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Edwin Hammett
One Maritime Plaza
4th Floor, Toledo
Ohio 43604.

September 30, 2010

Dear Mr. Hammett,

Please find attached the final report for Project SG-363-09 on "Alternatives to Using Potable Water to Flush Toilets and Their Impact on L. Erie". This final report includes the project abstract, the technical report, and the final accounting.

The small grant from the Lake Erie Protection Fund led to much progress on evaluating the alternatives to use of potable water in toilet flushing. The findings from this project are forthcoming in two peer reviewed articles to be published in Journal of Environmental Management and Journal of Green Building. An additional publication is currently under preparation for submission to the Journal of Building and Environment. Project results were shared with approximately 300 people through nine presentations made to a variety of audiences. A mini wiki website was developed that has thus far received approximately 400 unique visitors. In addition, an excel model, Economic and Environmental Analysis of Sanitation Technologies (EEAST) was developed to facilitate easier comparison of the alternative technologies by others.

I appreciate the support of LEPF for development of all these products. These products will lay the foundation for further assessment of reducing the use of potable water in flushing toilets and ultimately its impact on the Lake Erie watershed.

Sincerely,

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Alternatives to Using Potable Water to Flush Toilets and Their Impact on L. Erie

FINAL REPORT
LAKE ERIE PROTECTION FUND (PROJECT SG-363-09)

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Submitted to:
Ohio Lake Erie Commission
One Maritime Plaza, Fourth Floor Toledo, Ohio 43604-1866

September 29, 2010

This project was funded in part through the Lake Erie Protection Fund. The LEPF is supported by the voluntary contributions of Ohioans who purchase the *Erie…Our Great Lake* license plate featuring the Marblehead lighthouse.

Alternatives to Using Potable Water to Flush Toilets and Their Impact on L. Erie

Defne Apul, Chirjiv Anand, Hannah West
Department of Civil Engineering University of Toledo

Abstract

In today's buildings municipally supplied potable water is used to flush toilets. Once used, this wastewater is conveyed to and treated at a wastewater treatment plant. This process can have a large environmental and economic footprint. The goal of this study was to evaluate and compare alternatives to the use of potable water in toilet flushing. First, the current water infrastructure was explored in the context of ecological design principles. This work showed that the use of potable water in toilet flushing is at odds with ecological design principles. To design sustainable water infrastructures, it is necessary to match water quality to its intended use, have some level of decentralized system, and develop and maintain an efficient system. Second, composting toilets and rainwater flushed toilets were compared to the standard toilets in two engineering buildings at University of Toledo. This work showed that both composting toilets and use of harvested rainwater in high efficiency toilets had lower life cycle environmental impacts and costs compared to the standard toilet system. Finally, these results were expanded for a preliminary analysis for Lucas County, which showed that 12 billion gallons of rainwater could theoretically be annually harvested from roofs of all commercial and residential buildings in Lucas County.

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1. Overview of Activities

The goal of this study was to evaluate and compare alternatives to the use of potable water in toilet flushing. First the implications of this approach were further investigated in the context of ecological design principles. This investigation led to a peer reviewed publication in the Journal of Green Building. Second, the use of composting toilets or harvested rainwater flushed toilets was compared to standard toilets in the Nitschke and Palmer buildings of the University of Toledo. This work led to a peer reviewed publication in the Journal of Environmental Management. A third publication evaluating the use of rainwater in toilet flushing versus for irrigation is also currently in preparation for submission to the Journal of Building and Environment. The first two publications are attached to this report. The third manuscript is currently in preliminary form but if published, it will acknowledge the Lake Erie Protection fund (as did the other publications). Finally, the effect of the use of harvested rainwater in toilet flushing was evaluated for Lucas County.This was a preliminary analysis and is discussed in section 3.

2. Work Products

2.1.Publications

Work related to this project will be published in three manuscripts. The first two manuscripts are currently in press. The uncorrected proofs of these manuscripts are attached to this report. The third one is currently in preparation.

Apul, D.S. (in press to appear in 2010, vol 5, issue 3) Ecological Design Principles and Their Implications on Water Infrastructure Engineering, *Journal of Green Building*

Anand, C. and **Apul, D.S.** (in press) Cost, Energy, and CO_2 Emissions Analysis of Standard, High Efficiency, Rainwater Flushed, and Composting Toilets, *Journal of Environmental Management.*

West, H., Anand, C., and **Apul, D.S**., Life cycle based evaluation of rainwater use in toilets and for irrigation, In preparation for submission to *Journal of Building and Environment*.

2.2 Model Developed: EEAST

The new framework developed for comparing alternative sanitation technologies was coded in an excel model: Economic and Environmental Analysis of Sanitation Technologies (EEAST). EEAST was developed to compare sanitation technologies based on cost, carbon implications, and energy payback time. Technologies included in EEAST Beta version are standard toilets, high efficiency toilets, composting toilets, rainwater flushed toilets and use of rainwater for irrigation. The model takes input parameters such as number of people, roof area, and number of flushes per day to compare the technologies.

EEAST presents the results in terms of payback time and Net Present Value (NPV) for each alternative sanitation technology. In addition, it outputs energy consumption and associated CO_2 emissions for each of the technologies studied. This model can be used by students and professionals to understand the cost, energy, and global warming implications of different sanitation technologies to be used in a given building.

EEAST is available for download on the UT water sustainability website:

http://utwatersustainability.wikispaces.com/

2.3 Presentations

We presented our work at nine different meetings to various audiences. Through these presentations, we were able to outreach to approximately 300 people related to this project.

<u>Presented by PI Dr. Apul:</u>

"Comparative Sustainability Analysis of Water Management Options in Buildings", Engineering Sustainability 2009: Innovations that Span Boundaries, Pittsburgh, PA, April 19-21, 2009
Outreach to ~20 people.

"Towards ending the use of potable water to flush toilets: Water, energy, and CO2 implications of alternative technologies", (Association of Environmental Engineering and Science Professors) AEESP Biannual conference, Iowa City, Iowa, July 26-28, 2009
Outreach to ~20 people.

"Sustainable water infrastructure and alternative technologies for sanitation management", First International Congress on Sustainability Science and Engineering (ICOSSE), Cincinnati, OH, August 9-12, 2009
Outreach to ~50 people.

"Path towards a sustainability water infrastructure includes finding and evaluating the alternatives to using potable water to flush toilets" Chemistry Department, University of Toledo, OH, April 2009
Outreach to ~30 people.

"Life cycle assessment of technologies that use rainwater as a resource", *USEPA and Raingarden Initiative Workshop on Managing Wet Weather Using Green Infrastructure*, November 2009, Toledo, OH.
Outreach to ~75 people

<u>Presented by PI's graduate and undergraduate students:</u>

Anand, C. and Apul, D.S. (2009) Energy and global warming implications of alternatives to using potable water to flush toilets, University Clean Energy Alliance of Ohio's Conference on Putting the Pieces Together: The New Energy Paradigm in Research, Education, Business and Public Policy, April 2009, Columbus, OH
Outreach to ~15 people.

West, H. and Apul, D.S. (2009) Documenting the Connection Between Water and Energy in Buildings: A Comparative Case Study on Environmental Footprint of Sending Rainwater to Sewers, Using Rainwater to Flush Toilets and to Irrigate, Posters at Capitol event for undergraduate students, April 2009, Columbus, OH
Outreach to ~15 people

Anand, C. and Apul, D.S. (2009) Towards stopping the use of potable water to flush toilets: Water, energy, and CO_2 implications of alternative technologies, Energy Symposium at Toledo Early High School, April 2009, Toledo, OH
Outreach to ~40 people

West, H., Robinson, L., and Apul, D.S. *A Comparative Sustainability Analysis of Water Management Options for the Collier Building Addition on Health Science Campus of University of Toledo*, to be presented by undergraduate student H. West at Air and Waste Management Association's 102nd Annual Conference and Exposition, Detroit, MI, June 16-19, 2009
Outreach to ~30 people

2.4 Proposal Submissions

Using data obtained by the help of LEPF funds, the PI prepared and submitted two NSF proposals. The first submission was declined, the second submission is currently under review. In addition, as part of the proposed work, the PI met multiple times with board members of the Northwest Ohio Chapter of the US Green Building Council (NWO-USGBC). These meetings led to the joint submission of a proposal to the Walmart Foundation regarding outreach activities on building water sustainability in the Northwest Ohio region. The proposal was submitted in August 2010. Dr. Apul is the PI on the proposal and NWO-USGBC is a collaborator.

2.5 Wiki Development

A mini Water Sustainability Wiki was developed that contains information related to the project. This wiki was launched in October 2009. The html address of the wiki is as follows: http://utwatersustainability.wikispaces.com/
This wiki site received 59 unique visitors in 2009. As of September 28, 2010, this wiki site had received 359 unique visitors. Therefore, since its launch in October 2009, we were able to outreach to 418 unique visitors related to this project.

3. Extrapolation of Results to Lucas County

3.1 Introduction

Combined sewer systems are designed to collect storm water runoff, domestic sewage and industrial wastewater. When heavy rain events occur, wastewater treatment facilities often times are unable to treat the large volume of water that the sewers are transporting. When the volume of sewage exceeds the treatment capacity, the excess wastewater is discharged directly into nearby waterways. There are major water pollution concerns with the approximately 772 cities in the U.S. that have combined sewer systems (EPA, 2010). The city of Toledo, located in Lucas County, has 67 combined sewer overflow (CSO) locations on either the Ottawa River, Swan creek or the Maumee River (figure 1). Over one billion gallons of wastewater are discharged into Toledo's waterways each year (Environment Ohio, 2007). By harvesting rainwater, clean water can be kept out of the combined sewer system and become available for use.

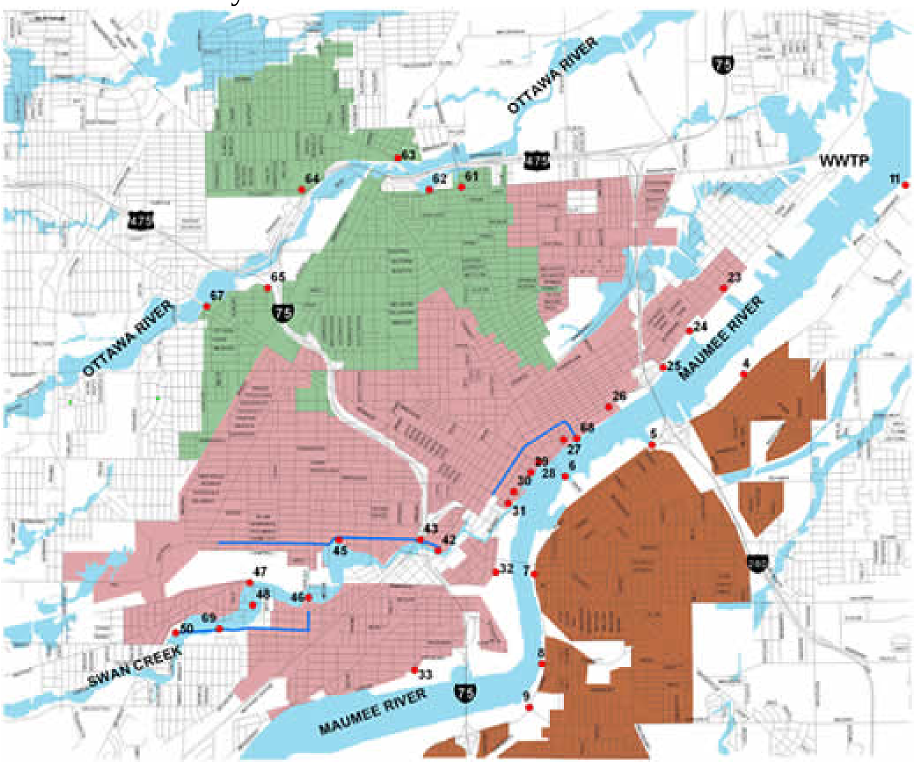

Figure 1. Combined sewage overflow locations in Toledo, Ohio.

The duration of each CSO event is recorded by the City of Toledo for each of the 67 CSO locations (Toledo Waterways Initiative, 2010). Data was obtained from January 1st to August 21st 2010. The duration of discharge from each CSO was summed for this period of eight months and totaled 89 days. Rainwater harvesting and its use in toilet flushing is one way to reduce these CSO occurrences. This approach and its impact on CO_2 emissions was analyzed for Lucas County.

3.2. Methods and Results

Building data available on the Auditor Real Estate Information System (ARIES) dvd was obtained from the Lucas County auditor. The disk provided building characteristics for every property in Lucas County. Properties are categorized by their use (residential, commercial, condominiums and apartments). Building type, address, square footage and number of stories are just a few of the characteristics available from ARIES. Lucas County is comprised of over 26,000 commercial and 172,000 residential properties and nearly 7,000 condos and apartments. It was assumed that rainwater would be collected at each property by roof only. Roof area was calculated using equation 1.

Equation 1. Roof area = building square footage / # of stories.

The volume of rainwater available for collection was estimated using the average annual precipitation for Toledo (33.21 inches per year) and each building's roof area. For each inch of rainfall, each square foot collects 0.623 gallons of rain. Of that, 25%-30% can be lost before ever entering the cistern (Krishna, 2005). Using these parameters, the volume of roof runoff available for capture was determined at approximately 6.9 billion gallons annually (table 1). It was discovered that commercial buildings account for 75% of the counties rainwater collection (figure 2). This is due to the large average roof area of commercial buildings (12,871 sf) as compared to the average roof area of homes (598 sf).

Table 1. Volume of rainwater available for capture in Lucas County

Rainfall data for Lucas county.		Commercial Buildings	Condos and Apartments	Homes	Total for all buildings
Month	**Precipitation**	**Rainfall Collected (gallons)**	**Rainfall Collected (gallons)**	**Rainfall Collected (gallons)**	**Rainfall Collected (gallons)**
January	1.93	303,450,741	4,421,493	92,480,565	400,352,799
February	1.88	295,589,323	4,306,947	90,084,695	389,980,965
March	2.62	411,938,312	6,002,235	125,543,564	543,484,111
April	3.24	509,419,897	7,422,611	155,252,347	672,094,854
May	3.14	493,697,060	7,193,518	150,460,608	651,351,186
June	3.8	597,467,780	8,705,531	182,086,086	788,259,397
July	2.8	440,239,417	6,414,602	134,168,695	580,822,714
August	3.19	501,558,479	7,308,064	152,856,477	661,723,020
September	2.84	446,528,551	6,506,239	136,085,390	589,120,181
October	2.35	369,486,653	5,383,684	112,605,869	487,476,206
November	2.78	437,094,850	6,368,783	133,210,347	576,673,980
December	2.64	415,082,879	6,048,053	126,501,912	547,632,844
Total	**33.21**	**5,221,553,941**	**76,081,760**	**1,591,336,555**	**6,888,972,256**

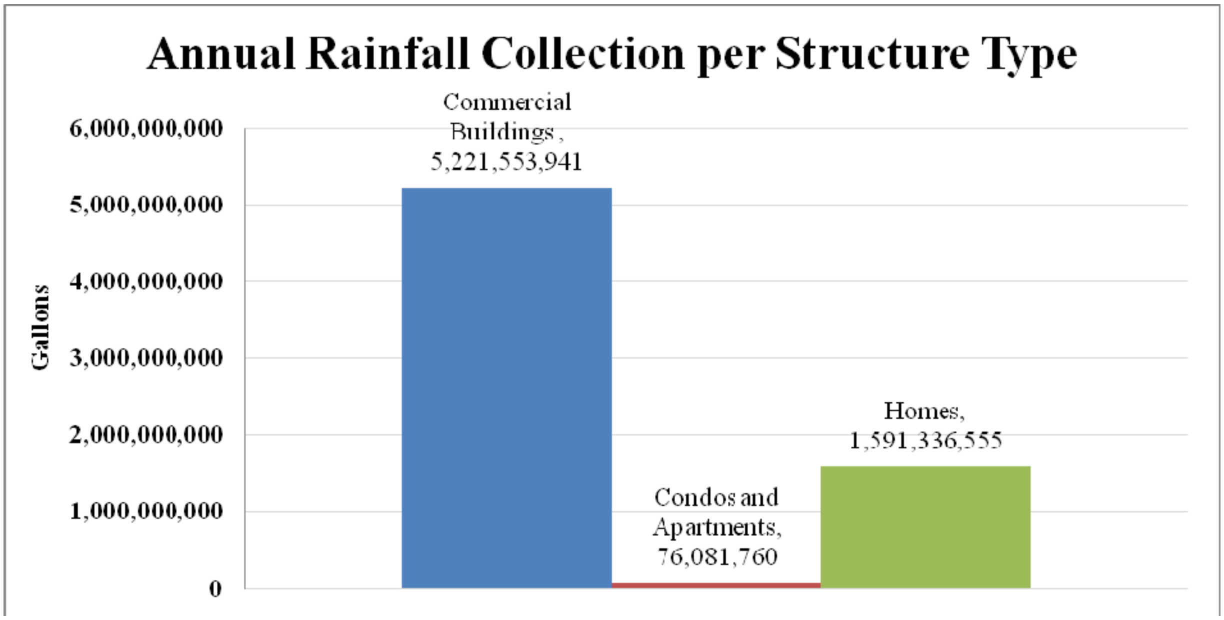

Figure 2. Annual collection volume per structure.

Utilizing the harvested rainwater for toilet flushing was considered for the entire Lucas County population of 650,955 people. It was assumed that residents live and work within Lucas County. An average of 6 flushes per person per day and standard toilets which require 1.6 gallons per flush were assumed (Vickers, 2001). It was determined that 2.3 billion gallons are required annually for toilet flushing. The volume of rainwater available is approximately three times greater than the volume needed to flush toilets. This would leave 4.6 billion gallons of rainwater to use for irrigating purposes throughout Lucas County.

Energy and chemical reductions as well as CO_2 emissions equivalence were calculated for using rainwater for flushing toilets and irrigating and flushing toilets combined. Values for emissions and mass per volume were obtained from Sahely and Kennedy 2007 (table 2).

Table 2. Values obtained from Sahely and Kennedy 2007

Wastewater Treatment		
Energy required to treat wastewater	1.70E-03	kWh/gallon
Chemicals required to treat wastewater	5.70E-05	kg/gallon
CO2e chemical productin	7.04E-06	kg/gallon
CO2 e wastewater treatment	1.82E-03	kg/gallon
Water Treatment		
Energy required to treat water	0.002196	kWh/gallon
Chemicals required to treat water	0.000053	kg/gallon
CO2 water treatment and distribution	0.0000028	kg/gallon

If building owners throughout Lucas County were to harvest rainwater, the combined sewage overflow issue could be resolved. If every commercial building in Lucas County implemented a rainwater harvesting system, over 5 billion gallons of rainwater could be kept from entering the combined sewers. If residences harvested rainwater as well, the volume would increase to 6.9 billion gallons.

Chemicals and energy that are needed to treat the wastewater at the treatment facility would also be reduced if rainwater were collected throughout the county and kept out of the combined sewers. If every building in Lucas County were to collect rainwater and use it for irrigating and flushing toilets energy consumption related to water treatment would decrease by approximately 27 GWh. Also, 835 tons of chemicals required to treat the rainwater if sent to combined sewers and potable water to flush toilets would be eliminated thus reducing the counties carbon footprint by 12,585 MTCO2e.

3.3 References

1. http://cfpub.epa.gov/npdes/home.cfm?program_id=5
2. http://www.toledowaterwaysinitiative.com/sewer_overflows.asp
3. Gomberg, A. Environment Ohio Research and policy center, Sewage overflow, billions of gallons of sewage contaminate lake erie, 2007
4. Krishna H. J.The Texas manual on rainwater harvesting, edition 3, Texas water development board 2005 http://www.twdb.state.tx.us/publications/reports/RainwaterHarvestingManual_3rdedition accessed October 2009
5. Vickers A. Handbook of Water Use and Conservation, 1st edition, Amherst: Waterplow press 2001
6. Sahely H.R., Kennedy C.A. Water use model for quantifying environmental and economic sustainability indicators, ASCE Journal of Water Resources Planning and Management 2007; 133(6): 550-59

3.4 Appendix

Example of data available from AREIS dvd. Data shown is for condominiums in Lucas County. Only 20 of the 26,271 properties are shown below.

Assr No.	Parcel	PrimStructType	PropertyType	Stories	GBA
30215017	7852421	110	20	1	1830
30215018	7852424	110	20	1	2792
30215020	7852444	48	13	1	10500
30220019	7868527	123	8	1	14466
30220024	7868561	118	10	1	6012
30220025	7868564	66	10	1	1400
30226037	7859877	46	8	1	9456
30227012	7852418	64	8	1	1680
30232001	7834634	60	8	1	21402
30233002	7834894	42	8	1	30750
30233014	7834907	74	8	1	8644
30235036	7875981	23	7	1	2640
30253004	7862104	61	8	1	21402
30253016	7862184	46	8	1	3200
30253017	7862191	46	8	1	11760
30253039	7862107	46	8	1	14514
30253041	7862105	61	8	1	6888
30255029	7855297	46	8	1	2100
30255035	7855534	46	8	1	6216

4. Barriers Encountered

In the initial proposal we aimed to include the use of greywater (sink water) in toilet flushing in our analyses. However, data on this approach proved to be difficult to collect and required many more assumptions than the other technologies. Therefore, our final analysis does not include this option.

In the initial proposal we aimed to calculate environmental impact not only in terms of global warming potential but also in life cycle impact categories of acidification, eutrophication, and human toxicity potential. Due to lack of data, the analyses could be done only for CO_2 emissions and energy demand. Further research will involve adding these impact categories to the developed framework.

5. Attachments

- Apul, D.S. (in press to appear in 2010, vol 5, issue 3) Ecological Design Principles and Their Implications on Water Infrastructure Engineering, *Journal of Green Building*

- Anand, C. and Apul, D.S. (in press) Cost, Energy, and CO_2 Emissions Analysis of Standard, High Efficiency, Rainwater Flushed, and Composting Toilets, *Journal of Environmental Management*.

- Supplementary material for Anand and Apul paper.

- Final budget.

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. 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 the 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, economical, 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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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 our societies 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 on 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 to be 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 the 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 starting point is existing knowledge or peer reviewed literature) (Dieter and Schmidt 2009).

Of the 11 references, the principles developed by Hannover, Sanborn, and Van der Ryn (and Cowan)

TABLE 1. Ecological design principles compiled from 11 studies.

Sanborn (S)[1]	Todd (T)[2]	McClennan (M)[3]	Shu-Yang, Freedman, Cote (SFC)[10]
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)[4]**	**Hannover (H)[6]**	**Holmgren (Premaculture) (P)[11]**
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

Q: "Permaculture"?

Anastas and Zimmerman (Green Engineering) (AZ)[8]	Mitsch and Jorgensen (MJ)[7]
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	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
Bergen, et al. (BE)[9]	
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	

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

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. McClennan (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, as well. 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 can include the stakeholders in the design and management process, the ideas included in the human dimension theme can be more easily incorporated into design because most of these ideas could possibly come more easily and pushed forward more easily by the stakeholders than by the 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 the 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

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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

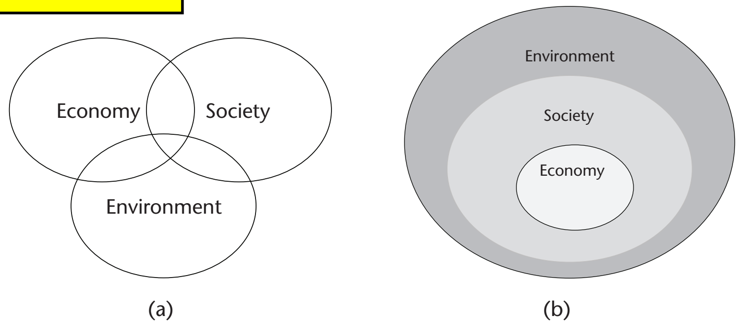

FIGURE 2. Three pillars of sustainability conceptualized as (a) three separate but overlapping subsystems and as (b) economy being a subsystem of the human society which itself is a subsystem of the natural world.

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 the 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.

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3.4 Complex Systems Properties Sub-theme

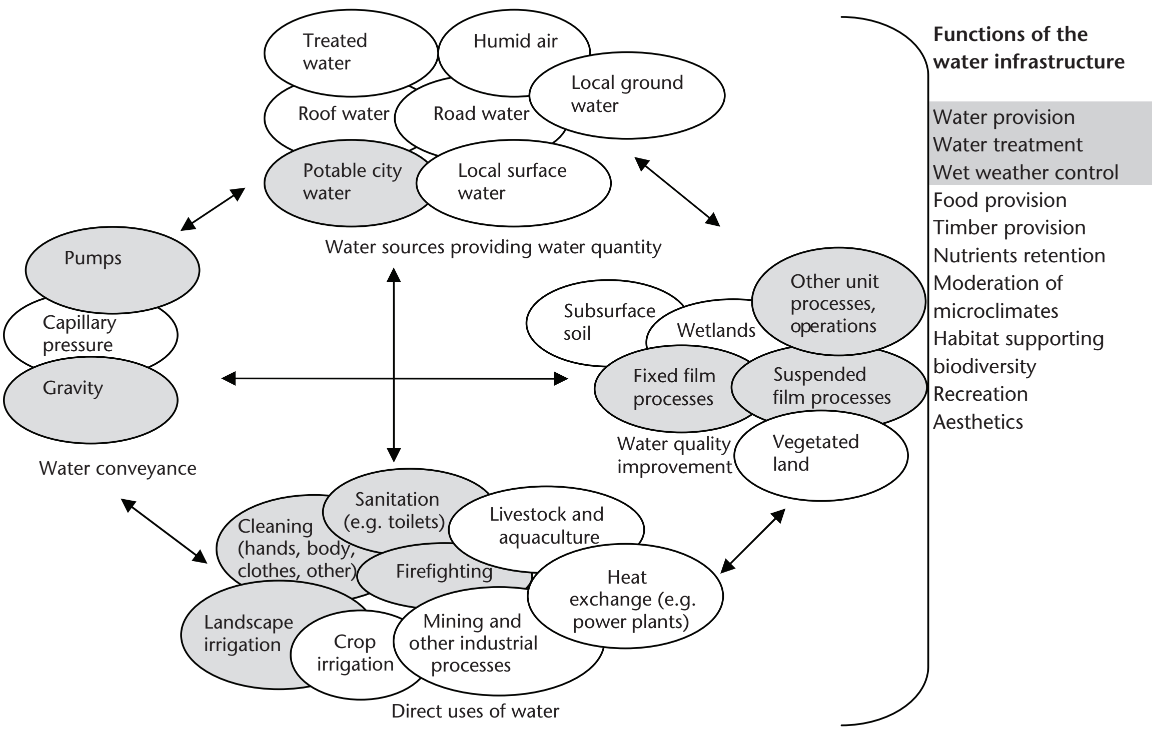
Nature is a complex system, and, therefore has complex system properties. A complex system can be most simply defined as one whose properties are not fully explained by an understanding of its component parts (Gallagher and Appenzeller 1999). Eleven of the ecological design principles describe properties 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 the 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 the water infrastructure were considered as an important aspect of the systems perspective of the water infrastructure.

This conceptualization of the water infrastructure is well aligned with the 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

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



and Iyaduri 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, identification of autonomous agents, 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.

The 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, sewerage 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 the 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 the 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. The 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 infra-

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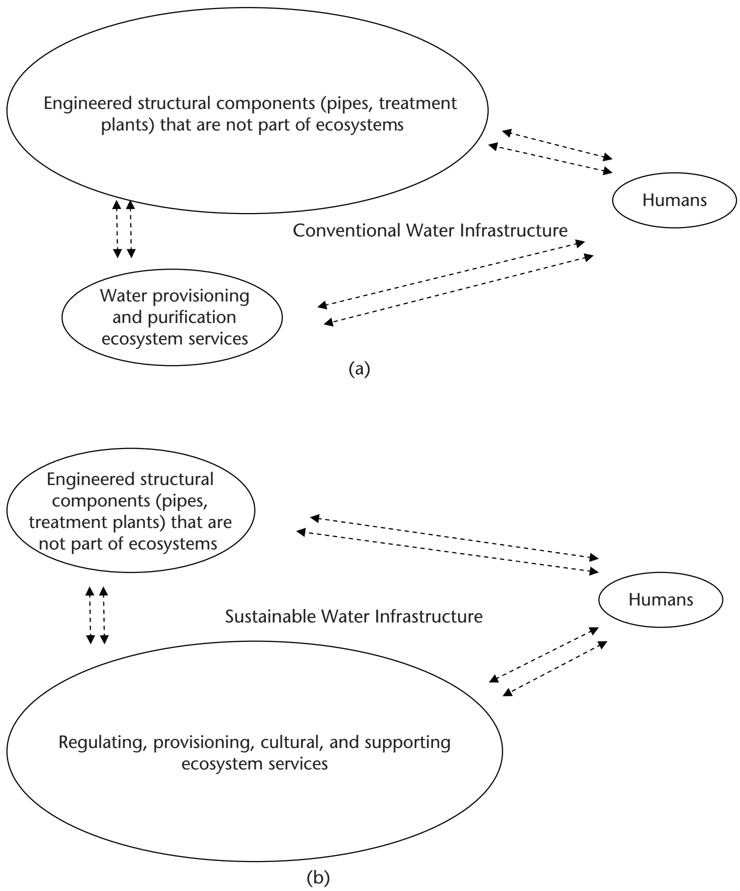

FIGURE 4. Traditional water infrastructure (a) heavily depends on engineered structural components that are not part of ecosystems. Traditional water infrastructure is designed to benefit only from water provisioning and purification services. The sustainable water infrastructure (b) is designed to benefit 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.

structure design. The ecosystem services provided 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 the 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 to 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 the 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 the 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 provision 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 the 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 will 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 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 'overtreating' 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.

4.3 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 very 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 non-permanent 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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Economic and environmental analysis of standard, high efficiency, rainwater flushed, and composting toilets

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The current sanitation technology in developed countries is based on diluting human excreta with large volumes of centrally provided potable water. This approach is a poor use of water resources and is also inefficient, expensive, and energy intensive. The goal of this study was to compare the standard sanitation technology (Scenario 1) with alternative technologies that require less or no potable water use in toilets. The alternative technologies considered were high efficiency toilets flushed with potable water (Scenario 2), standard toilets flushed with rainwater (Scenario 3), high efficiency toilets flushed with rainwater (Scenario 4), and composting toilets (Scenario 5). Cost, energy, and carbon implications of these five design scenarios were studied using two existing University of Toledo buildings. The results showed that all alternatives to the standard system were viable options both from an investment and an environmental performance perspective. However, Scenario 3 had very high payback periods, energy demand and CO_2EE and would therefore is the least preferable option among alternatives considered. High efficiency fixtures that use potable water (Scenario 2) is often the most preferred method in high efficiency buildings due to reduced water use and associated reductions in annual water and wastewater costs. However, the cost, energy, and CO_2EE analyses all showed that Scenarios 4 and 5 were preferable over Scenario 2. Cost payback periods scenarios 2, 4 and 5 were less than 10 years; in the future, increase in water and wastewater services would further decrease the payback periods. The centralized water and wastewater services have high carbon footprints; therefore if carbon footprint reduction is a primary goal of a building complex, alternative technologies that require less potable water and generate less wastewater can largely reduce the carbon footprint. High efficiency fixtures flushed with rainwater (Scenario 4) and composting toilets (Scenario 5) required considerably less energy than direct energy demands of buildings. However, the annual carbon footprint of these technologies was comparable to the annual carbon footprint from space heating. Similarly, the carbon savings that could be achieved from Scenario 4 or 5 were comparable to a recycling program that can be implemented in buildings.

1. Introduction

The design of standard sanitation technologies in developed countries is based on the premise that excreta are waste and that waste is only suitable for disposal (Esrey et al., 2001). This 'waste' is collected centrally in sewer pipes by using centrally provided potable quality water as the transport medium. One person produces about 1.0–2.5 L 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 centralized system uses about 6–15 times of water for flushing it. In residential buildings, about 45–100 L per capita per day or 27% of the indoor water is used just for toilet flushing (Mayer and William, 1999; Gleick, 1996). In educational and office buildings this percentage is likely higher since toilets and sinks are the primary uses of water in these buildings.

Use of large volumes of potable water to move human excreta over large distances is not only a poor use of water resources but is also inefficient, expensive, and energy intensive. Many drinking water systems lose as much as 20% of their treated potable quality water due to leaks in their pipe networks (Mehta, 2009). In Eastern and Midwestern parts of the United States, the wastewater is typically conveyed in combined sewers that also convey storm water. This causes wastewater treatment plants to unnecessarily treat storm water runoff. Every year, during events of huge rainfall about 3.2 billion cubic meters of combined sewer overflows contaminate the U.S water bodies with raw sewage (USEPA, 2004). Even separate sewers are not very efficient with respect to water conveyance due to rainwater and groundwater infiltration and

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inflows. The current centralized water infrastructure in the U.S. has a large energy toll. The treatment and conveyance of water uses approximately 3% of the entire U.S. energy demand and $4 billion are spent annually to produce this energy (EPRI, 2002; USEPA, 2009a).

Alternative sanitation technologies such as low flush fixtures, rainwater-flushed-toilets and composting toilets can reduce or eliminate the use of potable water to flush toilets. Current standards for toilets and urinals in the U.S require 1.6 gallons (6.0 L) and 1.0 gallon (3.8 L) per flush, respectively. High efficiency fixtures require less water and are designated in the U.S. with a 'Water Sense' label. When harvested rainwater is used to flush toilets, the need for centrally provided potable water may be reduced or eliminated for toilet flushing purposes, although wastewater flows would remain the same. Composting toilets neither require water nor generate wastewater and, consequently, are an alternative, decentralized approach to management of human excreta. These alternative technologies can have good technical performance (Ghisi, 2006; Gajurel et al., 2003; Fewkes, 1999; USEPA, 2008) and if they have comparatively lower costs and environmental impacts they could replace the current potable water based sanitation systems in the future.

Since centralized water and wastewater treatment systems are the norm, the life cycle impacts of water treatment and supply (Stokes and Horvath, 2009; Vince et al., 2008; Friedrich et al., 2008) and wastewater treatment systems (Gallego et al., 2008; Zhang and Wilson, 2000; Emmerson et al., 1995) have been extensively studied. Nevertheless, to this date, there is only limited information available on comparative life cycle impacts of technologies that reduce potable water use in toilets. These studies suggest that composting toilets and use of rainwater to flush toilets may in some cases have lower environmental impacts compared to standard systems (Remy and Jekel, 2008; Chiu et al., 2009; Crettaz et al., 1999). A direct comparison of rainwater technology, composting toilet technology, and high efficiency fixtures technology has not been previously studied; even though this information is essential for selecting appropriate and more sustainable technologies of the future.

The goal of this study was to compare the cost, energy, and global warming implications of the use of standard and alternative sanitation technologies in new buildings. The alternative technologies considered were high efficiency toilets and urinals; rainwater harvesting to flush standard toilets and urinals; rainwater harvesting to flush high efficiency toilets and urinals; composting toilets and waterless urinals. NPV, payback period and life cycle assessment (LCA) methods were used to compare the technologies. The technologies were evaluated for manufacturing and operation life cycle phases of five hypothetical design scenarios. Calculations were modeled after two existing buildings on The University of Toledo's engineering complex.

2. Methods

2.1. Buildings description

Nitschke (NI) and Palmer (PL) are the two primary buildings that house The University of Toledo's engineering students, faculty, and staff. Calculations were based on these two buildings because they are representative of other higher education buildings. A combined analysis of these two buildings provides an estimate of impacts from a higher education engineering complex. Buildings were not analyzed and presented separately because faculty, staff, and students use both buildings. A clear distinction between users of a given building could not be made. Similar to other educational buildings, both NI and PL have classrooms, computer and research labs, faculty, staff, and graduate student offices. The primary water use in both of these buildings is in toilet flushing. In both of these buildings, water is also used in restroom sinks, labs, and as make-up water for chillers. Since, the goal was to compare toilet-based technologies; these uses were not included in calculations.

The total number of students, faculty, and staff using NI and PL buildings on a daily basis is approximately 2200, of which 87% are males. NI is a five story building and has 42 toilets and 10 urinals. PL is a three-storey building with 20 toilets and 8 urinals. The gross area of NI and PL buildings is 12 278 m^2 and 6228 m^2, respectively. The buildings are located within 37 m of each other and are approximately 16 and 19 km from the water and wastewater treatment plants, respectively. Lake Erie water is treated to potable quality at the LucasCounty water treatment plant and conveyed to the buildings. Wastewater from buildings is collected, conveyed to and treated at the Bay View Wastewater treatment plant and released to Maumee River, which is a tributary of Lake Erie.

2.2.. Scenarios considered

Five scenarios were evaluated (Fig. 1). The base scenario (Scenario 1) was the standard system in which potable water from the water treatment plant was used to flush standard toilets and urinals, and wastewater from flushing was conveyed to the wastewater treatment plant. The other four scenarios were alternatives to scenario 1. In Scenario 1, standard toilet and urinal fixtures were used. These required 6.0 L and 3.8 L of potable water per flush, respectively. In Scenario 2, standard toilets and urinals were replaced with high efficiency fixtures that required 4.8 L per flush (lpf) for toilets and 1.9 lpf for urinals. In Scenario 3, rainwater was harvested and used for flushing standard toilets and urinals. Scenario 4 was the same as Scenario 3 except that high efficiency fixtures were used. Due to growing interest in sustainability, Scenario 2 is a relatively well established and accepted design practice in the United States. Scenarios 3 and 4 are also gradually entering the professional practice where these design approaches appear to make sense. Scenario 5 was a composting (waterless) system that required no water to operate. Composting toilets are used more commonly in developing countries (Morgan, 2007) whereas their use in developed countries is typically limited to some single family uses, cottage house, or recreational parks. To our knowledge, composting systems have not been used in educational or office type buildings in as high a capacity as required for the engineering complex at The University of Toledo. While composting toilets are viewed as an ecological sanitation method and are likely to be more popular in the future, to this date, detailed designs and well established performance for large capacity use in office and educational buildings do not exist. Therefore, our modeling of Scenario 5 is only a preliminary and rough assessment.

In a composting toilet system, human urine, feces, and toilet paper are collected by gravity in a composting tank. While potable water would still be required for hand washing, the composting toilets themselves do not require any water for flushing and are, disconnected from the municipal water and sewer systems. The compost from dry toilets and urine from waterless urinals are both excellent nutrient-rich resources and can be used as a fertilizer or soil conditioner but they need to be managed safely due to the presence of pathogens. Management of compost was beyond the scope of this study because science and performance-based approaches for management and disinfection of the human compost is not fully established; it is an area of ongoing research (Vinneras et al., 2003; Winker et al., 2009; Niagara, 2009). In Scenario 5, urine from waterless urinals was not managed separately; it was combined with sink water and sent to sanitary sewer.

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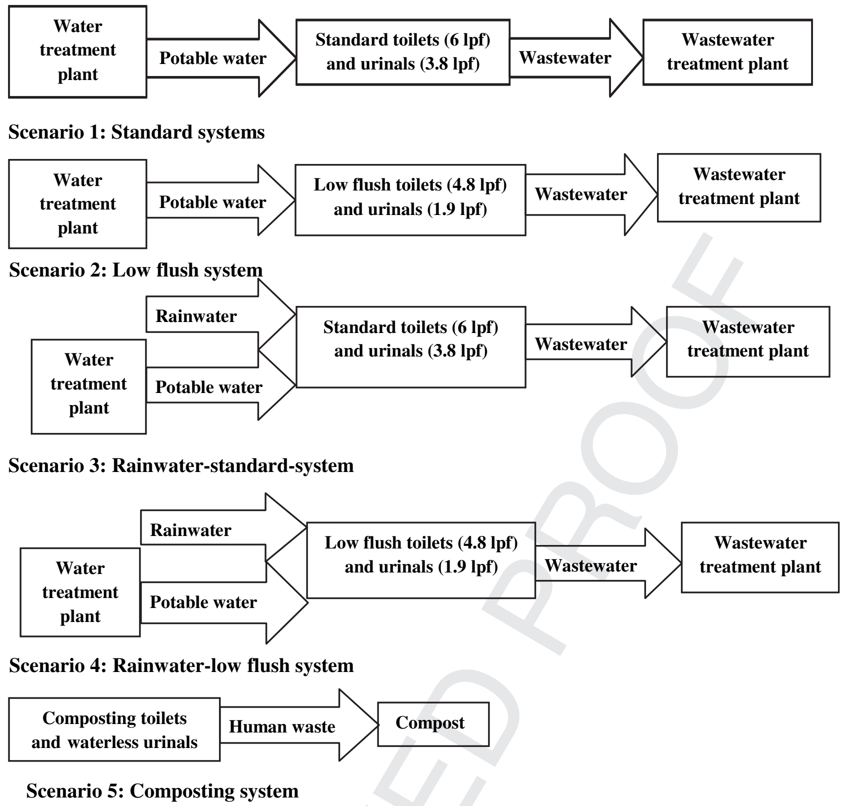

Fig. 1. Five design scenarios modeled for buildings resembling NI and PL.

2.3.. *Life cycle assessment method*

The five different design scenarios were compared using LCA. LCA is the primary method accepted within the environmental research community by which alternative materials, components, and services can be compared. An LCA evaluates the environmental aspects of a product or service through all its life cycle phases. It allows coherent comparison between different schemes providing the same service or "function". Only, the manufacturing and operational phases were considered in our study. Both for buildings and water infrastructures, the construction and end of life management phases are negligible (Scheuer et al., 2003; Friedrich et al., 2009) and were not included in our analyses. The functional unit for our study was the provision of sanitation services for 2200 people that used NI and PL buildings. The solids from a composting tank or a wastewater treatment plant can be further processed and used in agriculture or disposed of in landfills or incineration. However, the management of the solids was excluded in this work, in accordance with the scope of the study and corresponding selection of the functional unit.

Economic Input-Output Life Cycle Assessment (EIO-LCA) provides a comprehensive estimate of a sector's or a group of sectors' energy demand and emissions. Previously, the EIO-LCA method was used in comparing standard roofs to green roofs (Muga et al., 2006). In this study, the EIO-LCA method was used to estimate the energy demand and carbon dioxide equivalence emissions (CO_2EE) for manufacturing and operating phases of the five sanitation design scenarios (Hendrickson et al., 2006). In running a simulation for a given sector in EIO-LCA, material extraction, processing, and manufacturing are included in the simulation output. Therefore, the manufacturing phase included material extraction and processing as well.

EIO-LCA is based on the U.S. Department of Commerce annual input-output model of U.S. economy from 1997, and considers the interactions between 480 commodities or services in the United States (Hendrickson et al., 2006). EIO-LCA was used to factor in the direct and indirect effect of the resources related to each of the scenarios. For the expenditure in an economic sector, EIO-LCA calculates the relative emissions due to expenditure in that sector as well as in the supply chain. The monetary values used in the model represent the value of the currency in the year of the model (1997). So, the 1997 U.S. benchmark model is based on 1997 U.S. dollar values. Consumer price index (CPI, 2010) was used to convert the current prices to 1997 values before the dollar amounts were input in the EIO-LCA model.

2.4.. *Potable water demand and wastewater volume estimation*

For life cycle inventory of the operation phase, it is necessary to estimate the potable water demand and wastewater generated. Potable water demand was estimated assuming that females use the toilets three times a day and males use toilets and urinals, once and twice a day, respectively (Scheuer et al., 2003; USGBC, 2005). Restrooms were assumed to be in operation 269 days per year; Weekends use was assumed to be negligible. For these two educational buildings, the annual potable water demand for Scenarios 1 and 2 were 8.5 and 5.7 million liters, respectively. Resultantly, a 33% reduction in potable water demand was possible by using high efficiency fixtures.

The rainwater tanks in Scenarios 3 and 4 were sized based on the roof area and monthly precipitation data for Toledo, Ohio. The Texas manual for rainwater harvesting (Krishna, 2005) with a roof water collection efficiency of 80% (Boulware, 2009) was used to size the rainwater tanks. Since this sizing method is a demand-based-largest-storage approach, the rainwater tank sizes are different for Scenarios 3 and 4. Three cylindrical tanks (each 257 m^3 or 68 000 gal capacity; 8 m diameter and 5 m height) were considered for

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Scenario 3 and one cylindrical tank (384 m^3 or 101 500 gal capacity; 10 m diameter and 3 m height) was considered for Scenario 4. The tank sizes were suitable with regards to the available space between NI and PL buildings where they were assumed to be placed.

For Scenario 3, the annual rainwater volume that could be collected from the roof was less than the demand; therefore 22% of the water necessary for flushing was supplied by potable water. No municipal potable water was required for Scenario 4. Due to the lower water demand of high efficiency fixtures, the roof water collected would be sufficient for flushing needs in both buildings for Scenario 4. Wastewater generated was equal to the volume of water flushed in the restrooms. The annual wastewater volume generated from Scenarios 1 and 3 was 8500 m^3 and from Scenarios 2 and 4 was 5700 m^3.

2.5.. *Life cycle inventory of the manufacturing phase*

The life cycle inventory for all five scenarios is given in supplementary material (Table S1). Costs of all inventory items were obtained from vendors. Toilet fixtures, urinals and flush valves included were similar in the inventory of Scenarios 1, 2, 3, and 4 except for the specifications of fixtures (Scenarios 2 and 4 used low flush fixtures). Compared to Scenarios 1 and 2, Scenarios 3 and 4 included additional equipment such as rainwater tanks, filters, pumps and pipes (for conveying rainwater from tank to toilets). Tank type which affected the tank price and life cycle impacts was specified as corrugated steel tank with inner linings. Pipe lengths required were estimated assuming that the rainwater tank(s) would be placed in between the NI and PL buildings. A floating tank filter was included. The purpose of the floating filter is to deliver water from a depth slightly below the water surface in the tank and filter this water before it leaves the tank. Solids settle to the bottom of the tank and lighter organics float to the surface, so intake from below the water surface provides the cleanest water. A pump was connected to the filter intake.

Scenario 5 included a composting system similar to Sun Mar's Centrex 3000 A/F extra high capacity composting toilet systems; the system included plastic toilet fixtures (other scenarios included porcelain toilets), waterless urinals, plastic composting tanks, pipes, a 12 V 2.5 W fan for venting odors, and a heating element to keep the compost warm. Composting tanks (0.8 m × 0.7 m × 1.8 m) were assumed to be placed in the basement of buildings and every two toilets were assumed to be connected to one single composting chamber. Similar designs have been used in Germany (Berger, 2006). The fan and heating elements were assumed to have negligible contribution to the initial cost and environmental impacts and were not included in the inventory for the manufacturing phase.

The materials in the inventory were assumed to be replaced after their effective life time. The toilets were considered to be replaced after 35 years, pumps after every 20 years, and filters after every 5 years (Kirk and Dell'Isola, 1995). Various service lifetimes have been used for buildings. Previous building life cycle analyses studies have used building service lifetimes of 50 (Dimoudi and Tompa, 2008; Bribian et al., 2009) or 75 years (Scheuer et al., 2003). Towers et al. (2008) reports a service life time of 44 years for office buildings. In this study, we assumed the service life time of the NI and PL buildings to be 50 years. All scenarios were analyzed for 50 years.

2.6.. *Life cycle inventory of the operation phase*

Inventory for the operation phase of Scenarios 1 and 2 included the use of water and wastewater treatment services (Supplementary material, Table S1). Due to aggregation of sectors in EIO-LCA, both the water and wastewater treatment services were modeled using the same sector. In reality, the wastewater treatment services may have greater emissions and energy requirements than water treatment and supply; however, this distinction could not be modeled. In Scenarios 1–3, both potable water and wastewater volumes were included in the inventory. In Scenario 4 only wastewater volume was included in the inventory since only rainwater was used for flushing the fixtures.

In some locations, the city water pressure may not be sufficient at upper floors of a multi- story building and booster pumps are required in these situations. In the current analysis, the booster pumps were not included in the inventory for scenarios 1 and 2 because the city water pressure (50 psi) at NI and PL was adequate to supply water to all floors. However, booster pumps were included in the inventory for Scenarios 3 and 4 for delivering water from the rainwater tanks to the restrooms. The energy requirement for the pumps was estimated using the standard pump power equation:

$$P = (Q^*\gamma^* (h_e + h_p) (1 + a))/\eta$$

Where, P = energy delivered to pump [W], η = combined mechanical and hydraulic efficiency of the pump [−], Q = flow rate [m^3/s], γ = specific weight of water [N/m^3], α = percentage of energy lost to friction [−], h_e = elevation head provided by pump [m], h_p = pressure head provided by pump [m].

The flow rate (Q) was estimated as the annual water demand from restrooms in both buildings. In reality, pumping power required for each floor is different. However, as a conservative approach, h_e was set equal to the height of the top floor of NI. Minimum pressure required by flush valves (30 psi) was used as h_p. Head loss due to friction varies based on flow rate of the water and type and diameter of the pipe but for simplicity, it was assumed to be 30% ($\alpha = 0.3$) (Cheng, 2002). A pump mechanical and hydraulic efficiency of 65% was used (Cengel and Cimbala, 2005).

For Scenario 5, the electricity consumption from venting the air and from heating the compost was included in the operation phase of the inventory. In some composting toilets, additives (e.g. saw dust, wood ash, lime, straw, or manufactured bulking agents) are used to reduce odors and enhance primary treatment of the compost by affecting conditions (e.g. carbon to nitrogen ratio, pH, level of aeration) which impact the inactivation rate of pathogens. Additives and other processes for managing the compost were not included in the life cycle inventory.

2.7.. *Economic analysis*

NPV and discounted payback period analyses were used to evaluate the economic implications of using the alternative scenarios in NI and PL buildings. When comparing which project to invest in, NPV is often preferred over other investment criteria by financial officers (Brealey et al., 2007). Conventional approach is to invest in only in projects with positive NPV. In this study, NPV of Scenarios 2, 3, 4, and 5 were calculated with respect to the cash flows of Scenario 1 using the following equation;

$$NPV = \sum_{t=0}^{50} C_t/((1 + r)\exp t)$$

Where, t = time (years) r = discount rate (initially 0%; varied from 0% to 12% for a sensitivity analysis), C_t = cash flow of evaluated scenario minus the cash flow of standard scenario for year *t*

Discounted payback period is another financial criterion used to determine whether to invest in a project. NPV method is often preferred over a discounted payback period, since the payback period ignores the cash flows after the cut-off time of the project. In this paper both methods were used to evaluate the projects because most institutions cannot plan for 50 year budgets and the payback period becomes an important criterion to determine whether to invest in a project.

3. Results and discussion

3.1.. Economic analysis

Costs for all five scenarios for a life time of 50 years are shown in Table 1. The manufacturing cost of Scenario 3 was almost three times as that of Scenarios 1 and 2. Scenarios 4 and 5 had comparable initial costs. The manufacturing costs of Scenarios 3, 4 and 5 were very high compared to those of Scenarios 1 and 2 due to the purchase of expensive rainwater or composting tanks required for these scenarios. For Scenario 1, the annual operation cost due to water and wastewater services was about $13 000. The initial cost of the low flush design scenario (Scenario 2) was the same as the standard scenario but its operation phase was approximately 35% lower (about $ 8500) (Table 1). Due to similar initial but reduced operation costs, Scenario 2 is typically the first alternative technology considered for reducing water demand in high efficiency (e.g. LEED certified) buildings.

While manufacturing costs of rainwater and composting based systems were higher, their annual operation costs were lower compared to the other scenarios. The cash flows of rainwater based systems are sensitive to precipitation, catchment area, fixture flushing demand, and water utility rates and therefore, would vary for different locations. Water utility rates are expected to increase due to increasing energy prices, aging infrastructure, and shortage of available funds to maintain them. As water utility rates increase, the operational cash outflows for the standard and low flush scenarios would also increase making the rainwater cases beneficial. The initial cost for the rainwater tank was the most expensive component of the rainwater harvesting scenarios (Table S1). Large volume rainwater tanks may be constructed from steel, concrete, or wood. Less expensive rainwater tanks made from concrete or wood would reduce the cash outflows of Scenarios 3 and 4. The cash flows depend on the type of processes and products involved. These cash flows would change if management of solids from wastewater treatment plants or composting tanks were considered.

At 0% discount rate, the low flush scenario paid pack in 1 year, as both Scenarios 1 and 2 had the same initial investments but Scenario 2 had a lower annual operational cost (Table 1). The rainwater standard scenario came very close but did not payback within 50 years. Since, rainwater that could be collected for Scenario 3 was not sufficient to fulfill the demand this scenario used potable water to fulfill the requirements in addition to rainwater. Due to use of potable water the operational cost of this scenario (about $10 500) did not reduce significantly compared to the standard scenario's operational cost (about $ 13 000). Also, Scenario 3 had an initial investment which was 3 times more than that of Scenarios 1 and 2. Hence, no payback was seen within 50 years. The rainwater low flush (Scenario 4) showed a payback time of 9 years. Due to the use of low flush toilets the demand in this case reduced by 33% compared to case 3. There was no potable water requirement in this case. Therefore, with a lower initial investment (about $70 000 less compared to Scenario 3) and higher savings on annual operational costs (about $4000 less compared to Scenario 3) Scenario 4 paid back in less than 10 years. The payback time of the rainwater scenarios could improve with the choice of less expensive rainwater cisterns. The composting scenario had a low payback time of 5 years; its initial investment was higher, but comparable to that of the rainwater low flush scenario. In higher education institutions, payback periods of 5 years or less are typically preferable (Harvey Vershum, personal communication); only Scenarios 2 and 5 met this criterion.

The 50 year cost of Scenario 1 was about $704 000 (Table 1). In comparison to Scenario 1, at 0% discount rate, Scenarios 2, 4, and 5 resulted in a positive NPV for the 50 year analysis (Fig. 2). The composting scenario had the highest NPV of about $490 000. Scenario 3 did not result in a positive NPV within 50 years. The composting scenario showed the highest NPV of $2, for every dollar invested. The rainwater low flush scenario had a better NPV ($0.6 for every dollar invested) compared to the low flush scenario ($0.4 per dollar invested). The rainwater low flush scenario had a 50 year NPV nearly 20% larger and composting scenario a 50 year NPV about 60% larger compared to the low flush scenario. Based on the cash inflows and outflows of all scenarios, composting case would be the best alternative and rainwater standard scenario the worst investment alternative, for replacing the standard toilets at NI and PL buildings. Therefore, the composting scenario is a favorable scenario compared to the rainwater standard and the rainwater low flush scenarios based on both NPV and payback time analysis.

Table 1
Cost, energy, and carbon footprints of NI and PL buildings in a 50 year period. The life time operational and manufacturing costs are from the cash flows using a 0% discount rate.

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
Cost	$	%	$	%	$	%	$	%	$	%
Initial manufacturing cost	34 490	5	34 490	7	155 837	22	87 729	19	93 980	50.0
Annual Operational cost	12 696		8548		10 314		6460		542	
Total manufacturing cost	68 979	10	68 979	14	197 357	28	129 249	29	187 960	87.4
Total Operational	634 785	90	427 396	86	515 700	72	322 998	71	27 111	12.6
Total cost	703 765	100	496 376	100	713 057	100	452 247	100	215 071	100.0
Energy	TJ	%	TJ	%	TJ	%	TJ	%	TJ	%
Initial manufacturing energy	0.3	4.4	0.3	6.3	1.1	18.1	0.6	16.0	0.8	18.8
Annual Operational energy	0.11		0.07		0.10		0.06		0.05	
Total manufacturing energy	0.5	8.8	0.5	12.6	1.4	22.3	0.9	22.7	1.5	37.5
Total operational energy	5.4	91.2	3.6	87.4	4.9	77.7	3.1	77.3	2.5	62.5
Total	5.9	100.0	4.1	100.0	6.3	100.0	4.04	100.0	4.00	100.0
Emissions	MT CO_2EE	%	MT CO_2EE	%	MT CO_2EE	%	MTCO2EE	%	MTCO2EE	%
Initial carbon emissions	18.4	0.5	18.4	0.7	92.5	3.0	50.7	2.6	57.6	21.2
Annual operational carbon emissions	74.5		50.2		60.8		38.1		4.3	
Manufacturing	36.7	1.0	36.7	1.5	111.6	3.6	69.8	5.7	115.2	42.4
Operational	3706.6	99.0	2491.6	98.5	3020.6	96.4	1887.6	94.3	156.2	57.6
Total	3743.4	100.0	2528.4	100.0	3132.2	100.0	1957.4	100.0	271.4	100.0

*Total manufacturing cost, refers to life time manufacturing cost and total operational cost refers to life time operational cost.

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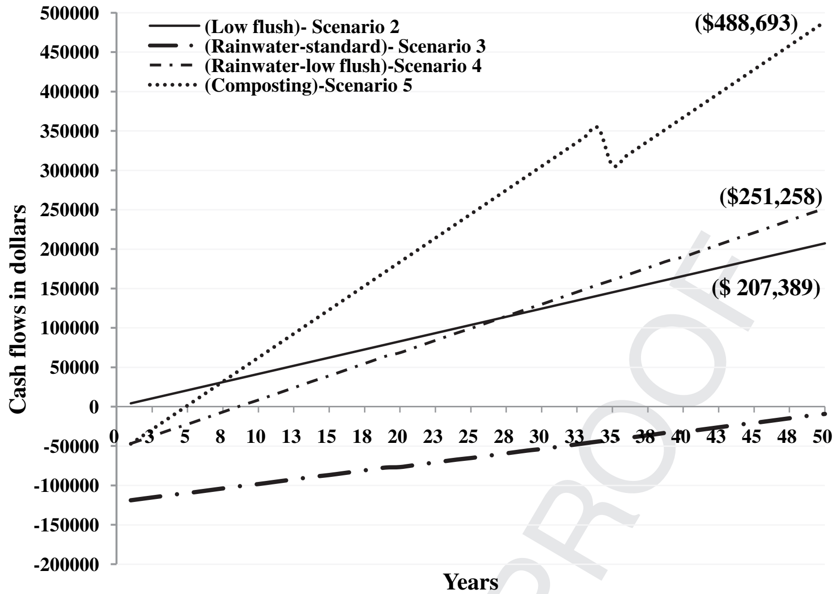

Fig. 2. Cash flows of all scenarios from a 50 year analysis with 0% discount rate. The figures at the end of cash flows represent the NPV of that particular scenario. The composting scenario had a sudden decrease in the cash flows at the 35th year because composting toilets, composting tanks, and waterless urinals were more expensive to replace compared to replacement of Scenario 1's toilets.

The payback time of Scenario 3 decreased rapidly with increase in discount rate from greater than 50 years at 0% discount rate and 37 year at 2% discount rate to 17 years at 12% discount rate (Fig. 3). The payback time of other scenarios decreased more gradually with increase in discount rate. Scenario 4 payback time reduced from 9 years to a little over 5 years at 12% discount rate. The payback periods for Scenario 4 were lower and for Scenario 3 comparable to the payback periods reported for high rise buildings in Australian cities (Zhang et al., 2009). Using a discount rate of 6.5%, the payback periods of Australian rainwater harvesting systems vary from 8 to 22 years depending on the city and level of water efficiency measures implemented in the buildings (Zhang et al., 2009).

The NPV's of all scenarios increased with an increase in the discount rate (Fig. 4). NPV of Scenario 3 was positive at 2% (about $ 70 000) and higher discount rates. At 0% and 2% discount rates the NPV of Scenarios 2 and 4 were close (Fig. 4). However, with an increase in discount rate, Scenario 4 showed better NPV compared to the NPV of Scenario 2. Higher NPV of Scenario 4 can be attributed to the lower operational costs of Scenario 4. Similarly, the NPV of Scenario 3, at 2% was much less than that of Scenario 2. At 12% discount rate the NPV of both these scenarios are comparable. This increase in NPV was due to the comparatively low operational costs of Scenario 2. At 2% discount rate, all alternatives had NPVs of less than half a million whereas at 12% discount rate, the NPV of the alternative Scenarios varied from about $5 million - $27 million. The composting scenario showed the highest NPV and rainwater standard scenario the lowest NPV for all the alternatives compared at all discount rates.

Though Scenario 2 had a payback time of 1 year with different discount rates, the NPV of Scenario 2 was less than that of the rainwater low flush and the composting scenarios for all discount rates. This was also due to the low operational cost of Scenarios 4 and 5, compared to the operational cost of Scenario 2.

The composting scenario was a preliminary analysis. The transport and management of the composted end product was not considered since solids management was not considered for any of the scenarios. The other factors that are not included but can impact the cost, energy and carbon emissions are further treatment of the compost than what is achieved within the composting tank, transportation of compost from the site to a farming area, sale of the compost, and emissions due to the composting process. These factors if included would change the NPV of Scenario 5. In addition, composting toilet systems may present other issues that may affect

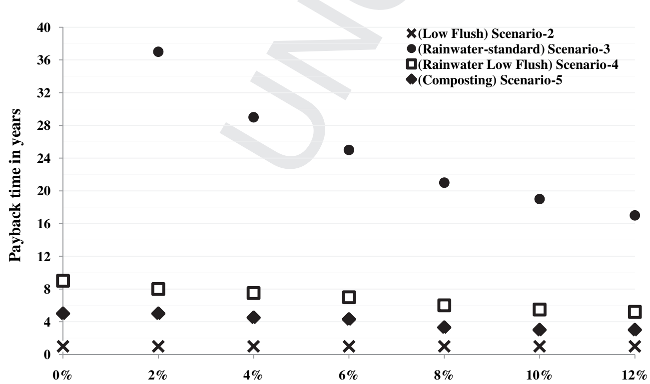

Fig. 3. Variations in payback time with variations in discount rate.

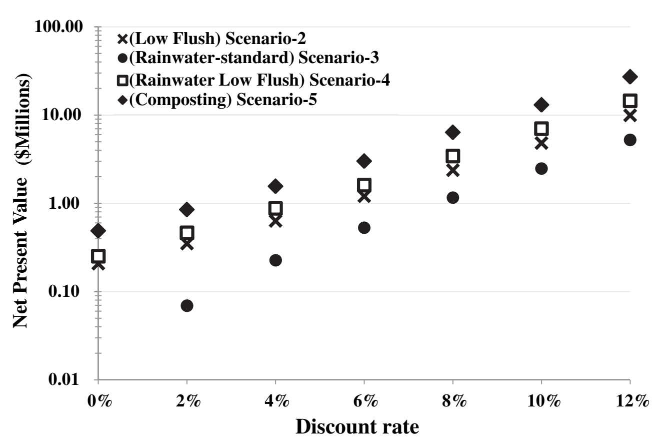

Fig. 4. Variations in NPV with variations in discount rate.

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whether to invest in such projects. For example, bad odor, retro-fitting buildings to install piping for composting toilets, acceptance by users and operational issues need to be considered prior to selection of the composting scenario (Niemczynowicz, 1997).

3.2. Energy use

The order of scenarios based on highest to lowest total costs and total energy demand was the same: Scenario 3 > Scenario 1 > Scenario 2 > Scenario 4 > Scenario 5. However, the cost and energy payback periods of the scenarios were different. Initial and annual energy demand for Scenarios 4 and 5 were close. Scenario 4 had a payback time of 8.3 years and scenario 5 had a payback time of 8.4 years (Fig. 5). For Scenario 5, the energy payback period was higher than the cost payback period. The reverse was observed for Scenario 4; the energy payback period was lower than the cost payback period. This change in order was primarily due to the energy intensity level of the operation phase of these two scenarios. The annual operational cost of Scenario 4 ($6460) was much greater than that of Scenario 5 ($542); yet the annual energy demand of Scenario 4 (0.06 TJ) was close to that of Scenario 5 (0.05 TJ). The energy demand of Scenario 4 was primarily from potable water use whereas that of Scenario 5 was from electricity consumption and (on a unit cost basis) electricity consumption results in almost 11 times more energy demand in the US economy than water consumption.

Both the energy and cost analyses showed that rainwater harvesting without high efficiency fixtures (Scenario 3) was not a viable option. For Scenario 3, the need for large volume rainwater tanks and supplemental potable water resulted in no energy payback within the life time of the building. Therefore, Scenario 3 was not a preferable option in terms of cost or energy demand. However, rainwater harvesting with high efficiency fixtures (Scenario 4) was a viable option and may be preferred over high efficiency fixtures that use potable water (Scenario 2). In energy consumption, Scenario 4 performed better than Scenario 2 after 42 years (Fig. 5). In cost, Scenario 4 would be preferred over Scenario 2 after 27 years (Fig. 2).

Another way to interpret these data is to consider the life time of the building. Initial investments in cost and energy may often be small when the entire life time of the building is considered. Such was the case also for the scenarios analyzed in this study. For a 50 year operational life, Scenario 2 would require a total of 4.12 TJ and Scenario 4 would require 4.04 TJ (Table 1). Therefore, in 50 years about 0.08 TJ of energy would be saved if rainwater harvesting with high efficiency fixtures were preferred over the low flush scenario. Both the initial cost and initial energy requirements for the manufacturing phase in a 50 year life time were less than 8% for Scenario 2 and less than 20% for Scenario 4. Among all scenarios considered, Scenario 5 (4.0 TJ) had the smallest total energy demand in a 50 year life time period.

3.3. Carbon emissions

In a 50-year operational life, the carbon footprint was the highest for Scenario 1 (3743 MT CO_2EE) (Table 1). Scenario 2′s 50 year carbon footprint was 2528 MT CO_2EE. Scenario 2 required 22% less potable water compared to Scenario 1; this reduction in water resulted in 33% carbon savings. While Scenario 3 had the highest total cost and energy, the CO_2EE analysis showed that Scenario 1 (3743 MT CO_2EE) surpassed Scenario 3 (3132 MT CO_2EE) in carbon emissions. Ranking of other scenarios were the same based on total cost, energy, and CO_2EE; Scenario 2 > Scenario 4 > Scenario 5. Scenario 5 (271 T CO2EE) had a much smaller carbon footprint than any of the other technologies. Scenario 4 also had a low 50 year carbon footprint that would reduce the carbon emissions by 48% compared to Scenario 1 and by 23% compared to Scenario 2.

The CO_2EE pay back periods for all four Scenarios were less than six years (Fig. 6). The CO_2EE pay back periods were much shorter (compared to those of energy or cost) because the use of water and wastewater services in the operational phase largely increased the CO_2EE in the operation phase. The water sector has large methane and nitrous oxide emissions and these global warming gases have high characterization factors. (One ton of methane emission is equivalent to 23 tons of CO_2 emissions, and one ton of nitrous oxide emission is equivalent to 296 tons of CO_2 emissions.) For example, on a unit cost basis (i.e. for every dollar of product), the use of water and wastewater services emits almost nine times more CO_2EE than manufacturing of toilet fixtures and valves and most of this CO_2EE comes from very high methane (66 times higher) followed by high nitrous oxide (332 times higher) emissions. Therefore, while water and wastewater may not be expensive, these services have major CO_2EE implications on the operational phase of sanitation services. A reduction in the use of water and wastewater services would greatly reduce the CO_2EE life cycle emissions of the sanitation technology.

In a 50-year operational life, the CO_2EE from Scenarios 1, 2, 3, and 4 were all very small (less than 3% of total 50 year CO_2EE) (Table 1) for manufacturing phase. For Scenario 5, the manufacturing phase

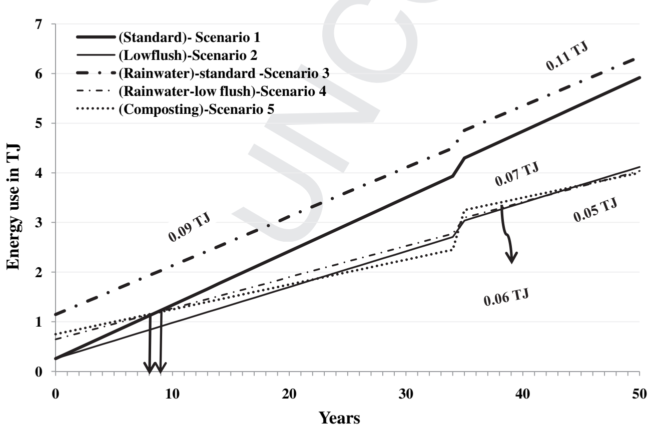

Fig. 5. Energy use in manufacturing and operational phases of the technologies. Energy values presented over each line represent the annual energy demand for that scenario (TJ = Tera Joules).

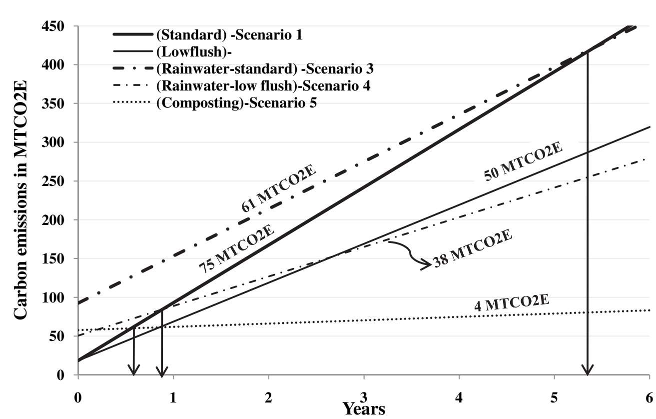

Fig. 6. Carbon emissions due to operation, and manufacturing phases of the technologies. Annual carbon emissions from the operation phase are given above the lines (MT = Metric Tons).

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CO_2EE (21% over a 50 year life) was greater because its operation phase was not as carbon intensive as other scenarios. The carbon intensiveness of the operation phase was also evident in the percentages of initial energy and CO_2EE for Scenarios 1, 2, 3, and 4. The initial energy percentages (4–18%) were greater than the initial CO_2EE percentages (0.5–2.6%) for these scenarios.

3.4. Cost, energy and carbon implications of minor components

Rainwater based systems require dual piping and this requirement is often viewed as a major disadvantage of using rainwater to flush toilets. Therefore, we had hypothesized that minor components such as additional piping required, pumps, and filters might have important contributions to cost, energy, and CO_2EE of rainwater based systems. However, the analyses suggested otherwise. The cost contribution of pumps, filter, and additional piping was very low for Scenarios 3 and 4 compared to the contribution of rainwater cisterns. This was due to the low cost of the pipes and pumps. Minor components such as pumps ($695/pump), additional piping ($1.02/m), and filter ($425/filter) contributed to only 0.2%–0.9% (for Scenario 3) and 0.2% - 1.1% for (Scenario 4) of the initial investments whereas the cisterns ($0.63/gal for Scenario 3 and $0.50/gal for Scenario 4) contributed much more (60% in Scenario 3 and 40% in Scenario 4).

Similarly, pumps, filters, and additional piping contributed to less than 1% of the initial energy and CO_2EE of both Scenarios 3 and 4. The operational phase contributions of the pump energy and CO_2EE were also small (less than 3% of annual operational CO_2EE and less than 1% of annual operational energy for Scenarios 3 and 4). These results imply that energy and CO_2EE associated with rainwater technology specific components are much less than the energy and CO_2EE associated with centralized water and wastewater services.

3.5. Energy and carbon comparison of sanitation and other building services

The US Department of Energy compiles and publishes data on energy consumption of buildings. Using USDOE's estimates for a 20–29 year old commercial (office) building (USDOE, 2003) and the square footage of NI and PL buildings, we would expect NI and PL to have a direct energy demand of 12.5 TJ every year. When USDOE's energy expenditures data (USDOE, 2003) for higher education was used, the energy demand estimate for buildings similar to NI and PL was eight TJ every year. These energy values are for typical buildings that use municipal water and centralized wastewater treatment services. In buildings, water bills are seperate than energy bills and the indirect energy associated with the use of water services is included in the water bills themselves not in the energy bills. Therefore, in reporting energy demand (as in USDOE estimates), the energy associated with sanitation services is not included. Our results showed that the annual energy demand for sanitation services included in this study varied from 0.05 TJ to 0.11 TJ. Even when upstream and downstream effects are considered (in addition to direct energy demand), the energy associated with sanitation services was considerably lower than the direct annual energy needs of the building (e.g. for lighting, heating, cooling, ventilation, computers).

While sanitation services may have relatively smaller energy footprint compared to direct energy demands of buildings, the carbon footprint contributions of sanitation services may be greater. A recent study used 10.5 kg CO_2EE per m^2 per year just for space heating of building (Bribian et al., 2009). Using this estimate, the emissions from NI and PL just for space heating would be 194 MT CO_2EE. This number is relatively closer to the annual operational CO_2EE associated with Scenarios 1, 2, 3, and 4 (38–75 MT CO_2EE). Therefore, while sanitation technologies may have a very small annual energy footprint compared to the direct energy demand of buildings, the carbon footprint of sanitation technologies would need to be considered in attempts to reduce the carbon footprint of buildings.

3.6. Reducing carbon footprint by recycling programs

With the onset of greater sustainability awareness and changing regulations, reducing the carbon footprint of buildings has now become an important goal for building designers and managers. In such efforts, the focus is often in reducing the direct energy demand of the building (e.g. by more efficient lighting or heating). However, ancillary efforts such as recycling may also reduce the carbon footprint of a building. We wondered if CO_2EE savings that can be achieved by alternative sanitation technologies were comparable to savings that may occur due to recycling programs implemented in NI and PL type buildings. In 2009, 11 285, 1994, and 4936 kg of paper, cans/bottles, and cardboard were generated from these two buildings which would be equivalent to 5.1 kg of paper, 0.9 kg of cans/bottles, and 2.2 kg of cardboard per person. These numbers are a low estimate of possible recyclable waste generated from these two buildings since there are fewer recycling bins than trash bins in NI and PL. Some of the recycling bins have not been clearly labeled until recently. Waste Reduction Model (WARM) (USEPA, 2009b) was used to analyze the reduction in greenhouse gas emissions due to recycling as an alternative to land filling the above mentioned solid wastes. About 106 MTCO_2E could be saved if NI and PL buildings switched from land filling to recycling. This number is comparable to carbon savings that can be achieved by rainwater-low-flush and composting technologies. If the buildings were designed using Scenarios 4 or 5, 36 MTCO_2E and 70 MTCO_2E could be saved annually compared to what would have been emitted from Scenario 1. However, recycling would require transportation of materials to a recycling plant. While trying to mitigate the carbon emissions due to land filling, carbon emissions could arise due to transportation and recycling process and then transportation to supply the recycled material for use could all together add a significant amount of emissions due to recycling. Therefore, the carbon savings due to selection of rainwater based or composting based sanitation technology would be less but still within the same order of magnitude compared to CO_2EE savings that can be obtained from recycling.

4. Conclusions

In this study, cost, energy, and CO_2EE implications of standard, high efficiency, rainwater flushed, and composting toilets were compared for the first time in literature. The analyses were representative of a higher education building complex for 2200 people. Modeling of composting toilet scenario was preliminary due to absence of data on this technology in large scale uses. The economic implications of the alternative scenarios were analyzed using NPV calculations. A sensitivity analysis was used to determine the impact of discount rate on the NPV and payback period. Use of the EIO-LCA approach had some shortcomings such as our inability to separately account for water and wastewater services. Yet, the EIO-LCA estimates provided comprehensive and nationwide averages of energy and CO_2EE effects for the scenarios modeled in this study.

Our study showed that all alternative scenarios except Scenario 3 had positive NPV event at 0% discount rate suggesting that they are more attractive investment options compared to the standard system (Scenario 1). The NPV of the scenarios was less than half a million at 0% discount rate but was increased to a range of $ 5–27

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million at 12% discount rate suggesting that these alternative designs can be valuable investments for an institution. Scenario 3 outperformed the standard system and had a positive NPV at 2% and greater discount rates. However, Scenario 3 had very high payback periods (17 years event at 12% discount rate) suggesting it is not a preferable option compared to the standard system. The energy demand and CO_2EE of Scenario 3 was also very high. These results implied that rainwater harvesting system without high efficiency fixtures is not a preferable option for these buildings.

This study showed that Scenarios 2, 4, and 5 all had considerably better economic and environmental performance compared to the standard system (Scenario 1). In considering alternatives to the standard design, high efficiency fixtures that use potable water (Scenario 2) is often the most preferred method in high efficiency buildings; yet our analysis showed that composting toilet systems (Scenario 5) and a rainwater harvesting system coupled with low flush fixtures (Scenario 4) outperformed the high efficiency system (Scenario 2) in long term cost, energy, and CO_2EE. Scenario 2 did have the lowest payback period but payback periods of Scenarios 4 and 5 were also reasonably low at less than ten years even at 0% discount rate. These payback periods would further decrease if water and wastewater service rates increase in the future (see Supporting Material). Therefore, our results suggest that Scenarios 4 and 5 should be considered in building design in addition to Scenario 2.

Among all scenarios considered, the composting system (Scenario 5) had the lowest cost, energy, and CO_2EE. Therefore, if solids management is not considered, this option clearly outweighs all other scenarios. Future research is necessary to evaluate the relative performance of this and other scenarios using a greater system boundary that includes solids management.

The centralized water and wastewater services have high carbon footprints; therefore if carbon footprint reduction is a primary goal of a building complex, alternative technologies that require less potable water and generate less wastewater can largely reduce the carbon footprint. High efficiency fixtures flushed with rainwater (Scenario 4) and composting toilets (Scenario 5) required considerably less energy than direct energy demands of buildings. However, the annual carbon footprint of these technologies was comparable to the annual carbon footprint from space heating. Similarly, the carbon savings that could be achieved from Scenario 4 or 5 were comparable to a recycling program that can be implemented in buildings. These results suggest that sanitation systems should be considered in building LCA analysis as they can have important contributions to the operational CO_2EE

This study showed that rainwater flushed toilets and composting toilets should be considered as viable building design options due to their better economic and environmental performance. Yet, neither one of these methods is widely accepted in practice partially due to lack of knowledge on installation and operation of these systems. Development of guidelines on installation, use, and maintenance of both the rainwater and composting systems are necessary to promote these technologies.

Coombes et al., 2002; Herrmann and Schimda, 2000; Russell, 2010

Acknowledgements

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Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi: 10.1016/j.jenvman.2010.08.005.

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Supplementary Material

1. Detailed life cycle inventory of the five scenarios

Table S1 Life cycle inventory for all five scenarios **(Inventory for operation phase is for one year)**

System	Phase	Sector #	Sector Name	Materials required	No of Units	Total 2009 prices $
Scenario1- Standard	Manufacturing	32711	Vitreous china plumbing fixture manufacturing	Toilets	62	12 065
				Urinals	18	6931
		33291	Metal valve Manufacturing	Flush-o-meters for toilets	62	11 662
				Flush-o-meters for urinals	18	3831
	Operation	221300	Water sewage and other systems	Potable Water	8 521 m^3	3238
		221300	Water sewage and other systems	Waste water	8 521 m^3	9 458
Scenario 2-Low Flush	Manufacturing	32711	Vitreous china plumbing fixture manufacturing	Toilets	62	12 065
				Urinals	18	6 931
		33291	Metal Valve Manufacturing	Flush-o-meters for toilets	62	11 662
				Flush-o-meters for urinals	18	3 831
	Operation	221300	Water sewage and other systems	Potable water	5 737 m^3	2 180
		221300	Water sewage and other systems	Wastewater	5 737 m^3	6 368
Scenario 3- Rainwater-standard	Manufacturing	32711	Vitreous china plumbing fixture manufacturing	Toilet	62	12 065
				Urinals	18	6 931
		33291	Metal Valve Manufacturing	Flush-o-meters for urinals	18	3 831
		332420	Metal tank, heavy gauge, manufacturing	Rainwater tank	3 tanks of 237 m^3 capacity	119 220
		333911	Pump and pumping equipment manufacturing	Pumps	2	1390
		333319	Other commercial and service industry machinery	Floating tank filter	1	425
		326120	Plastics pipe, fittings, and profile shapes	Pipes	307 m	313
	Operation	221300	Water sewage and other systems	Potable Water	1 745 m^3	720
		221300	Water sewage and other systems	Wastewater	8 521 m^3	9458
		221100	Power generation and supply	Energy use by pumps	2	136
Scenario 4- Rainwater -low flush	Manufacturing	32711	Vitreous china plumbing fixture manufacturing	Toilet	62	12 065
				Urinals	18	6 931
		33291	Metal Valve Manufacturing	Flush-o-meters for toilets	62	11 662
				Flush-o-meters for urinals	18	3 831
		332420	Metal tank, heavy gauge, manufacturing	Rainwater tank	384 m^3	51 111
		333911	Pump and pumping equipment manufacturing	Pump	2	1390
		333319	Other commercial and service industry machinery	Filter	1	425
		326120	Plastics pipe, fittings, and profile shapes	Pipes	307 m	313
	Operation	221300	Water sewage and other systems	Wastewater	5 737 m^3	6368
		221100	power generation and supply	Energy use by pump	2	92
Scenario 5- Composting	Manufacturing	32711	Plastics plumbing fixtures and all other plastics products	Toilets fixtures	62	18 290
		32711	Vitreous china plumbing fixture manufacturing	Waterless urinals	20	6840
		32619	Plastics plumbing fixtures and all other plastics products	Central composting units	30	68 850

	Operation	221100	Power generation and supply	Heat	370 W 115 V 6 hours per day	502
		221100	Power generation and supply	Fan	2.4 watts	41

2. Effect of disinfecting the rainwater

Health and safety of the use of rainwater to flush toilets is not currently regulated by the federal government or by most state or local goverments in the US. The Texas manual on rainwater harvesting suggests that if rainwater is used for non-potable purposes, treatment of the water beyond filtration would not be necessary (Krishna, 2005). Chemical disinfection of harvested rainwater is also not recommended or widely practiced for non-potable water uses in Germany and Australia (Herrmann and Schimda, 1999; Coombes et al., 2002). Rainwater might attain a color from organic matter in atmospheric pollutants or roofing materials. Activated carbon filters are generally used to remove the organic compounds in rain water and thus get rid of color and odor in rainwater (Russell, 2010). In general, the microbiological quality in toilets supplied with rainwater can be approximately the same as in toilets supplied with potable water (Albrechtsen, 2002). Rainwater supplied toilets may have some pathogens that are not found in toilets supplied with potable water (Albrechtsen, 2002); However, human health risks may nevertheless be minimal since humans would not have any direct contact with toilet water.

Disinfection of rainwater prior to its use in toilets may be the preferred approach in some cases (e.g. Chilton *et al.*, 1999), so we investigated the effect of adding chemical disinfection to Scenarios 3 and 4. Including sodium hypochlorite in the life cycle inventory (40 ml of liq. Sodium Hypochlorite per 1000 L of rainwater initially and 4 ml of liq. Sodium Hypoclorite per 1000 L of rainwater weekly) would have a negligible increase in annual energy impacts (0.005TJ for Scenario 3 and 0.004TJ for Scenario 4) and carbon emissions (0.27 $MTCO_2EE$ for Scenario 3 and 0.24 $MTCO_2EE$ for Scenario 4). Therefore, as in other minor components (e.g. dual piping, filter, pumps), the chemical desinfectioin also did not contribute much to the overall environmental impact of rainwater based systems.

3. Effect of increased water prices

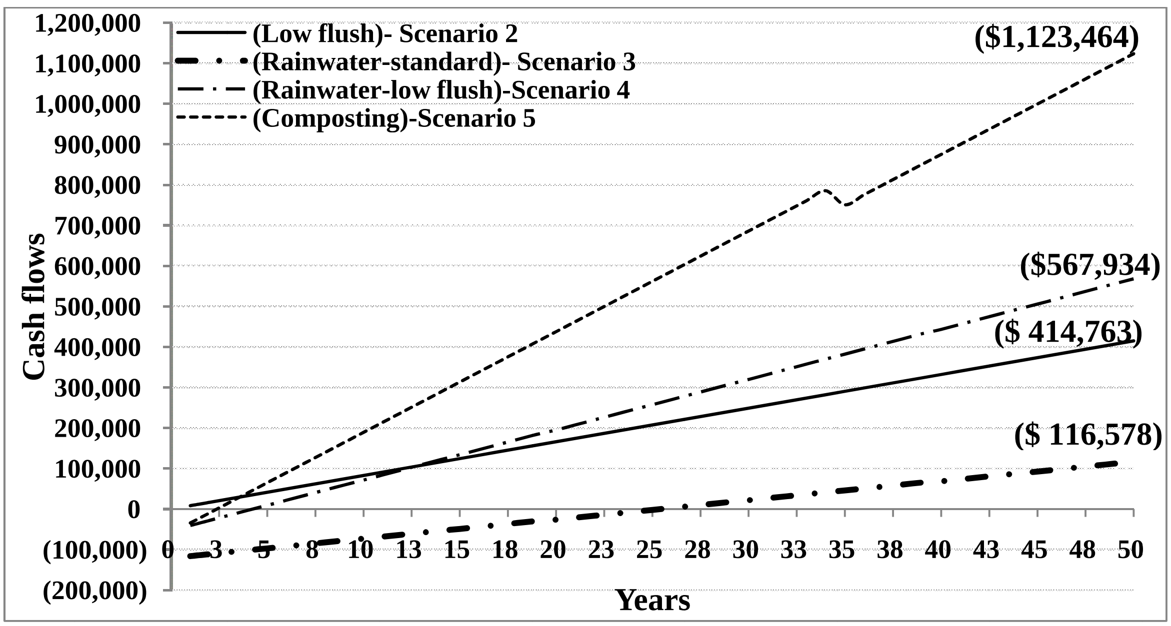

Figure S1 Impact of increased water prices on pay back time and NPV at 0% discount rate. **(The figures at the end of cashflows represt the NPV of the particular scenario)**

An additional scenario with increased water prices was run to identify the impact of water prices on cost. The increase in water prices increased the net present value of all alternative scenarios (Figure S1). In this additional analysis local utility rates were increased by two fold (from $0.38/m^3 for potable water and $1.11/m^3 for wastewater to $0.76/m^3 for potable water and $2.22/$m^3$for wastewater). A 0% discount rate was adequate for all the cases to show a positive net present value (Figure S1).

The payback period of all scenarios reduced with an increase in water prices. The payback period of Scenarios 2, 4 and 5 were less than 6 years for a 0% discount rate. The payback time of Scenario 2 remained 1 year. Scenario 3 showed a payback time of 26 years. However, nearly 3 decades is not a favorable payback time. Scenario 4 showed a payback time (5 years) reduced by 4 years, and Scenario 5 showed a payback time (3 years) reduced by 2 years compared to the Scenario 5 with current water rates. Therefore, in the future with an increase in water prices the alternative scenarios with very small payback time can prove to be more beneficial.

With increased water rates, Scenario 3 resulted in a NPV of $1 221 975 in 50 years. The NPV of all scenarios increased with an increase in water rates. At 0% discount rate the NPV of the scenarios ranged between $415 000 - $ 1 125 000 approximately. The rainwater standard scenario still had the lowest NPV among all the alternatives compared. Similar to the case with original water prices though the payback time of Scenario 2 is the lowest, the NPV of the composting scenario is much larger (about $700 000 more) than the NPV of Scenario 2. Therefore according to our analysis Scenario 5 should be preferred over Scenario 2.

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LAKE ERIE PROTECTION FUND

SMALL GRANT - FINAL ACCOUNTING

Grant Number: SG-363-09

v2010

Budget Categories	Orignal Budget	Funds Spent	Current Balance	Matching Funds
A. Salaries & Wages				
Summer Salary for Dr. Apul	5658	5658	0.00	
Undergraduate Stipend	1075	1075	0.00	
B. Fringe Benefits				
for Dr. Apul	1765	1765	0.00	
for Student	0.20	6.20	-6.00	
C. Total Salaries & Benefits (A+B)	$8,498.20	$8,504.20	-$6.00	$0.00
D. Non-expendable Equipment				
E. Expendable Materials & Supplies				
F. Travel				
G. Services or Consultants				
H. Computer Costs				
Software and Data Purchase	5136.80	5200.00	-63.20	
Computer Maintenance	0.00	50.00	-50.00	
I. Publications/Presentations				
J. All other direct costs				
K. Total Direct Costs (C thru J)	$13,635.00	$13,754.20	-$119.20	$0.00
L. Indirect Costs				
	1364.00	855.43	508.57	
Total Costs (K + L)	$14,999.00	$14,609.63	$389.37	$0.00

I certify that the grant expenditures listed and descriptions of the charges are true and accurate to the best of my knowledge. These expenditures represent approved grant costs that have been previously paid for and for which complete documentation is on file.

	Signature	Date
Project Director	[signature]	9/28/10
Authorizing Agent	[signature]	9/29/10
Fiscal Agent	[signature]	9/28/10

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