti 1990; Bucciarelli 1994; Dale et al. 2021). While they will rely on "engineering judgment" this is thought to be a temporary need, with uncertainty decreasing over time (Vincenti 1990). In engineering, there is the belief that all things can be known, and eventually be controlled (Ferguson 1992; Funtowicz and Ravetz 1993). In contrast, Ecology views the natural world as interlinking dynamic processes that are but always changing and shifting; the goal is to understand the underlying processes in a system, what state it is in at any one time is not as important, and unpredictability is an essential part of nature (Bocking 2004; Matsler, Miller, and Groffman 2021).

There is a subtle difference in scale between the two professions. Engineers need to set clear boundaries around design process, focusing primarily on a technology that will need to later fit into the world outside the design boundaries (Ferguson 1992; Bucciarelli 1994). Ecology is less focused on setting boundaries, starting with a holistic view of the ecosystem before zooming in on a specific process or species to study (Bocking 1997; Kingsland 2005). The difference here is subtle, both must do their work in the context of the real world, considering both the small scale and the large, but there is a difference in focus. Engineering processes start at the smaller scale, ecologists start with the larger scale. This highlights the technocentric and ecocentric differences in the two KSs (Matsler 2019).

Engineering does not have a tradition of questioning its own basic foundational principles, with principles being relatively consistent across sub-disciplines (Vincenti 1990; Dale et al. 2021). Instead, the focus is on finding new and creative ways to solve problems within existing engineering assumptions about the world. Ecology, on the other hand, has been called “a remarkably heterogeneous discipline” (Bocking 1997, 5). Ecology pulls together the knowledge and skills from varying sub-specialties to solve problems (Worster 1977; Bocking 1997; Kingsland 2005). And, the basic assumptions and foundational orientation toward problem solving has been contested throughout its history (Bocking 1997; 2004; Kingsland 2005). Ecologists are trained to constantly question themselves in a way engineers are not.

Over the last few decades there has been a call to develop an ecological engineering profession that would integrate the best features of ecology and engineering (Mitsch 2012; Dale et al. 2021; Schönborn and Junge 2021). While environmental engineering is still based very solidly in the engineering KS (Dale et al. 2021), ecological engineering is structured around a hybrid KS, rooted in engineering in some of the areas highlighted above (changing the world, quantification, building a consistent KS), and ecological in others (humans as part of nature, focusing on the watershed scale) (Mitsch 2012; Dale et al. 2021; Schönborn and Junge 2021). Where the most hybridity has been discussed in the literature is in the dimension of predictability, using self-design and co-production with nature to provide predictable functions within a probabilistic and dynamic framework (Dale et al. 2021). This is still mostly an aspiration, though, as very few programs exist for training ecological engineers and the basic values, principles, and definition of the profession are still being debated (Dale et al. 2021; Schönborn and Junge 2021). Within water organizations, ecological engineers do not exist in large numbers and have not yet changed the professional dynamics.

Engineers and ecologists are trained to think about the world in different ways. These are summarized in Table 1. These professional differences lead to different ideas about how to approach problems and find solutions. As with all groups, individuals within these professions will vary in their beliefs and orientations, but professional training is an important part of the cultures within organizations. This raises a question: what does this mean for integrating engineering and ecological KSs within water organizations? If GI is to become more widespread, resolution of the different approaches of the two professions will be vital. This paper examines how the two KSs have been negotiating these differences over the course of three decades of GI implementation at one organization.

Engineering Knowledge System	Ecological Knowledge System
Changing the world – improving on nature so that people benefit	Understanding the world – knowing nature so that it can be protected and restored
Separation of People & Nature: control of nature	Humans are part of nature, but history of working to benefit humanity
Quantify everything; monetization is unproblematic, helps compare things	Also value quantification, but allow exceptions. Nature has existence value: it is immoral to value nature in dollars.
Predictability is very important; want certainty of goals	Dynamic system: changing conditions require changing goals
Primarily Project and Technology Scale: then fit into larger world. Clear boundaries are important	Watershed/Ecosystem Scale: individual projects only make sense within a holistic framework
Consistent Knowledge System: Professional Engineering certification	Heterogeneous Knowledge System: multitude of disciplines and orientations

Table 1: Highlighted Differences Between Engineering and Applied Ecology/Environmental Science Knowledge Systems. Citations are in the text of Section 1.3.

2 Methods

2.1 Data Collection and Analysis

The research was conducted during 2020 and 2021 using semi-structured interviews and document review as a qualitative single case study of a water sector organization that has a robust GI program for stormwater management. Yin (2013) outlines that case studies generally focus around a decision or set of decisions. In this study, the decisions to be studied were around the implementation of asset management. The case study method is useful for examining decisions in a non-experimental context and when the boundaries between what is inside and outside the decision context may be blurry (Yin 2013). Both of those conditions apply to this study. Qualitative case study methods are good for understanding processes and causal explanations within particular contexts and to help in understanding complex social situations and events (Maxwell 1994; Kohlbacher 2006; Yin 2013).

Nineteen interviews were conducted, ranging from 30 to 90 minutes in length, with current and former employees of the organization using Zoom. Table 2 shows the interview questions for the study. The interviews were recorded and transcripts generated by the Zoom platform, which I then edited for accuracy and corrected for transcription errors. Interviewees were selected to represent the work teams, locations, and professional orientations where decisions were made about prioritization of infrastructure implementation. Interviewees included long-serving employees who had direct experience in initial adoption of GI, people who had left employment at the organization, and relatively new employees. Toward the end of each interview, I asked who else should be interviewed, making interviewee selection partially based on a snowball sampling technique. Documents focused on recent discussions of decision making and prioritization.

Questions Asked
1. Why do/did you work at BES? What is special about BES? How is BES unique?
2: How are decisions made about what gets funded and built? Who makes the decision and what data/information is used? Do you think the right people/information is currently used in decision making? Why or why not? Do you think BES strikes the right balance in putting resources toward different types of infrastructure?
3. What types of water infrastructure do you think will be needed in the future? What do you think will be different from now, and what do you think should stay the same? How should the organization decide? Who should be involved in those decisions?
4. Do you believe BES is innovative? Do you want it to be? What are some recent innovations? What changes have you made that you are most proud of?
5. Who pushes for changes at BES? Who pushes back to maintain the status quo? What types of changes are frequently discussed? What types of changes are most likely to be implemented? Who are the internal change agents/external influences?
6. How do you find out about new technologies and trends in the industry? How do you find out about new issues that may become relevant to your work? Internal and external experts you rely on? Anyone you don't consider an "expert," but still rely on?
7. How was the decision to start implementing asset management made? How did implementation of asset management change how decisions were made about what infrastructure is funded and built? Who was involved in the decisions?
8. How did you find out about asset management? Where did you look to understand it better and start designing a program here?
9. What have been the biggest challenges in implementing asset management?
10. What influenced the decision to look at green infrastructure solutions in the 1990s? What are the external influences (prompt if they're confused: regulations, community groups, lawsuits, professional associations)? What are the internal influences (prompt: leadership, younger employees, what their background/profession was)?
11. When you first came to BES, how would you describe the culture? What was most noticeable to you? Did any particular profession or work group have greater influence on decisions in the organization than others?

Table 2: Interview Questions

During the research study, I was employed at the study site. Until the early 2000's, insider research, where the researcher is a member of the organization or culture being studied, was discouraged (Brannick and Coghlan 2007). But, in view of the current emphasis on collaborations between researchers and practitioners, this is no longer the case. Some of the unique issues to consider with insider research are: obtaining secondary access, power and supervisory issues, role conflict, and objectivity (Coghlan and Brannick 2005; Yin 2015). Access to the study site and secondary access were facilitated by employment there. I did not supervise any staff and had the support of my supervisor and the rest of the bureau's leadership team for this research, so supervisory issues did not arise. Role conflict is when it is hard to distinguish between the dual roles as researcher and employee, or when these two roles cause conflict (Brannick and Coghlan 2007). This was not a concern for me because my primary work role was mostly unrelated to the research topic. The research was not performed as part of my job, and I clearly distinguished when I was acting as an employee and when I was acting as a researcher. Interviewees knew when their discussions with me were going to be used for research purposes. Finally, scholars now understand that objectivity is an illusory goal, especially in social science, and have been recognizing that all research is in some ways subjective (Porter 1994; Denzin 2017; Daston and Galison 2021). I accounted for my own subjectivity by discussing thoughts and preliminary findings along the way with a wide variety of research subjects. The combined subjective views of me and the research subjects about events and meanings are reflected in the analysis and conclusions in this study.

Data analysis consisted of thematic analysis using ATLAS.ti. Thematic analysis is defined as "systematically identifying, organizing, and offering insight into patterns of meaning (themes) across a data set" (Braun and Clarke 2012, 57). This analysis involved adjusting and refining codes in an iterative manner as codes were sorted and different themes were linked together to reveal meaning (see Brawley-Chesworth 2022). The final step in the analysis process was to present the preliminary findings to leadership at the organization to obtain their reactions and opinions on the conclusions of the study. Discussing and negotiating findings with those who are being researched is known as communicative validation (Kohlbacher 2006), and while I did not attempt to reach full consensus with leadership of the organization, listening to their reactions helped refine and validate the results.

2.2 Case Selection

The City of Portland Bureau of Environmental Services (BES) started developing a GI program for stormwater management in the mid-1990s and is recognized internationally as being innovative in GI implementation (Brown, Ashley, and Farrelly 2011). To implement GI, new employees were brought into the engineering-oriented organization who had training in landscape architecture, biology, and ecology (these professionals are referred to as ecologists or ecologically oriented employees in this paper).

In the early 2000s, BES started implementing asset management (AM) to help structure decisions around the bureau's traditional "grey" infrastructure, consisting of things like pipes, pumps, and wastewater treatment plants. Since then, there have been periodic attempts to construct an overall AM program that would work for all the bureau's activities, including GI. That has been more difficult because AM in the water sector was designed around the needs of grey infrastructure (Alegre and Coelho 2013).

Asset Management is a decision-making system. First used in finance and accounting, it began to be adopted in the water industry for infrastructure decisions in the 1990s (Grigg 2012; Alegre and Coelho 2013). The basic elements of AM had been used in the infrastructure world for a long time. The AM concept combined them into a framework that could be applied as a coherent program (Grigg 2012). Definitions of AM differ in what is emphasized, most include several key features: focusing on asset condition, evaluation of success in meeting service targets known as Levels of Service, risk management and risk reduction, and examining the cost effectiveness of infrastructure decisions using lifecycle costs and benefits (Alegre and Coelho 2013; Grigg 2012;

Pathirana, Heijer, and Sayers 2021). This study focuses on efforts to establish an organization-wide AM framework at BES.

3 Analysis

BES was created in 1983 when wastewater and stormwater functions were removed from a larger public works bureau in Portland. At the time of its creation, BES was a traditional water organization with a predominant engineering KS. Interviewees who were around at the time talked about the identity of the bureau being tied to being a “pipe bureau” with the focus on “pumps, plants and permits,” with a culture oriented toward engineering. This began to very slowly change in the mid-1990s when it became one of the earliest utilities in the US to begin using GI for stormwater management (Brown, Ashley, and Farrelly 2011; McPhillips and Matsler 2018; Matsler 2019). At that time, new ecologically oriented employees started being brought into BES.

3.1 Integrating Engineering and Ecological knowledge systems

GI work at BES started with small experiments, such as vegetated test plots and parking lot swales. The organizational unit where the work was located was small and separate from the rest of the bureau. This is known in the literature as a niche. Niches are formed when there is a new problem that cannot be solved using current technologies and KSs (Kemp, Schot, and Hoogma 1998). Niches are protected spaces where experimentation can occur and the predominant assumptions and general rules of the organization can be ignored (Hodson and Marvin 2006). This meant that the dominant engineering KS and the new ecological KS were able to coexist semi-autonomously. Interviewees talked about the work being siloed and decisions being made separately, each group using their own criteria and decision processes. There was also agreement among employees, supported by documents, that the engineering decision processes did not change, the non-GI work used the same assumptions and decision processes that were used before ecologists entered the organization.

Employees and leadership within the organization were not, however, satisfied with keeping the two types of work separate. There was a desire to prioritize and resource work using a common set of criteria and methodologies. Efforts to integrate traditional water infrastructure and GI decision processes within BES focused on establishing an organization-wide AM program. Within BES, negotiating how to implement this program involved negotiating the different KSs – engineering and ecological. The following subsections of this paper outline how the differences in professional KSs influenced the AM conversations.

3.1.1 Predictability or Dynamic System Orientation?

For engineers, infrastructure must do what it is designed to do, and clear goals are necessary in the planning, design and construction processes. Goals constrain design processes and define what considerations will be taken into account (Grabowski et al. 2017). Within AM, this is achieved through adoption of clear Levels of Service (LOS), defined as “a statement of outputs or objectives that an organization or activity intends to deliver to customers and stakeholders” (American Water Works Association 2018, 3). Engineers at BES viewed the need for clear, unchanging, and numeric LOS as necessary. As one interviewee said, “. . . we need to figure out what Level of Service we want to have, and how to develop the tactics to get there, and how much it's going to cost, and then get the resources to do it." This simple linear process reflects the engineering knowledge system's desire for predictability.

There was an effort to adopt bureauwide LOS in 2012. And, while some work teams in the bureau used those to guide their work, according to interviewees they were never officially adopted by leadership because some non-engineers in the bureau objected. This was because the ecologically oriented employees viewed setting goals as a more dynamic, holistic, and iterative process. They valued an adaptive management approach where goals changed over time as the system shifted and as more was learned. Instead of using specific and unchanging numbers, the ecologists in the bureau preferred a watershed health index, which included four multifaceted goals that were each rated on a sliding scale. They expressed resentment and "PTSD" over the 2012 LOS effort, feeling like the engineers ignored their objections and tried to push through something that did not fit with their processes and values.

The failure to achieve consensus on LOS in 2012 suggests that the engineering KS was being challenged. However, bureau documents consistently stated that adopting LOS was a goal. This suggests that the ecological KS had not taken over either. The different KSs could not come to agreement, so different systems were still in use for the different types of infrastructure decisions, frustrating the goal of having a consistent process throughout the organization.

3.1.2 Humans Separate or Part of Nature?

There was another element of the LOS discussion where the conflicts between the two KSs could be seen. That disagreement was about how broadly to look at the goals of the organization. In separating humans and nature, the engineering KS traditionally oriented the bureau toward the narrowly focused goals of stormwater management and wastewater collection and treatment. Any other benefits derived from the bureau's work, such as urban heat island amelioration or preserving fish species, were considered peripheral and not to be considered when allocating bureau resources. In fact, some engineers within the bureau saw a conflict between GI work and the bureau's core work, as they defined it, relating to traditional wastewater and stormwater infrastructure. For them, working to improve nature and working on public health were in opposition.

Ecologists in the bureau disagreed on the ultimate goals of BES's work. This difference was not generally discussed explicitly. It was, however, an underlying factor in disagreements between engineers and ecologists. Ecologists in BES were taking a more expansive and holistic view of the purpose of the organization. For these employees, environmental improvements were at the heart of BES's work. They talked about risks to endangered species and watershed health as being risks to BES fulfilling its commitment to the people in the community. For them, work to improve the natural environment and work to improve public health were inherently interconnected. Including benefits to the community, while not inherently part of the ecological KS, is more in line with the holistic orientation of ecologists.

Interestingly, while there was a clear difference between the engineers and ecologically oriented employees at BES overall, some of the engineers who otherwise expressed thoughts that were consistent with an engineering KS, also talked about the importance of integrating the environmental and wider community benefits of BES's work. This was tied to recent discussions about bringing equity and climate resilience into the bureau's work in a more significant way than in the past. This was a reflection, at least in part, of the ecological KS's more holistic orientation influencing BES, creating something that was a hybrid of the two knowledge systems.

3.1.3 Monetization or Existence Value?

The more traditional engineers at BES upheld monetization of risk as essential to implementing a robust AM program. One interviewee said, "I believe that that's really the proper way to do asset management, to quantify your risk in dollars." Bureau documents talked about more mature AM systems requiring monetization of risks because that was the only way risks could be compared and ranked across the organization.

Employees with an ecological KS, however, contested the efforts being put toward assigning dollar values to GI and risks of endangered species extinction. There were also discussions of AM not valuing things in the right way, or in a way that made sense. Employees with an ecological KS objected to the idea that dollars were a neutral metric with which to compare things. They recommended using alternative decision tools such as multi objective ranking.

The bureau had not abandoned the expressed goal of monetizing all risks, and other decision support tools that did not monetize risks were seen as inferior interim methods or substitutes for the more mature monetary framework. There was some contestation of monetization among ecologically oriented employees on moral and ethical grounds, but at the time of this research that view was subordinated to those who valued quantification in dollar terms. Final resolution of this different had not been fully resolved, but at the time of the research the traditional engineering practice was still being held up as the "best" way to do things.

3.1.4 Boundaries: Focus on assets or systems?

Another major topic that has been contested is the question of whether the bureau should focus on assets that the bureau owned or on the overlapping public and private systems that provided services to the community. This is not a clear distinction between engineering and ecological KSs in the existing literature, but was found to be important in this study and should be explored more.

Focusing on owned assets is consistent with a technocentric engineering KS that sets clear boundaries around design process. For engineers at BES, there was a belief that work should focus on managing and controlling assets, which were defined in part by ownership. One interviewee said, "I don't think we can worry about treating private assets as assets right now . . . I don't know why we would want to work so hard to tackle private assets, when we don't have a good asset inventory for the assets we do own."

For ecologically-oriented employees, the system that needed to be the focus of the work was the whole watershed, built or not, regardless of ownership. As one employee said regarding how to overcome a definition of assets based in ownership, "by looking at services and community outcomes again, I think it breaks you out a little bit of some of those narrow definitions, because you kind of have to make it hold together and work." For ecologists, ownership was a bureaucratic hurdle that needed to be overcome to do work the right way, not something that should define the boundaries of the work.

This was a topic that was still being debated at the time of the research. There were some decision processes in the organization that focused primarily on services, and some non-asset solutions, such as a program that provided funding and technical assistance for private property retrofits of stormwater management facilities. But, there was also a significant push to get back to the "core" functions of the organization and focus on the bureau's assets.

3.1.5 Cohesiveness or Heterogeneity?

In the literature about engineering and ecology, one of the most striking differences is the heterogeneity of ecology compared to engineering. Engineers at BES were frustrated by the slow pace of adoption of AM, believing that implementing a program that was consistent with industry standards was straightforward and desirable. Ecologists, however, endorsed reimagining AM and making some fundamental changes. One interviewee said, in reference to the GI work, "you can't just apply the same measures that you did on the pipe side. You had to be able to look at it differently."

BES had been in the process of implementing AM for over 30 years but was still disagreeing about whether water industry AM was compatible with GI work. Official documents continued to support the use of AM, and in 2020 a new AM strategy function was created, but the bureau was still debating some foundational elements of the program and what actions needed to be taken to move it forward.

This continuing contestation of some of the basic foundational principles of AM is perhaps the most significant indicator that BES no longer had a fully engineering-oriented KS. BES was rethinking AM. One non-engineer said,

> I think every discipline should also question its own, sort of, expertise and wisdom. I think asset management should do the same. That's why, when I speak about building an asset management of the future, we should always be willing to pause and . . . identify the shortcomings and fix them, not persist them.

As discussed above, this orientation toward questioning the assumptions of one's profession is a theme that runs through the history of ecology, but not engineering.

3.1.6 Summary

The introduction of new types of professions into BES in the 1990s has resulted in contestations and conflict. The conversations around adoption and evolution of AM in BES highlights this. This is not to say that BES should be looked at as a field of battle where two competing armies, engineers and ecologists, face off in opposition. While some in BES have felt there was an "us versus them" attitude among staff, others felt that everyone was working toward the same goals, and that conflict was due to misunderstandings and the difficulties inherent in change.

For some of the engineers in BES, AM provided a framework for bringing the GI work up to proper (i.e., engineering) standards, and the challenges the bureau faced in implementing GI was mainly because the ecologically oriented employees did not understand how to do things the "right" way. For these employees AM was a tool that could be used to uphold the supremacy of the engineering KS. They tended to see AM as a rigid system with rules that must be followed.

One engineer said of GI work, “they need to be more part of our business stream, they need to be taken more seriously, all of those other categories of work, and brought up to the same level of maturity.” This was because they believed bringing GI decisions into a more engineering-oriented AM system would help the ecologists be successful. They talked about AM providing “common ground” and being “foundational” for decision making.

On the other hand, there were employees at BES who viewed AM as a way to move away from strict engineering-based decision making. They talked about the flexibility of the AM framework and insisted that it did not have to be based in engineering principles. For them, the different ideas and orientations of the engineers and ecologists in BES provided the opportunity to create something new, something better. One engineer said,

> I do think that our diversity of assets and our diversity of professionals and subject matter experts to inform on the investment and management and value of those assets certainly has brought a more robust way of looking at asset management, hands down.

Another ecologically oriented employee described how the contestations around AM were creating a new and innovative system that could be a model for the water industry,

> It's not an either-or thing. A bunch of us are very comfortable with the notion of integrating the two, recognizing that there are shortcomings in doing that, but Portland being Portland, we are in a perfect position to, kind of, change and evolve asset management from a natural infrastructure perspective or a watershed approach.

At the time of this research the bureau was slowly moving forward with creating a new, more heterogeneous asset management approach that combined elements of the engineering and ecological approaches, though key elements were still being contested. The engineering KS had not been replaced, but rather was being supplemented. In some ways the two KSs were competing for influence; but another way to look at is that the two complemented each other, and in the process a new, more heterogenous KS was being produced.

4 Conclusions

4.1 Integrating the engineering and ecological knowledge systems in the water sector

This research has shown that bringing in new types of expertise to an organization can change the knowledge culture of the organization, but that it can take a long time. Adding new types of expertise can change the KSs, but it does not guarantee a change in the organization’s decision-making processes without purposeful efforts to negotiate the differences. For infrastructure organizations, decision structures, regulations, and the assets being managed can influence how much and how quickly the KS changes. For example, this research found that BES’s overall orientation toward an engineering KS did not begin to change until after the GI work moved outside of a niche. What this suggests is that decision processes need to be critically examined, with participation by the new experts, in order for the overall knowledge orientation to begin to change. Even then, this will not be a quick process, and potentially will never be completely resolved. BES has been attempting to develop a consistent, overall decision process for the organization’s varied grey and green infrastructure for approximately three decades, and many fundamental questions about how decisions should be made were still in flux at the time of the research.

This raises the question: what would a hybrid engineering and ecological KS look like and how does BES's compare? There could be many answers to the question of what a hybrid KS would look like, as there are many combinations of ways to choose between the dimensions shown in Table 1. No one combination is necessarily better than any other. Where BES was at the time of this study is shown in Table 3. Water industry organizations that are trying to integrate employees with different training would benefit from discussing the primary differences between the KSs and coming to agreement on what works for them. Each of those fundamental differences in Table 3 is likely to cause friction in an organization trying to integrate the two.

Engineering/Ecological KS Difference	**Current Hybrid BES KS**
Changing the world/ Understanding the world	Changing the world. As a utility, the mission is to protect public health and the environment. This includes actively engaging in wastewater treatment, stormwater management, and watershed restoration and protection.
Separation of People & Nature/ Humans are part of nature	Hybrid, leaning toward humans being part of nature with focus on communities. Control is a key component.
Monetization/ Existence value	Quantification and monetization are upheld as goals, but how to do that is not well understood or agreed upon.
Predictability/ Dynamic systems	Still being contested.
Project and technology scale (technocentric)/ watershed and ecosystem scale (ecocentric)	Primarily Project and Technology Scale, but still being contested and looking at the watershed scale in specific cases. Continuing contestations around the importance of boundaries.
Consistent/ Heterogeneous KS	There are attempts to create one consistent KS through adoption of AM, but it's currently a heterogeneous KS.

Table 3: Comparing the current BES KS to the Engineering and Ecological KSs

The most contested dimension at BES is also the most emphasized dimension for developing ecological engineering, the orientation toward predictability. As explained by Dale (2021, 355), engineers are oriented toward static and reliable designs, while ecological thinking is oriented toward "probabilistic and dynamic" designs to work with "the self-organising nature of ecological systems." The particular importance of this element is also highlighted by Matsler et al. (2021), where it is discussed as measurement challenges. Negotiating the tensions between these two orientations toward predictability is a key open question for GI implementation to become more mainstream. Disagreements in this area cause ongoing disagreements in determining the goals of a project, and whether a completed project was successful. Because engineers are less comfortable with ontological uncertainty than ecologists, going back into a project site to make adjustments is indicative of failure to an engineer, but not to an ecologist. Agreeing ahead of time about the acceptability, and desirability, of adaptive management may help the engineers feel more comfortable with the process. Discussing all the differences shown in Table 3 could also help members of the organization understand and appreciate the value each other brings to the organization, opening up new possibilities for collaboration and creativity.

In water organizations, it is standard practice for leadership to put thought into what new technical skills are needed and making a business case for establishing a new position. But less common is a robust discussion of how the organization, and the knowledge culture, may need to change to accommodate a new way of thinking and get the most out of increasing the diversity of professional backgrounds. While scholars have been examining interdisciplinarity and how to successfully integrate KSs (T. Miller et al. 2008; Lennon et al. 2016; Freeth and Caniglia 2020), this has not yet become widespread in water organizations. The main recommendation from this research for water organizations looking to establish GI programs is to be intentional about discussing knowledge system differences when bringing in employees with a different professional orientation.

The following questions could help water managers and educational institutions moving forward: Do you know what underlying assumptions and values are embedded in your knowledge culture? Are you willing to change the decision processes and assumptions that go into your work? Are you willing to consider a different point of view and values on an equal footing with your traditional views and values? Do you have a culture that promotes productive disagreement and continuous learning? If not, these would be good first steps to implement before hiring new types of professionals. Otherwise, you may be unintentionally creating an environment that delays or prevents the changes you need to solve your most difficult problems.

4.2 Research Recommendations

Further research into how to integrate a new professional KS more quickly into an existing organization could help move the water industry, and other organizations, forward. There are other types of diversity in organizations, looking at how the tools used for racial, gender, and other types of diversity could be applied to an organization with a diversity of professional knowledge systems could be a fruitful area for future research. In addition, current research into interdisciplinarity focuses on either research settings or collaboration between different organizations or departments. Future research could focus on how to improve interdisciplinary work within a single organization to reach common goals when approaching the work from multiple perspectives. And, the main point of continued disagreement in GI implementation, the need for predictability versus comfort with adaptive management, could use more exploration.

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