ECOLOGICAL DESIGN PRINCIPLES AND THEIR IMPLICATIONS ON WATER INFRASTRUCTURE ENGINEERING

Defne Apul, PhD[1]

ABSTRACT

Today's water infrastructures are the outcome of an industrial revolution-based design that are now at odds with the current sustainability paradigm. The goal of this study was to develop a vision for engineering sustainable water infrastructures. A list of 99 ecological design principles was compiled from eleven authors and grouped into three themes: (1) human dimension, (2) learning from nature (biomimicry), and (3) integrating nature. The biomimicry concept was further divided into six sub-themes; (1) complex system properties, (2) energy source, (3) scale, (4) mass and energy flows, (5) structure, and function, and (6) diversity and cooperation. The implications of these concepts on water infrastructure design suggested that water infrastructure should be conceptualized in a more holistic way by not only considering water supply, treatment, and storm water management services, but also integrating into the design problem other provisioning, regulating, cultural, and supporting ecosystem services. A decentralized approach for this integration and innovation in adaptive design are necessary to develop resilient and energy efficient water infrastructures.

KEYWORDS

water sustainability, water infrastructure, ecological design principles, biomimicry, nature

1. INTRODUCTION

Engineered systems in the developed world evolved as products of the industrial revolution. Design principles of the time were different. Dominant and accepted ideas were economics of scale and meeting a specific limited function. Design and development of the water infrastructure system is no exception. In the industrialized world, the water infrastructure was designed initially to supply water to the city, then to sewer the city, and finally to drain the city to avoid flooding (Brown et al. 2009). This design led to the current centralized water infrastructure that consists of a large network of pipes (1.5 million miles of pipes in the US; GAO, 2004) and centralized water and wastewater treatment plants where treated water is conveyed to point of use and from there wastewater is conveyed to a wastewater treatment plant.

The current water infrastructure has served very well in meeting its design purposes of water supply, sanitation, and flood control and has thus contributed much to the improvement of public health and quality of life in the 20th century. However, we now realize that the current water infrastructure design is at odds with today's environmental, economic, and social sustainability paradigms. Energy, water, and materials (e.g. plastic, steel, and concrete, and asphalt) are scarce resources of the future world that will host a much greater population than today. These resources are expansively (and in many cases inefficiently) used in today's water infrastructure. Their shortage would have major implications on water infrastructure performance. Sustainability suggests eliminating waste and local management of resources; yet within the current traditional water infrastructure both storm water and wastewater are nuisances and neither is managed locally. Current water infrastructure contributes little to social sustainability since it is hidden from the public and managed only by specialists. In addition, the current water infrastructure in the United States is old and in need of repairs; so far, funds to maintain it are not available (ASCE 2009).

In response to the surmounting problems and the growing interest in sustainability, the literature

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[1] Department of Civil Engineering, MS 307, The University of Toledo, 2801 W. Bancroft St., Toledo, OH, 43606, USA. Email: Defne.apul@utoledo.edu, Phone: +1 419 530 8132, Fax: +1 419 530 8116.

on water infrastructure sustainability has rapidly expanded in the past few years. The engineering perspective typically focuses on water reuse and other alternative technologies (e.g. Goddard 2006; Huertas et al. 2008; Urkiaga et al. 2008) as well as conceptual and modelling based integrated approaches to urban water management (e.g. Devesa et al. 2009; Liu et al. 2008; Schenk et al. 2009; Hermanowicz 2008; Chung et al. 2008). Some studies focus on human and institutional dimensions of water sustainability (e.g. Starkl et al. 2009; Brown et al. 2009). Ecologists and environmental scientists typically have a different perspective of the water management problem; their starting point is ecosystem health and ecological management of water (e.g. Min et al. 2007; Richter et al. 2003; Baron et al. 2002). Baron et al. (2002) noted that the people (hydrologists, engineers, and water managers) who design and manage the water infrastructures are "rarely taught about management consequences to ecosystems, nor are ecologists trained to think about the critical role of water in human society." This disparity in ecology and engineering fields has been a barrier to progress in designing sustainable water infrastructures.

In order for society to engineer sustainable water infrastructures, the fields of ecology and engineering will need to merge. In practice, some of this merger is taking place with the active role of many landscape architect and environmental architect/design firms that specialize in sustainable construction and integration of natural systems and processes into urban settings (e.g. Wenk Associates; Andropogon Associates; William McDonough and Partners). The landscape ecology literature (e.g. Lovell and Johnson 2008; Termorshuizen and Opdam 2009) will also contribute to this merger. Perhaps, however, the most appropriate home for this merger is within the ecological engineering domain because ecological engineering is "the design of sustainable systems, consistent with self design and other ecological principles, which integrate human society with the natural environment for the benefit of both" (Bergen et al. 2001). Ecological engineering originated with constructed wetland design and has now emerged as a new branch of engineering (Mitsch and Jorgensen 2003) that will play an important role in sustainable development (Gosselin 2008).

The goal of this study was to coalesce the engineering and ecology perspectives on water management within one vision that could guide the engineering of sustainable water infrastructures. Developing a vision is important because it is the first step towards solving a problem both in the engineering context and the sustainability context. While it has been criticized (Upham 2000), the Natural Step remains one of the most prominent sustainability frameworks. In the Natural Step framework, the first step is the 'visioning' process during which a sustainable version of the system is imagined. This vision then drives the entire process toward sustainability (and backcasting is used to determine the steps that will lead to the vision). From an engineering perspective, the vision helps to properly define the problem. Problem definition is the first step in the engineering design process (Dieter and Schmidt 2009), and in dealing with complex systems, inadequate definition of goals or vision is one of the most common mistakes (Wahl 2006).

To develop a vision for engineering sustainable water infrastructures, a list of 99 ecological design principles were compiled from the literature (Table 1). This list was compiled from 11 references. Since this is a long list, it was neither useful nor practical to discuss each one of the principles and their implications on water infrastructure. Furthermore, such a detailed discussion was beyond the scope of this study. Instead, implications of these principles on water infrastructure engineering was analyzed (i) by identifying common themes threaded through the 99-item list, (ii) by reconceptualizing the water infrastructure within the context of these common themes, and (iii) by providing specific examples and ideas for possible implementation of some of these themes.

2. COMPILED ECOLOGICAL DESIGN PRINCIPLES

A literature review on ecological design principles identified 14 different references. However, three of these focused on design principles that were developed for specific contexts such as green chemistry (Anastas and Warner 1998), green cities (Newman and Jennings 2008), and green living (Ludwig 2003). Since the principles in these three references were not broad enough to be applied to water infrastructure design, they were eliminated from the list. A total of 99 ecological design principles were compiled from the remaining 11 references (Table 1). This list included ecological design principles published not only in the peer reviewed literature, but also in books and websites. Book and website based principles were not eliminated and instead, were included in this study because the authors of these references were state-of-the-art practicing designers. Their perspective was deemed important to be included since state-of-the-art is the starting point for design (unlike science where the starting point is existing knowledge or peer reviewed literature) (Dieter and Schmidt 2009).

TABLE 1. Ecological design principles compiled from 11 studies.

Sanborn (S)[1]	Todd (T)[2]	McLennan (M)[3]	Shu-Yang, Freedman, Cote (SFC)[4]
S1. Ecologically responsive S2. Healthy, sensible buildings S3. Socially just S4. Culturally creative S5. Beautiful S6. Physically and economically accessible S7. Evolutionary	T1. The living world is the matrix for all design T2. Design should follow, not oppose, the laws of life T3. Biological equity must determine design T4. Design must reflect bioregionality T5. Projects should be based on renewable energy sources T6. Design should be sustainable through the integration of living systems T7. Design should be coevolutionary with the natural world T8. Building and design should help heal the planet T9. Design should follow a sacred ecology	M1. Respect for the wisdom of natural systems—The Biomimicry principle M2. Respect for people—The human vitality principle M3. Respect for place—The ecosystem principles M4. Respect for the cycle of life – The "seven generations principle" M5. Respect for energy and natural resources—The conservation principles M6. Respect for process—The holistic thinking principle	SFC1. Meet the inherent needs of humans SFC2. Meet toward resource sustainability SFC3. Maintain ecological integrity Emulate natural ecosystems SFC4. Eliminate natural debt SFC5. Protect natural habitat SFC6. Increase environmental literacy
Van der Ryn and Cowan (VC)[5]	**Benyus (Biomimicry) (B)[6]**	**Hannover (H)[7]**	**Holmgren (Permaculture) (P)[8]**
VC1. Solutions grow from place VC2. Ecological accounting informs design VC3. Design with nature VC4. Everyone is a designer VC5. Make nature visible	B1. Nature runs on sunlight B2. Uses only the energy it needs B3. Fits form to function B4. Recycles everything B5. Rewards co-operation B6. Nature banks on diversity B7. Demands local expertise B8. Curbs excesses within B9. Taps the power of limits	H1. Insist on rights of humanity and nature to co-exist H2. Recognize interdependence H3. Respect relationships between spirit and matter H4. Accept responsibility for consequences of design H5. Create safe objects of long term value H6. Eliminate the concept of waste H7. Rely on natural energy flows H8. Understand the limitations of design H9. See constant improvement by the sharing of knowledge	P1. Observe and interact P2. Catch and store energy P3. Obtain a yield P4. Apply self-regulation and accept feedback P5. Use and value renewable resources and services P6. Produce no waste P7. Design from patterns to details P8. Integrate rather than segregate P9. Use small and slow solutions P10. Use and value diversity P11. Use edges and value the marginal P12. Creatively use and respond to change

continues on next page

TABLE 1 (*continued*) Ecological design principles compiled from 11 studies.

<table>
<tr><th>Anastas and Zimmerman (Green Engineering) (AZ)[9]</th><th>Mitsch and Jorgensen (MJ)[11]</th></tr>
<tr><td>AZ1. Inherent rather than circumstantial
AZ2. Prevention instead of treatment
AZ3. Design for separation
AZ4. Maximize mass, energy. Space and time efficiency
AZ5. Output-pulled versus input-pushed
AZ6. Conserve complexity
AZ7. Durability rather than immortality
AZ8. Meet need, minimize excess
AZ9. Minimize material diversity
AZ10. Integrate local material and energy flows
AZ11. Design for commercial "afterlife"
AZ12. Renewable rather than depleting</td><td rowspan="3">MJ1. Ecosystem structure and functions are determined by the forcing functions of the system
MJ2. Energy inputs to the ecosystems and available storage of matter are limited
MJ3. Ecosystems are open and dissipative systems
MJ4. Attention to a limited number of factors is most strategic in preventing pollution or restoring ecosystems
MJ5. Ecosystems have some homeostatic capability that results in smoothing out and depressing the effects of strongly variable inputs
MJ6. Match recycling pathways to the rates to ecosystems to reduce the effect of pollution
MJ7. Design for pulsing systems wherever possible
MJ8. Ecosystems are self-designing systems
MJ9. Processes of ecosystems have characteristic time and space scales that should eb accounted for in environmental management
MJ10. Biodiversity should be championed to maintain an ecosystem's self-design capacity
MJ11. Ecotones, transition zones, are as important for ecosystems as membranes are for cells
MJ12.Coupling between ecosystems should be utilized wherever possible
MJ13. The components of an ecosystem are interconnected, interrelated, and form a network, implying that direct as well as indirect effects of ecosystem development need to be considered
MJ14. An ecosystem has a history of development
MJ15. Ecosystems and species are most vulnerable at their geographic edges
MJ16. Ecosystems are hierarchical systems and are parts of a larger landscape
MJ17. Physical and biological processes are interactive. It is important to know both the physical and biological interactions and to interpret them properly
MJ18. Ecotechnology requires a holistic approach that integrates all interacting parts and processes as far as possible
MJ19. Information in ecosystems is stored instructures</td></tr>
<tr><th>Bergen, et al. (BE)[10]</th></tr>
<tr><td>BE1. Design consistent with ecological principles
BE2. Design for site-specific context
BE3. Maintain the independence of design functional requirements
BE4. Design for efficiency in energy and information
BE5. Acknowledge the values and purposes that motivate design</td></tr>
</table>

1. Sanborn 2009; 2. Todd and Todd 1994; 3. McLennan 2004; 4. Shu-Yang et al. 2004; 5. Van der Ryn and Cowan 1996; 6. Benyus 1997; 7. McDonough and Braungart 1992; 8. Holmgren 2002. 9. Anastas and Zimmerman 2003; 10. Bergen et al. 2001; 11. Mitsch and Jorgensen 2004.

Of the 11 references, the principles developed by Hannover, Sanborn, and Van der Ryn (and Cowan) were primarily geared toward building construction design. The ecological design principles from these three references were previously compiled by Andrews (2006). Principles developed by Benyus' (1997) are referred to as biomimicry principles and are applicable to any kind of design. These principles are published in a book. McLennan (2004) approached design principles from a building perspective as well and proposed six design principles, one of which was based on the biomimicry principle. Holmgren (2002) developed design principles for human habitats; his perspective has been used mostly in agricultural systems.

In the peer reviewed literature, only four studies reported development of new ecological design principles and three of these were developed by ecologists. Bergen et al. (2001) identified the first principles of the ecological engineering design; their list was inspired by Todd and Todd (1994) and van der Ryn and Cowan (1996), among others. Mitsch and Jorgensen (2004) developed the longest list of ecological design principles that were discussed in a pioneering ecological engineering book. Shu-Yang et al. (2004) presented six key aspects of eco-design after reviewing previously published literature. Anastas and Zimmernan (2003) developed 'green engineering' principles; they are the only authors that approached ecological design principles from a primarily engineering perspective.

3. COMMON THEMES WITHIN THE ECOLOGICAL DESIGN PRINCIPLES

The 99-item list of ecological design principles was analyzed for common themes and after several revisions, the list was organized under three primary themes; human dimension, learning from nature (biomimicry), and incorporating nature (Figure 1). In addition, six sub-themes were identified within the biomimicry theme: (i) complex system properties, (ii) energy source, (iii) structure and function, (iv) scale, (v) mass and energy flows, and (vi) diversity and cooperation. These themes and subthemes can form the foundation for all engineering design projects and for engineering a sustainable water infrastructure. A summary of how they relate to conventional versus sustainable water infrastructure design is shown in Table 2. The points summarized in Table 2 are further discussed in this paper.

3.1 Human Dimension Theme

The human dimension theme addresses the social aspects of sustainability and 12 ecological principles relate to this concept. Some key words and ideas included within this theme are beautiful, creative, socially just, healthy, respectful, educational, value-driven, including stakeholders in the design process and meeting the needs of humans. Of these ideas, meeting the (water provisioning, wet weather control and public health) needs of humans is central to the current water infrastructure design but others would be foreign or secondary ideas for a water infrastructure engineer.

For example, infrastructure of pipes and treatment plants are hidden from stakeholders and designed and managed by specialists who are typically civil or environmental engineers. Yet, the ecological design principles suggest a framework that includes stakeholders as opposed to isolating them from the process. If engineers and designers include stakeholders in the design and management process, then the ideas included in the human dimension theme can be more easily incorporated into design as these ideas could more easily be pushed forward by stakeholders than engineers. In traditional engineering, designers by training and by time constraints are typically focused on limited engineering criteria such as meeting the necessary function (e.g. water provision, storm water removal), minimizing cost (weight, volume where appropriate) and increasing durability and quality (Pahl 2007). With stakeholder involvement, additional criteria in accordance with stakeholders' values would be incorporated into the design. As stakeholders help define their own needs, they would also take ownership of the project and act in ways (e.g. educate others, maintain and beautify some parts of it) that would contribute to economic, social, and environmental sustainability of water infrastructure.

3.2 Economic Perspective of the Ecological Design Principles

Sustainability is often considered as a three pronged approach that focuses on the environment, society, and economy. Ecological design principles explicitly incorporate social (human dimension theme) and environmental sustainability (incorporate nature and biomimicry themes). If ecological design principles are in alignment with the sustainability principles, they should also be addressing the economic aspects of the design. In conventional design, typically short-term and direct costs are considered and deemed very important; yet within ecological design principles, there is very little direct mention of economics; instead, indirect social and environmental long-term costs are implied within the principles.

For example, there are many ecological design principles that do not directly mention economics but focus on environmental ideas (e.g. energy efficiency, elimination of waste, design for commercial afterlife) that would affect the life cycle cost of the design. Similarly, economics is indirectly implied in some of the principles within the human dimension theme. Buildings that provide a healthy, beautiful, socially just environment would contribute to keeping the occupants healthy and therefore minimize the health costs of occupants. Among the 99

FIGURE 1. Themes and sub-themes identified across ecological design principles.

Ecological Design

Work With/Incorporate Nature
S1. Ecologically responsive
T1. The living world is the matrix for all design
T6. Design should be sustainable through the integration of living systems
T3. Biological equity must determine design
T7. Design should be coevolutionary with the natural world
T8. Building and design should help heal the planet
T9. Design should follow a sacred ecology
VC2. Ecological accounting informs design
VC3. Design with nature
H1. Insist on rights of humanity and nature to co-exist
MJ4. Attention to a limited number of factors is most strategic in preventing pollution or restoring ecosystems
MJ5. Ecosystems have some homeostatic capability that results in smoothing out and depressing the effects of strongly variable inputs
AZ5. Output-pulled versus input-pushed
BE1. Design consistent with ecological design principles
VC5. Make nature visible
SFC3. Maintain ecological integrity
SFC4. Eliminate natural debt
SFC5. Protect natural habitat
P1. Observe and interact

Human Dimension
S4. Culturally creative
S5. Beautiful
S2. Healthy, sensible buildings
S3. Socially just
M2. Respect for people—The human vitality principle
M4. Respect for the cycle of life—The “seven generations principle”
VC4. Everyone is a designer
H3. Respect relationships between spirit and matter
H4. Accept responsibility for consequences of design
BE5. Acknowledge the values and purposes that motivate design
SFC1. Meet the inherent needs of humans
SFC6 Increase environmental literacy

Biomimicry: Learn from Nature
(M1. Respect for the wisdom of natural systems—The Biomimicry principle; SFC3. emulate natural ecosystems; L1. Follow nature’s example)

Complex System Properties
M6. Respect for process—The holistic thinking principle
H2. Recognize interdependence
MJ8.Ecosystems are self-designing systems
MJ3. Ecosystems are open and dissipative systems
MJ12.Coupling between ecosystems should be utilized wherever possible
MJ13. The components of an ecosystem are interconnected, interrelated, and form a network, implying that direct as well as indirect effects of ecosystem development need to be considered
MJ17. Physical and biological processes are interactive. It is important to know both the physical and biological interactions and to interpret them properly
MJ14. An ecosystem has a history of development
MJ18. Ecotechnology requires a holistic approach that integrates all interacting parts and processes as far as possible
AZ6. Conserve complexity
S7. Evolutionary
P4. Apply self-regulation and accept feedback
P7. Design from patterns to details
P8. Integrate rather than segregate
P9. Use small and slow solutions
P11. Use edges and value the marginal
P12. Creatively use and respond to change

Energy Source
T5. Projects should be based on renewable energy sources
M5. Respect for energy and natural resources— The conservation principles
B1: Nature runs on sunlight
H7. Rely on natural energy flows
MJ2. Energy inputs to the ecosystems and available storage of matter are limited

Structure and Function
S6. Physically and economically accessible
B9: Taps the power of limits
MJ1. Ecosystem structure and functions are determined by the forcing functions of the system
MJ7. Design for pulsing systems wherever possible
MJ19. Information in ecosystems is stored in structures
AZ3. Design for separation
AZ7. Durability rather than immortality
AZ9. Minimize material diversity B3:Fits form to function
H8. Understand the limitations of design
H5. Create safe objects of long term value
AZ2. Prevention instead of treatment
AZ1. Inherent rather than circumstantial
AZ11. Design for commercial “afterlife”
BE3. Maintain the independence of design functional requirements

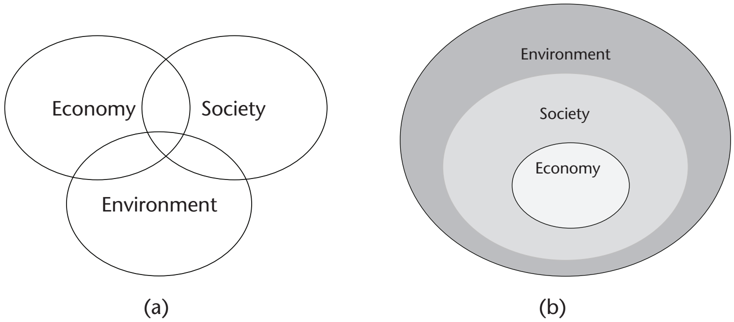
Scale
T4. Design must reflect bioregionality
M3. Respect for place—The ecosystem principles
B7: Demands local expertise
VC1. Solutions grow from place
MJ9. Processes of ecosystems have characteristic time and space scales that should be accounted for in environmental management
MJ11. Ecotones, transition zones, are as important for ecosystems as membranes are for cells
MJ15. Ecosystems and species are most vulnerable at their geographic edges
MJ16. Ecosystems are hierarchical systems and are parts of a larger landscape
AZ10. Integrate local material and energy flows
BE2. Design for site-specific context

Mass and Energy Flows
B2: Uses only the energy it needs
B8: Curbs excesses within
H6. Eliminate the concept of waste
MJ6. Match recycling pathways to the rates to ecosystems to reduce the effect of pollution
AZ4. Maximize mass, energy. Space and time efficiency
AZ8. Meet need, minimize excess
AZ12. Renewable rather than depleting
BE4. Design for efficiency in energy and information
B4: Recycles everything
SFC2. Meet toward resource sustainability
P2. Catch and store energy
P3. Obtain a yield
P5. Use and value renewable resources and services
P6. Produce no waste

Diversity and Cooperation
B5: Rewards co-operation
B6: Nature banks on diversity
H9. See constant improvement by the sharing of knowledge
MJ10. Biodiversity should be championed to maintain an ecosystem’s self-design capacity
P10. Use and value diversity

TABLE 2. Concepts of ecological design principles evaluated for conventional versus sustainable water infrastructure designs.

	Conventional	Sustainable
Integrating Nature	• Unconnected to other life forms; the primary integration way is by biological treatment which uses only a few species (bacteria, etc.) to treat water. • Structural components dominate. • Pipes convey storm water to surface waters. • Uses only water provisioning, flood control, and to some extent water purification ecosystem services. • Cost defines what can be done.	• Nature is integrated throughout not just in treatment. Design links sub-ecosystems. In treatment, more diverse set of organisms are used. • Structural components support non-permanent ecological design components. • Vegetated swales, bioretention basins, and wetlands retain and treat storm water • Uses many other (provisioning, regulating, cultural, and supporting) ecosystem services than water provisioning, water purification, and flood control. Food supply, habitat creation and other ecosystem services are incorporated in design thinking. • Environmental limitations define what can be done before cost is considered.
Human Dimensions	• Infrastructure of pipes and treatment plants hidden from stakeholders, designed and managed by specialists. • Typically no values are considered, there are narrow engineering goals (e.g. provide water, treat water). • Beauty is not a concern.	• Infrastructure accessible to stakeholders, stakeholder is involved in design and management and design process and outcome is educational. • Acknowledges values that motivate design, incorporates stakeholders. • Aesthetics, beauty may be a design criteria.
Biomimicry	• Irrelevant or marginally relevant.	• Central theme
Complex System Properties	• Centralized, one scale, uniform, rigid, fragmented design. • Disintegrated water, storm water, sewer components. • Static design functions within the tight bounds of treatment process parameters. • One way interactions among a limited number of components and services.	• Decentralized, hierarchical, diverse, adaptive, holistic design. • Integrated design achieves multiple functions including food production and energy production. • Use of organisms and non structural components and mindset about adaptability allow the design to have emerging properties that react to changes in inputs. • Designed with interdependence among components and services in mind.
Function	• Meets limited functions such as water supply, sewerage, and drainage. Water provisioning service only for municipal water supply.	• Meets multiple functions that are viewed in context of ecosystem services. All water provisioning services are included in the planning not just municipal water supply.
Structure	• Water is used once and sent to sanitary sewer. Potable water is used (e.g. toilets, irrigation) when even lower water quality would be acceptable. • Primarily hard structural components. • Traditional design.	• Water is used multiple times cascading from higher to lower quality and treatments in between. Water quality matches its intended use. • Structural components supported with renewable and non permanent components • Fits form to function; uses capillary pressure to move water and generate energy; geometrical design to reduce friction; wetland flows and treatments serve as 'treatment plants'; sanitation water requirements eliminated by use of composting and urine separation toilets.
Mass and Energy Flows	• Water is moved by pumps and gravity. • Energy from non-renewable resources. • Waste is inherently implied (e.g. wastewater).	• Water is moved by pumps, gravity, and capillary pressure. • Energy from renewable resources. • Eliminates concept of waste.
Energy Source	• Uses fossil fuel based energy sources.	• Uses renewable limited energy sources.
Scale	• Large one centralized system. • Large scale, limited function. • No exchange of water between buildings. • Designed for 50-100 year lifetime span. • Universal design for all locations.	• Many diverse, centralized and decentralized systems. • Smaller scale, multiple functions. • Buildings exchange water based on water quality and demand. • Designed for adaptability. • Designs are specific to location.
Diversity and Cooperation	• Centralized, one type of method moves and treats water. • Bacteria are primary species that improve water quality.	• Decentralized, multiple methods move and treat water at different locations. • Multiple species contribute to improving water quality.



(a) (b)

FIGURE 2. Three pillars of sustainability conceptualized as (a) three separate but overlapping subsystems and as (b) economy being a subsystem of the human society which itself is a subsystem of the natural world.

principles compiled, there is only one principle that directly mentions economics (S6: Physically and economically accessible) and as other principles, this principle also does not deal with the short term cost of the project but refers to social aspects of economics (economic access by stakeholders).

Ecological design principles, therefore, place a greater emphasis on the social and environmental dimensions of sustainability and consider the economic dimension of sustainability primarily through environmental and societal costs and not as direct costs. This perspective of the ecological design principles has major implications on how an engineering design problem would be defined. The perspective and associated goals and means of an engineering design project can follow that of Figure 2a where economy, society, and the environment are viewed as equally important criteria to be considered in the design process. A sustainable design can be achieved in the intersection of all three of these criteria (i.e. at the intersection of the society, economy, and environment circles). Alternatively, the perspective of an engineering design project can follow that of Figure 2b, where economic (and societal) aspects of the engineering project are constrained by environmental limits.

Among the compiled list of ecological design principles, principles relating to environmental sustainability are highest in number and are emphasized most. The next level of emphasis within the ecological design principles is social sustainability. Finally, there is very little emphasis on and almost no direct discussion of economics within the ecological design principles. Economics is indirectly included through societal and environmental costs. Therefore, the compiled list of ecological design principles aligns more closely with Figure 2b. Consequently, for engineering a sustainable water infrastructure, if ecological design principles are properly followed, the primary limiting criteria will be environmental and social constraints and not economic constraints. Economics and short term cost are almost always the primary constraints for traditional engineering projects. To accept that environmental (and social) goals will supersede the short-term cost constraints will be a major, and perhaps most difficult transition for engineers. Without this fundamental change in thinking, however, only incremental progress through minor modifications to the existing system can be made. As a result, a true alignment of water infrastructure with sustainability would not be possible.

3.3 Biomimicry Theme

Biomimicry is a very dominant theme within the compiled list of ecological design principles. Biomimicry is an ancient concept that was primarily popularized by Janine Benyus (1997) who described biomimicry as imitating life and nature's processes. Benyus (1997) argued that since nature has been around millions of years, it has already developed solutions to various problems and that as human beings we can learn from nature's solutions as we engineer our own systems. To practice biomimicry, designers need to understand how nature works. Six sub-themes were identified within the biomimicry theme as guiding concepts for understanding and mimicking nature. Other groupings or sub-themes could have also been identified but the ecological design principles most easily and comprehensively fit into these concepts: complex system properties, energy source, scale, mass and energy flows, structure and function, and diversity and cooperation.

3.4 Complex Systems Properties Sub-theme

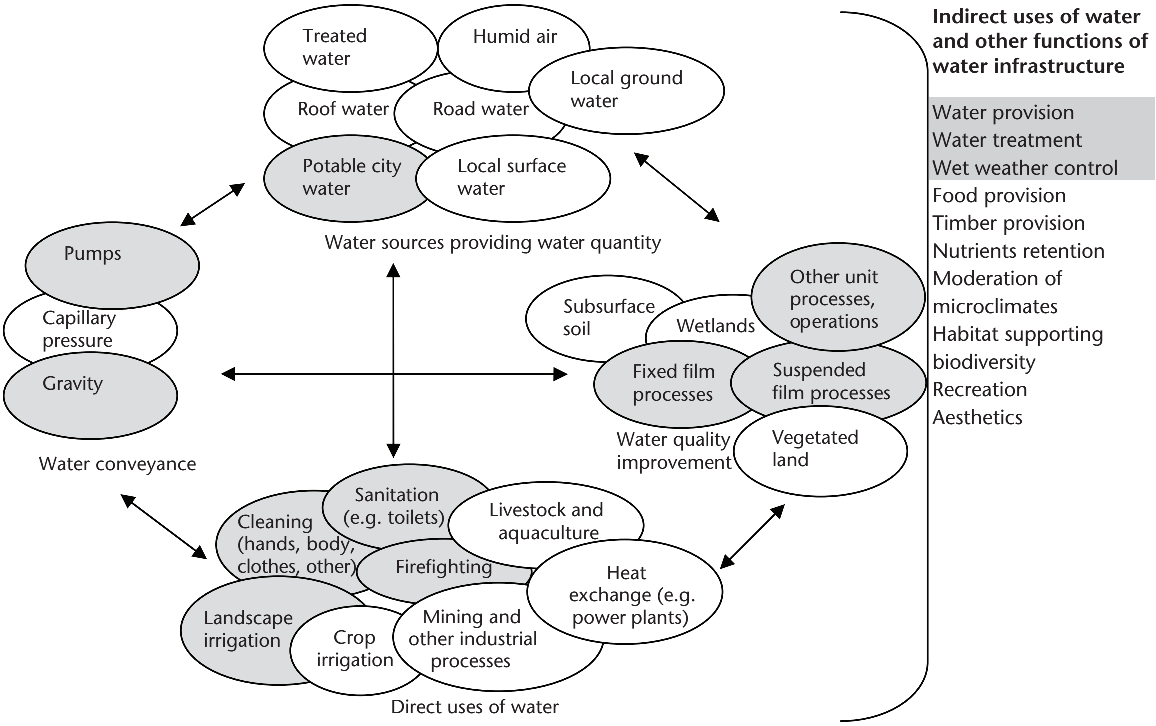
Nature is a complex system, and, therefore has complex system properties. A complex system can be most simply defined as one whose properties are not fully explained by an understanding of its component parts (Gallagher and Appenzeller 1999). Eleven of the ecological design principles describe properties of complex systems. These descriptions refer to integration of all interacting parts and processes that can lead to a holistic design in which the system evolves in time (i.e complex systems have a history). A holistic approach, interacting smaller scale components, and adaptability are inferred by the ecological design principles. These system properties can arise from decentralization which is a key concept for complex systems. In decentralized complex systems there are autonomous agents at the bottom of the hierarchy; these agents interact to develop emergence and self organization at a different level of observation than the agents themselves (Parrot 2002). Diversity of autonomous agents and their multiple interactions lead to unpredictable, adaptive and resilient behaviour.

3.5 Systems Perspective of the Water Infrastructure

Toward integrating these complex system properties into water infrastructure design, a systems perspective of water infrastructure was developed (Figure 3). In this systems perspective, the water infrastructure consisted of four sub-systems: water source, water treatment, water conveyance, and the direct use of the water. In addition, indirect uses of water or other functions of water infrastructure were considered as an important aspect of the systems perspective.

This conceptualization of water infrastructure is well aligned with integrated water management concepts and meshes and expands on previously discussed ideas. Previously, researchers have discussed integrating water, wastewater, and storm water infrastructures (Mitchell 2006; Anderson and Iya-

FIGURE 3. Ecological water infrastructure: re-conceptualization of the water infrastructure boundaries and components.



duri 2003), other uses of water (such as in energy, food production, and industry; Schenk et al. 2009) and stakeholders (Schenk et al. 2009; Brown et al. 2009) toward developing sustainable water infrastructures. These ideas are integrated within Figure 3 along with other ideas such as ecosystem functions and multiple approaches for water source, water conveyance, and water treatment.

In Figure 3, the shaded ovals depict the traditional, narrow visualization of the water infrastructure. The unshaded ovals represent a greater diversity of options for water source, conveyance, and treatment that could possibly be used in sustainable water infrastructures. Water is used directly for many purposes in the current water infrastructure but the uses represented in shaded and unshaded ovals are typically conceptualized and designed independent of each other. In contrast, in sustainable water infrastructure design, all water uses will be considered to better explore possible synergies arising from the integrated design process.

Traditional water infrastructure uses a groundwater or a surface water source to centrally produce potable water at a drinking water treatment plant which is then conveyed to users (i.e. buildings) where 'water' is consumed as a product. Water quality improvement is a critical component of the water infrastructure and is provided through the water and wastewater treatment plants. Traditional water infrastructure is a linear, one way system where water is pumped from a central water treatment plant to buildings, and wastewater from buildings typically flows by gravity to a wastewater treatment plant. Flood and wet weather control are provided by the storm water infrastructure which traditionally is a centralized approach with the goal of quickly removing the water from the site using storm water or combined sewer pipes. Thus, the conventional water infrastructure provides three primary functions: water provisioning, water treatment, and storm water management.

In Figure 3, consideration and integration of multiple functions of the water infrastructure (beyond the functions of water provision, treatment and wet weather control) is one key aspect to be considered in design of sustainable water infrastructures. In nature, many materials, surfaces, and devices have multiple functions (Bhushan 2009). In practice, an integrated approach to water, sewage and storm water planning can identify opportunities and cost savings that are not apparent when separate strategies are developed for each service (Anderson and Iyaduri 2003). Therefore, it is likely that such additional benefits may be realized when other functions are also integrated. In addition, the concept of waste can be more easily eliminated when multiple functions of water infrastructure are considered because what is considered waste can be used as a resource for a different function. One primary theme of the ecological design principles is integration with nature; therefore the additional functions of water infrastructure (e.g. food, timber provisioning, nutrients retention, moderation of microclimates, habitat supporting biodiversity, recreation, aesthetics) were conceptualized as services provided by nature (ecosystem services).

3.6 Integration with Nature Theme

Ecosystem services are the benefits people obtain from ecosystems (United Nations Millenium Ecosystem Assessment 2005). The relation of water infrastructure with ecosystem services is shown in Figure 4. Traditional water infrastructure is designed as a separate entity than the ecosystems. It is designed so that humans benefit from ecosystem services only when water is withdrawn from nature (water provisioning ecosystem service) and when wastewater water is released to the environment for further natural treatment (water purification ecosystem service) of wastewater-treatment-plant–treated water. Traditional water infrastructure relies heavily on engineered structural components of pipes, pumps, and treatment plants.

In contrast, the ecological design principles emphasize the need to integrate nature into the design. Therefore, the sustainable water infrastructure is embedded within the ecosystem and is thus inherently integrated with nature. Through this integration, sustainable water infrastructure allows humans to benefit from multiple ecosystem services not just water provisioning and water purification (Figure 4). Sustainable water infrastructure design also has engineered structural components but these have supporting roles for ecosystem services and are not as dominant as in the traditional water infrastructure design. The ecosystem services provided

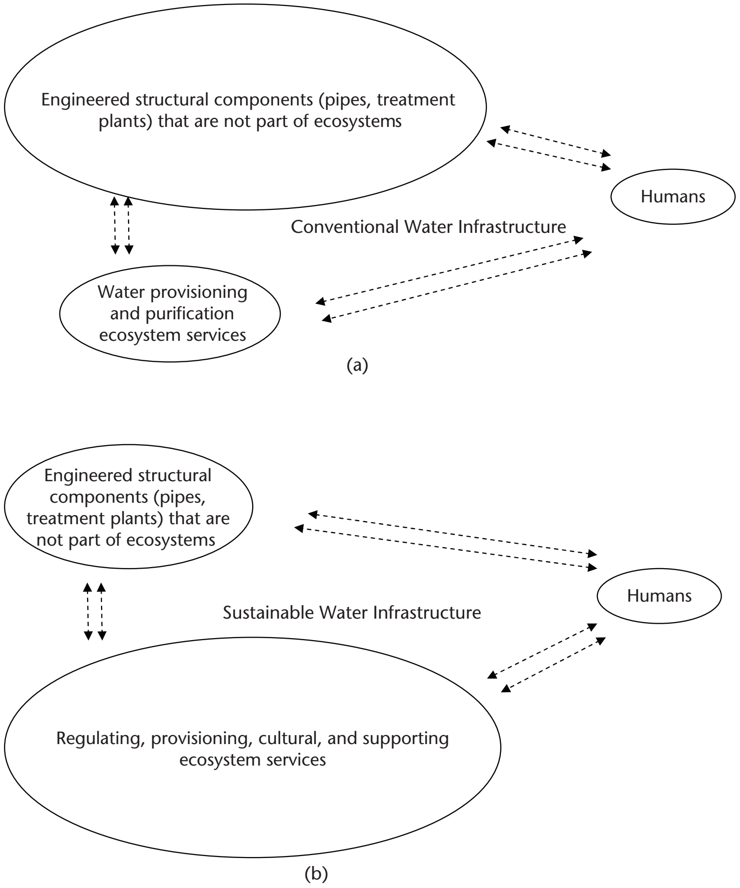


FIGURE 4. Traditional water infrastructure (a) heavily depends on engineered structural components that are not part of ecosystems. Traditional water infrastructure is designed to benefit only from water provisioning and purification services. The sustainable water infrastructure (b) is designed to benefit from multiple ecosystem services, not just water provisioning and purification. In sustainable water infrastructure design, engineered structural components provide support to the ecosystem services not vice versa.

by a sustainable water infrastructure can be provisioning (that provide water, food, and timber), regulating (water purification, moderation of microclimates), cultural (recreation, aesthetics, tourism), and supporting services (nutrient cycling, habitat supporting biological diversity) (Figure 3) (United Nations Millennium Ecosystem Assessment 2005). These multiple functions have not yet been explicitly incorporated into any of the engineered water infrastructures; engineering such water infrastructures will require major innovation since no examples are yet available.

3.7 Scale Theme

The scale concept of ecological design principles suggest a decentralized hierarchical design where individual designs are developed locally, and interact with other designs to become a part of the larger landscape. The interactions on the edges of the design are also critical. Accordingly, in the sustainable water infrastructure envisioned in Figure 3, the functions of water infrastructure are broader while its autonomous scale is smaller. In the context of landscape design, a similar approach was also proposed by Lovell and Johnson (2008). The first objective of landscape design is to improve landscape performance by developing design that integrates multiple functions in the landscape. This integration should happen within the same site (Lovell and Johnson 2008). The scale of the 'site' in the context of water infrastructure design could be a building or a cluster of buildings. A single building may in some cases be too small a scale. Design for a cluster of buildings would better allow integration of multiple ecosystem services into the design and the synergistic benefits these services will provide the users. In addition, a cluster of buildings would allow exchange of water between buildings which may optimize the use of water. The cluster of buildings could then be, in some cases, connected to other clusters within a watershed, thereby allowing the decentralized systems to be loosely connected with each other. A similar design approach with some decentralized systems and other ‘satellite’ systems was proposed by Gigas and Tchobanoglous (2009) not for a full water infrastructure but for a sanitation infrastructure. To avoid (virtual or actual) water transport across watersheds, a scale larger than the watershed would not be appropriate for designing sustainable water infrastructures.

Decentralization is not a new concept. It is intuitive to observe that conveyance of water over large distances is energy intensive and it disrupts natural hydrological cycles, especially with respect to runoff. While the centralized water infrastructure design is embedded within our societies, there is a growing concern about limited benefits of this centralization (Nelson 2008; Rocky Mountain Institute 2004). In energy infrastructure discussions, decentralized power generation is already an established concept and is considered a prerequisite for sustainable energy infrastructure (Karger and Hennings 2009). Decentralized storm water management (also referred to as green infrastructure or low impact development technologies) is an accepted and successful practice (Dietz 2007). Many of the authors that discussed water sustainability also argued and promoted the decentralization of water and wastewater infrastructures (Pahl-Wost 2005; Gikas and Tchobonouglous 2009; Engel-Yan et al. 2005; Peter Varnabets et al. 2009; Weber 2006; Mitchell 2006). Similarly, ecological design principles on complexity and scale also imply that decentralization is a requirement for a sustainable water infrastructure; yet, different from previous studies, the ecological design principles also imply that while the scale is decreased, the functions of water infrastructure should be increased and integrated.

Green infrastructure concepts and techniques provide a good example of how to implement decreased scale—increased function approach. Green infrastructure design has now become a relatively mature field. All of the green infrastructure techniques (e.g. permeable surface or vegetated solutions) are decentralized solutions. Many green infrastructure design techniques incorporate nature (e.g. green roofs, vegetated swales, tree box filters, raingardens). In green infrastructure design, the primary purpose of integrating nature is often for meeting storm water quantity and quality goals at the site. As proposed in this paper, if ecological design principles are followed, the multiple ecosystem services (e.g. habitat creation, micro-climate moderation, food provisioning) that the green infrastructure can serve will have to be considered explicitly as part of design goals instead of an additional benefit of the design outcome. This consideration for storm water management will likely pave the way for developing sustainable water infrastructures that integrate (currently isolated) designs for water provisioning, purification, and other ecosystem services.

3.8 Energy Source; Mass and Energy Flows Sub-themes

Our society and the proper functioning of wastewater treatment and water provisioning services for potable water, irrigation water, aquaculture, and livestock water are all dependent on fossil fuel energy inputs. Due to high energy density and wide availability of fossil fuels, these systems have been designed to be very energy intensive. Approximately 4% of national electricity consumption is used by the current water supply and treatment processes (EPRI 2002). Water supply and wastewater treatment annual national electricity use is 94×10^9 kWhr (EPRI, 2002). Water provisioning for other services are also very energy intensive. Irrigation requires the most energy (24×10^9 kWhr), followed by industrial, (3×10^9 kWhr) aquaculture and livestock (1×10^9 kWhr) (EPRI, 2002).

The energy source and mass and energy flow sub-themes of the ecological design principles focus on reduction of this high energy demand and its environmental impact. Ecological design principles and current practice both suggest that this can be achieved by energy conservation and efficiency; and by shifting of the energy source from fossil fuels to renewable energy. In a world past-peak oil, renewable sources such as wind, micro-hydro power, biomass, and sun will primarily be used to capture energy to meet the demands of the water infrastructure. Energy conservation and efficiency as a solution is also an important consideration and current water infrastructure with input from USEPA is already in a transition to more efficient pumps, blowers, and processes (USEPA 2006). Combined heat and power recovered from methane gas is also a viable solution that is now implemented in many wastewater treatment plants.

4. SOME INNOVATIVE EXAMPLES ON HOW TO IMPLEMENT THE THEMES AND SUB-THEMES IN WATER INFRASTRUCTURE ENGINEERING

4.1 Water Source

In traditional water infrastructure, potable city water, provided centrally from a surface or groundwater source is used throughout the urban environment. Similar to the energy sector's approach to going 'off grid,' the decentralized approach to water management can ultimately cut buildings off the centralized wastewater treatment and potable water supply services. To replace the centrally provided potable water, in sustainable water infrastructure, multiple local sources can be used. Rainwater that falls on roofs or on pavement can and has been used for various purposes including irrigation and toilet flushing. In the US, a popular way to manage pavement water is to direct it to vegetated swales or bioretention basins. Since these are ecological structures, they inadvertently provide not only water quantity and quality related services but also other ecosystem services such as biodiversity and natural habitat for wildlife. Humid air may be another source of water. Dehumidifiers extract water from humid air; we have the technology to use humid air as a resource. However we have not incorporated this source into water infrastructure design. Using biomimicry and following the model of desert amphibians that absorb water through the structure of their skin, dehumidifiers of the future will likely require less energy than today's dehumidifiers which can lead the way for using humid air as a water resource in some instances.

Treated water can also be a water source. As Pinkham (1999) proposed, water can be used multiple times by cascading it from higher to lower-quality needs (e.g. using household gray water for irrigation), and by reclaiming treated water for its return to the supply side of the infrastructure. The two way arrows in Figure 1 project this cyclic flow of water. Progress on this cyclic and cascading approach has so far been limited to completing only one section of the cycle. For example, water from sinks (grey water) has been treated and used as a water source for toilets and irrigation (Gual et al. 2008; Li et al. 2008). Water from toilets (wastewater) has been used to grow commercial flowers (Zurita et al. 2009). In sustainable water infrastructure, this concept may be expanded to develop multiple uses placed one after the other instead of a single re-use scenario.

4.2 Water Quality Improvement and Diversity

In the traditional water infrastructure, water quality is improved in centralized water and wastewater treatment plants that rely on physical, chemical processes and fixed film or suspended film biological processes. Carbon, nitrogen, and phosphorus removal in current wastewater treatment plants are biological processes. However, they primarily rely on a limited function of bacteria. The design and management of these processes are based on conventional engineering design and the organisms are managed as components of a machine. They operate within tight controls (Allen et al. 2003). Ecological design principles encourage diversity and incorporating nature. Therefore, to design sustainable water infrastructures, the treatment methods will involve a greater diversity of species. One way to achieve this objective is by subsurface and surface flow wetlands. Constructed wetlands have now become a widely studied topic and will play a major role in engineering sustainable water infrastructures. Another method that will have a role in sustainable water infrastructure is the 'living machines' concept that incorporates fauna, aquatic species and other organisms in the tank-based treatment system (Todd et al. 2003).

4.3 Water Conveyance

In conveyance of water, pumps and gravity are used in the conventional water infrastructure. In sustainable water infrastructure, the function can fit into form and the structure of the material can facilitate the movement of water. This can be achieved at low flow rates by capillary pressure. Trees move water up many meters using the capillary pressure principle. In soil, water in aquifers passively moves upward to the ground surface due to capillary pressure. Recent advances on synthetic trees that can move water to higher elevation (Wheeler and Strock 2008) are promising. Capillary pressure concept can even be used to generate electricity (Borno et al. 2009). With technological advances, the production rates of capillary pressure may increase.

4.4 Energy Conservation and Efficiency through Structural Changes to Water Infrastructure

One innovative solution for reducing the energy demand of water infrastructure is to make structural changes to it. Humans have relied on energy to design systems (which led to the energy intensive water infrastructure), whereas nature has relied on structure and information (Vincent et al. 2006). Biomimicking nature's approach, it should be possible to make structural changes to the water infrastructure system to reduce its energy requirements.

Primary energy consumption in the current water infrastructure is due to conveyance of water and air by pumps and blower motors (USEPA 2006). Many different structural changes to the water infrastructure can help reduce this energy demand. By shifting the water infrastructure to a decentralized system, the need to convey large volumes of water long distances can be reduced or ultimately eliminated. As technology develops (mimicking the natural processes of trees), capillary tension principles can be used to convey some water. This process would not require energy and can possibly be engineered instead to produce energy (Borno et al. 2009). The demand for pumped air can be eliminated or reduced in a decentralized system and through the use of diverse species to treat water in ecological machines or wetlands. Some of the energy supplied by pumps and blowers is lost in pipes due to friction. The current engineering approach is to use smooth pipes to minimize this frictional head loss. In sustainable water infrastructure, this frictional loss can be reduced not only by surface characteristics but also by geometrical design (Bhusan 2009). Companies have already begun decreasing energy losses in flow by using geometrical design inspired from nature (e.g. PAX company; http://www.paxscientific.com/tech_what.html).

Ecological design principles suggest that systems should be designed for efficiency, should use no more energy than they need, and minimize excess and recycle everything. These ideas can be partly achieved by considering the quality of the water for the intended use. Currently, municipally supplied potable water is used for all domestic uses and the wastewater resulting from multiple uses is typically not recycled or reused. Potable water quality is not necessary to fight fire, water gardens, flush toilets or for heat exchange (e.g. chillers) purposes. To overcome the energy inefficiency associated with 'over-treating' the water for its intended use, Pinkham (1999) proposed a cascading water system where water uses and quality match as water moves from one use to another. This way, there would be no 'excess treatment' and the water would be reused multiple times instead of the single use approach of the current water infrastructure.

Another way the sustainable water infrastructure can reduce the energy demand is by changing the way services are provided. Wastewater conveyance and treatment are one of the three primary services of the current water infrastructure. In locations where water is scarce, use of this water to convey 'waste' will be inappropriate. One person produces about 1.0–2.5 liters of urine and 120–400 g of feces per day (Rauch et al. 2003; Schouw et al. 2002) and for each liter of urine passed, the standard toilet and urinal fixtures in the US require about 6–15 times of water for flushing it. In residential buildings about one third of indoor water is used just for toilet flushing (Mayer et al. 1999). In educational and office buildings this percentage is likely higher since toilets and sinks are the primary uses of water in these buildings. From a sustainability perspective, the use of high quality water to dilute and convey 'waste' is unacceptable. Therefore, composting toilets and urine separation technologies are more ecological alternatives to the 'flush and forget' approach (Langergraber and Muelleger 2005). Ecological design principles recommend designing for separation; thus separating the feces or urine or both from other wastewater components may be a more effective way to manage the resources. In addition, composting toilets and urine collection systems can be dry systems and would not require any water. As a result, the use of water to flush toilets and the provision of sanitation services may possibly not be a service of the sustainable water infrastructure.

4.5 Adaptive Non-Permanent Design (Complex System Property)

Based on ecological design principles, the structure of the water infrastructure should be physically accessible and made from safe and durable (not permanent) materials that can be separated and re-used at the end of their design life. The materials should be manufactured within the temperature and pressure constraints of nature (i.e. tapping the power of limits). Current water infrastructure is in contrast to these ecological design principles. Metal, plastic, and concrete hardware such as pumps, pipes, and tanks form the structural materials of our current water infrastructure. With permanence in mind, large treatment plants were built and pipes were placed in the subsurface. Yet, since these materials have a design life of 50–100 years, despite being permanent structures, their functions are becoming obsolete. Inflexibility also creates a problem for adapting to future uncertainty in water demands and ecosystem flow requirements. Due to the current design approaches, it is now difficult to modify the water infrastructure so as to adapt to changing conditions and emerging problems (Melosi 2000).

Adaptability of the sustainable water infrastructure can possibly be achieved by multiple approaches. One approach may be to design systems so that materials can be disassembled and reused so that that the use of permanent materials such as metal or plastic do not require the permanence of the design itself. Another approach may be to use more of the renewable materials. For example, wood may not be as durable as concrete but its shorter lifetime would require the design to be continuously updated therefore giving an opportunity to adjust the design to current conditions. Short material lifetimes would be viewed negatively in traditional design but may provide an advantage in some cases for sustainable design. Another approach would be to use biota more extensively. Organisms are autonomous agents and adaptation is primarily possible in presence of autonomous agents. Therefore, using more of the biota would help facilitate more adaptive designs.

A social approach may also be used towards designing adaptive systems. The goal of this approach would be to instill an ‘adaptive’ mindset in the public. Rosemond and Anderson (2003) provided dam construction by beavers as an example of adaptive and non-permanent design. Instead of making indestructible structures, beavers adapt to the environment by locating to other locations. Beavers’ approach to design is therefore adaptive in nature. They do not expect their designs to last for very long times. Similarly, in progress towards designing adaptive water infrastructures, there would need to be a change in the societal values regarding what is defined as engineering and design. Adaptability would need to be the primary concept replacing permanence. Designing non-rigid adaptive systems is in its infancy. Innovation in this area will be crucial for developing sustainable water infrastructures.

5. CONCLUSIONS

In trying to ‘fit’ into existing building design practices, the most common ‘sustainable’ water practice in buildings has been the use of low flush fixtures. This is an unfortunate consequence considering it misses many other opportunities. This outcome is partially due to a lack of vision for a sustainable water infrastructure. Water is a central and essential aspect of human life and has a special role in how ecosystems provide their services to humans. Therefore, instead of having the water infrastructure fit into existing infrastructure thinking, it might be more advantageous to first envision and design the water infrastructure. In this way water, infrastructure can pave the way for design of other infrastructure systems (e.g. transportation, communication, energy, and buildings).

Development of a vision is the foremost step toward engineering sustainable water infrastructures. To address this step, a sustainable water infrastructure was conceptualized based on ideas discussed in ecological design principles. Common themes were identified within the list of 99 ecological design principles. Themes of learning from nature, incorporating nature, and human dimension applied to water infrastructure design suggested major changes to the way water infrastructure should be conceptualized and designed to meet sustainability goals. These changes were discussed throughout the paper and summarized in Table 2.

In this paper, sub-systems of water infrastructure were identified as water source, water conveyance, water use, and water treatment. In the conceptualized sustainable water infrastructure, each one of these subsystems had more diverse set of possibilities for meeting the function (e.g. water conveyance can be done not only by gravity and pumps but also by capillary pressure). In the conceptualized sustainable water infrastructure, water was considered as only one of the products of the water infrastructure and other provisioning ecosystem services were incorporated in water infrastructures planning. In this study, incorporating ecosystem services in water infrastructure design process was proposed. Future work is required to provide more details on how to implement this idea. An innovative starting point could be the coupling of water infrastructure with the food provisioning ecosystem service. Considering that the current food supply is also very centralized and relies on long distance transportation, incorporation of food supply in water infrastructure design thinking (e.g. including vegetable gardens in building design) can achieve major efficiencies.

The new vision for a sustainable water infrastructure has major implications on green building design. Use of water efficient fixtures, appliances, and irrigation techniques are the most common practices in designing high performance buildings. USGBC's LEED green building design credits focus primarily on water efficiency (inside and outside the building),storm water management, and innovation in 'wastewater' management. This study laid the framework for developing other credits that could be included in future rating methods. Accessible, educational design, multiple functions, decentralization, incorporating nature, multiple uses and sources of water, use of renewable and nonpermanent components, fitting form to function in design, and eliminating use of water to flush toilets are some examples of concepts that may be instilled in LEED in the future. In addition, this study laid a framework for how to think about sustainability in the context of infrastructure or buildings. The same framework can be applied to other building components; for example, in future work, a vision for heating, ventilation or energy components of buildings can be developed based on ecological design principles. The scope of the paper limited the study to just conceptualization of the sustainable water infrastructure. Further detailing of these ideas is necessary for implementation of these concepts.

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