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The Integration of biomimicry into a built environment design process model: An alternative approach towards hydro-infrastructure

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THE INTEGRATION OF BIOMIMICRY INTO A BUILT ENVIRONMENT DESIGN PROCESS MODEL: AN ALTERNATIVE APPROACH TO HYDRO-INFRASTRUCTURE

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ABSTRACT

The Integration of Biomimicry into a Built Environment Design Process Model: An Alternative Approach to Hydro-Infrastructure

by

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Current methods and processes that support the planning, design and construction of a sustainable built environment include ambiguous principles (Roseland 2000), lack feedback loops (Van Bueren and Jong 2007) and lack a common language between disciplines (Brandon et al 1997). As a result of 3.8 billion years of “research and development” (evolution), nature provides a set of design blueprints that may be used to guide us to create elegant, sustainable, and innovative designs for human technologies (Benyus 1997). The field of biomimicry analyzes nature’s best ideas and adapts them for human use (Benyus 1997). The built environment could benefit from the integration of a discipline such as biomimicry into the design process.

One example within the built environment where the field of biomimicry might offer sustainable practices is that of human hydro-infrastructure, since many systems are approaching the end of their useful life (Mays 2002, AWWA 2001). Hydro-infrastructure includes the management of water systems in order to support human civilization. This thesis integrates the field of biomimicry into a

design process model that supports the built environment. The design process model proposed in this paper allows a further distillation of components (functions) in order to seek organism strategies that accomplish the same function. These strategies are then translated into conceptual design options applicable to various scales within human hydro-infrastructure. Integrating biomimicry's "Life's Principles" into a built environment process model, will make biomimicry more accessible and thus more widely accepted throughout the industry, and the sustainability of all species will benefit.

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CHAPTER 1

INTRODUCTION

Background

Sustainable development has often been criticized as being ambiguous as an underlying principle for the built environment (Roseland 2005). Further obstacles within the planning, design and construction of the built environment include design approaches that lack feedback loops (Van Bueren 2007) and lack of a common language for multiple disciplines to assess built and natural environmental impacts (Brandon et al., 1997). The emerging field of biomimicry proposes that nature provides functions, strategies, and characteristics within a set of principles that serve as design blueprints and lay a foundation for all of life to survive and thrive on Earth (Benyus 1997). The Biomimicry Guild hypothesizes the incorporation of these principles, called Life's Principles (LPs), increase the likelihood of sustainability for a respective design, and make it more likely that the design will have a greater impact on sustainability for future generations of all species (Benyus 1997). This thesis utilizes Life's Principles as a foundation for a design process model intended for application on built environment projects at various scales.

Since the 1960s, linear thinking within the building industry has attempted to control environmental variables through design by limiting and controlling environmental resources (Van Bueren 2007). However, a paradigm shift from linear thinking to systems thinking (Table 1) has occurred in recent decades to acknowledge the environment as a dynamic system that behaves according to stocks and flows and feedbacks and thresholds (Van Bueren 2007; Meadows 2004). This is important because populations and ecosystems influence the design of the built environment due to many factors, including a depletion of resources, climate change and continuing global population growth both locally and more broadly (Yanarella 2009, Pulliam 2002).

Table 1 Linear Thinking versus Systems Thinking (adapted from Van Bueren 2007)

Linear Thinking	Systems Thinking
Approaching each building phase in isolation of one another	Acknowledging the interconnections between a number of life cycle stages
Internalizing the building's performance through Integrated Building Design (IBD)	Allowing large spatial scales to dictate proper environmental design instead of solely focusing at the building level
Integrating sustainable concepts on new buildings	Improving the performance of existing buildings
Viewing the environment as one physical system	Acknowledging the interconnections between ecological, social and economic issues

Sustainable building practices have been employed at local, regional, national and international levels and include the establishment of environmentally responsible standards, the use of 'green' products, and performing Life Cycle Assessments (LCAs) (Van Bueren 2007). However, a tremendous amount of research needs to be conducted in order for the built environment to be resource efficient and economically sustainable as previous sustainable building efforts have been welcomed with varying degrees by the industry, and factors such as climate change appear to be more serious than were previously predicted (Van Bueren 2007; Van den Berg 2007). Biomimicry seeks to further expand upon systems thinking and sustainable building practices through “principles” that include similar terminology such as leveraging interdependence, integrating cyclic processes and using life-friendly materials.

The intermountain west region, consisting of Arizona, Colorado, Nevada, New Mexico, and Utah is projected to continue its massive transformation through the coming decades as the fastest growing region in the country (Brookings Institution 2008). Five megapolitan areas within this region account for 80% of the population, and Las Vegas is expected to double its current population by 2040 (Brookings Institution 2008). At least two sustainability concerns arise from this discussion: one, infrastructure is required to support such growth; and two, whether an ecosystem, such as the Mojave Desert, where Las Vegas is situated, can offer adequate resources to support an anthropocentric model. In order to support this growth, the built environment will have to address a projected need for doubling the existing housing stock in addition to replacing and upgrading non-residential space to support the economic infrastructure (Brookings Institution 2008). Other major infrastructure concerns at both local and regional scales include transportation linkages and water and energy grid concerns.

More novel approaches toward water infrastructure need to be explored within the context of the Las Vegas Valley hydro-infrastructure. The future of water is likely the most important topic in regards to sustainability and human presence in the Mojave Desert (Webb 2009). Las Vegas may have the most insecure water in the nation supply due to problems with outward expansion that require expensive extensions and uncertain access to sufficient resources (Urban Land Institute 2007). Warming trends due to climate change are expected to provide less water to rivers from snow pack, and current water capture systems are not designed to handle the projected increase in severe flooding from periodic monsoon-like heavy rains (Brookings Institution 2008; Cromwell et al., 2007; Mulroy 2008). Collectively, these water concerns may speed water conservation approaches and consumption patterns that include planning, capture, re-use and delivery (Brookings Institution 2008).

This paper demonstrates how the incorporation of biomimicry “principles” and methods support a “living” design process applicable to built environment projects. This “living” design process model based upon an ecosystem functional cycle and principles of biomimicry is illustrated through an alternative hydro-infrastructure for the Las Vegas Valley. First, a literature review assesses the history of human hydro-infrastructure, identifying social and environmental drivers behind past decisions, critiquing them according to their effectiveness in accomplishing their goals, and ascertaining what functions can be reiterated. Second, case studies provide explicit examples of how nature accomplishes design strategies by function. Water collection, water distribution, and water processing are the selection criteria used to assess and evaluate biological organisms and natural systems that address the use of water in innovative and efficient ways pertinent to ecosystems relevant to the Las Vegas Valley.

Methods

Both a literature review and a case study analysis are used to inform the design process. These qualitative research approaches support a conceptual design that seeks to be exploratory and interpretive, resulting in multiple outcomes. Literature reviews support research that seeks to define and refine a design challenge, to aid in finding commonalities and discrepancies within existing literature, and to become familiar with relevant researchers within the field (Leedy 2005). Case studies support a more thorough inquiry into a topic, though they can be undermined by time constraints. The major weakness of the case study method is whether the findings are generalizable, or applicable to other situations (Leedy 2005). In this thesis paper, being generalizable is of concern as organism strategies might not translate sustainably into human design, and a respective design proposal might be irrelevant in different contexts and/or ecosystems. This paper attempts to limit this concern through the inclusion of Life's Principles (as mentioned in the introduction) as an attempt to apply the criteria in a way that is generalizable across all species, and to assess commonalities between multiple organisms.

This research integrates these methods in several stages. First, Chapter II utilizes a literature review in order to provide validity to the field of biomimicry by embracing disciplines that share similar ideologies, such as ecological design, while illustrating previous "bio"-design schools of thought that support biomimicry as a unique approach. This analysis becomes the basis for the design process model that supports the hydro-infrastructure analysis within this paper. Chapter

III (the Distillation Stage) includes a literature review that deduces patterns among functions, structures, and characteristics of human hydro-infrastructure in both environmental and social contexts. Chapter IV (the Discover Stage) utilizes a case study analysis in order to assess and evaluate biological organisms and natural systems that fulfill the selection criteria of water collection, water distribution, and water processing in order to address the use of water in innovative and efficient ways pertinent to ecosystems in the Las Vegas Valley. Chapter V (the Emulate and Evaluate Stage) proposes integral places to intervene in the system by illustrating how the respective organism strategies might translate into the built environment.

CHAPTER 2

THE BIOMIMICRY APPROACH

Nature and Design

Nature has occurred in various facets of design throughout time (Gruber 2007). Biophilia believes design supports an inherent desire for humans to "affiliate with natural systems and processes" (Kellert 2008). The terms "biomorphic" and "organic" have been utilized in design since the 1930s and relate to natural processes (Wunsche 2003). An approach that integrates ecological processes in order to minimize environmentally destructive impacts is often referred to as ecological design (Van der Ryn and Cowan 1996). This section addresses the integration of nature into design order and establishes how biomimicry expands sustainability principles.

The 1990s introduced many references to designing with nature such as Ken Yeang's Designing with Nature (1995) and Sim Van der Ryn and Stuart Cowan's Ecological Design (1996). A lack of understanding of systemic interactions and the structure of biological and physical components has resulted in considerable environmental damage (Yeang 1995). Sustainability will require a design approach that treats the built environment site as a "living and functioning ecosystem", not as a "physical and spatial zone" (Yeang 1995, p. 4). Designers need to understand how ecologists and environmental biologists approach a site in order to create one central unifying theory or commonly acceptable concept defining ecological architecture (Yeang 1995).

Van der Ryn and Cowan (1996) point out that the incorporation of nature into design is nothing new. What was mostly missing in early efforts of the late 19th century was a consideration of all species and a systemic approach towards addressing the repercussions of our design efforts on ecosystems. Van der Ryn and Cowan (1996) believes the 1960s brought about the first modern generation of ecological design while future models will require greater interdisciplinary efforts. Van der Ryn and Cowan (1996) suggests that design abide by the following principles: solutions grow from place; ecological accounting informs design; design with nature; everyone is a designer; and, make nature visible.

Eugene Tsui (1999) believes efficiency is the primary strength of designing like nature. "Living technology" combines nature and human ingenuity for a mutualistic relationship, to the extent that nature will drive industry and economics (Tsui 1999). In order to achieve efficiency in his designs, he attempts to extrapolate a set of principles, although it is difficult to claim efficiency alone is the end goal of nature. Evolution suggests that random mutations are responsible for new designs (innovation), and successful designs are evidenced through subsequent generations (niche discovery) (Orr 1998). In either case, Tsui's creation of principles is a means to achieve a common language between design and nature consistent with Yeang's philosophy.

Biomimicry, as proposed by Janine Benyus (1997), suggests that a design's best chance at approaching sustainability is through a "conscious emulation of nature's genius" (Biomimicry Institute 2008, entry portal) by directly mimicking the functional processes embedded in nature. This is accomplished by isolating an organism or system, dissecting a function down to the “how,” and proposing a deliberate mimicry of the function desired, grounded in a number of principles that collectively support sustainability. Biomimicry attempts to expand its designs beyond both the purely aesthetic (biomorphism) and the mere natural affinity for nature (biophilia).

Van der Ryn (1996), Yeang (1995) and Tsui (1999) all suggest the establishment of a common set of principles based upon how nature designs, and Biomimicry provides further credibility through a rigorous account based upon scientific precedent via Life’s Principles (LPs). Yeang (1995) feels biological knowledge by designers has been the missing variable in past design theory. Van der Ryn’s (1996) principles focus on design from an ecosystem point of view, and overlap with Benyus’s (1996) approaches towards the incorporation of nature. Examples include Benyus’s (1997) “nature as measure” and “nature as model and mentor” to Van der Ryn’s (1996) “ecological accounting,” and “designing with nature.” Tsui (1999) and Benyus (1997) might differ on the exact principles they propose, but both agree that this common language will drive the future of design and sustainability.

How Biomimicry “Fits”

The field of biomimicry is currently promoted through two co-organizations, the Biomimicry Guild and the Biomimicry Institute. “The Guild is the only innovation company in the world to use a deep knowledge of biological adaptations to help designers, engineers, architects, and business leaders solve design and engineering challenges sustainably” (Biomimicry, Entry Portal web page). “The Institute promotes learning from and then emulating natural forms, processes, and ecosystems to create more sustainable and healthier human technologies and designs” (Biomimicry 2008, Entry Portal web page). The Institute provides several universal design templates, tools and wiki-based resources meant to assist various disciplines with design challenges, all of which are utilized to support the design process model developed in this paper.

In order for biomimicry to be useful to the built industry, a design process model must be proposed that “fits” within the current process. The American Association of Architects (AIA) might consider the incorporation of biomimicry into the design process an “additional service” (2009) consistent with the expertise an architect offers through the development of a program. All consultants, including biomimetics, are recommended to be included within the early stages of a design proposal in order to suggest where biomimicry can be of most use. Biomimicry believes its approach to translating a client’s objectives into a “how would nature accomplish this?” task provides a deeper and more thorough inquiry into program development and conceptual design, although the integration of feedback loops (a Life’s Principle) suggest deliberate re-assessments by all disciplines throughout respective project.

Process Models

Design process models represent the relationship of research to a design’s content and process (Milburn & Brown 2003). Design process models are differentiated by various characteristics such as the source of ideas or concepts, the inclusion of research or evaluation phases, and various approaches towards problem solving (Milburn & Brown 2003). The value they provide depends on the individual and project structure (Milburn & Brown 2003). The following models illustrate different approaches to the incorporation of research into the design process in order to adapt, modify, or integrate them into biomimicry design as appropriate. Donald Schon (1963) claims a concept-test model supports the "creation of new design concepts to involve the projection of old ideas to new problems, followed by the assessment and alternation of the ideas to allow for situational differences" (Schon 1963 in Milburn & Brown 2003). As an intuitive process model, it can be expected that varying conceptual designs result according to respective designer's cognitive and emotive resources (Milburn 2003). The concept is evaluated according to pre-determined criteria in order to evaluate its appropriateness and functionality (Milburn 2003). Figure 1 illustrates that a personal repertoire of typologies are compiled during "Idea Generation," and these are used to create multiple concepts evaluated according to the "Design Problem" (Figure 2).

Ledewitz (1985) presents the complex intellectual activity model that allows the individual to "deconstruct the problem into a series of structural relationships, which are then reorganized through reframing of the problem" (Milburn & Brown 2003, p. 52). The establishment of selection criteria at the conceptual stage is not as deliberate as was the case with the concept-test model. Eugene Tsui (1999) suggests that the challenges in designing like nature include: finding suitable structural systems, seeking time and labor conserving means of construction, and the amount of time required to perform additional research. Within this design process model impacts and relative success are evaluated post-construction and documented to inform future design endeavors (feedback loop), as can be seen in both Figures 3 & 4.

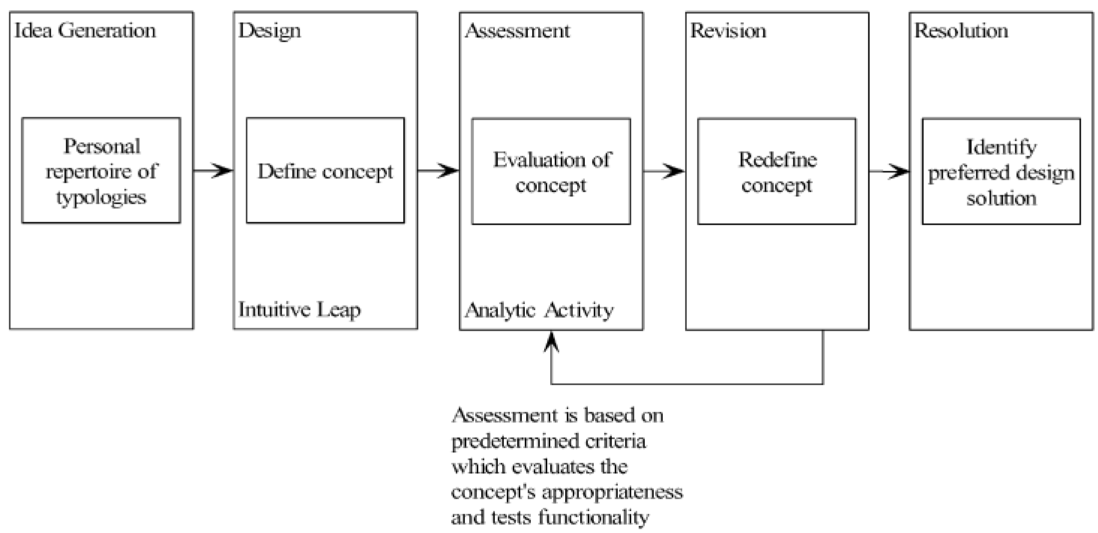

Figure 1 Concept-test model: relationship between research & design (Milburn 2003)

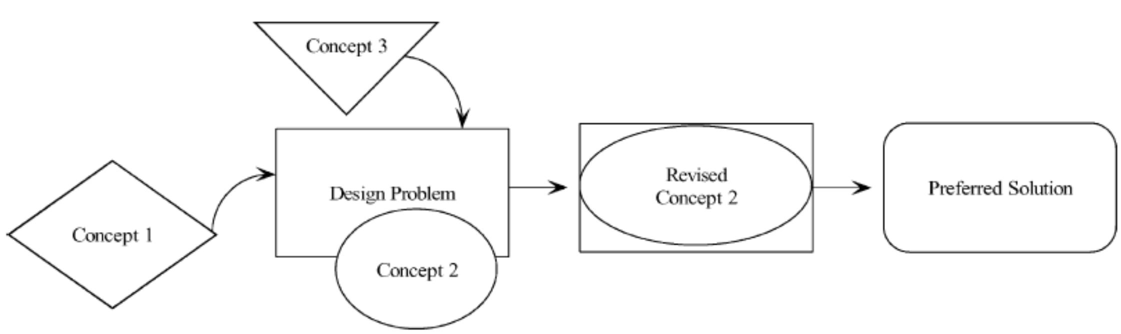

Figure 2 Concept-test model: schematic diagram (Milburn 2003)

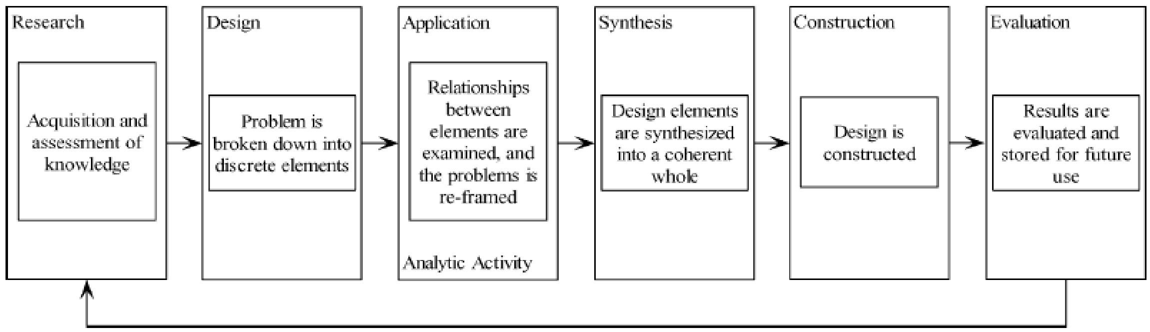

Figure 3 Complex Intellectual Activity Model (Milburn 2003)

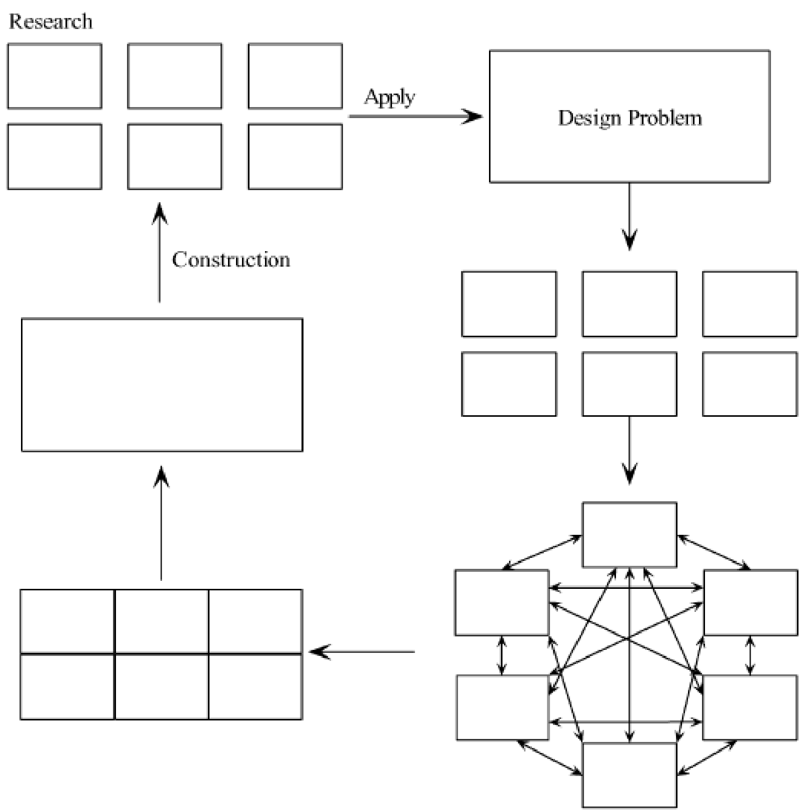

Figure 4 Complex Intellectual Activity Model: Schematic Design (Milburn 2003)

The Biomimicry Institute's design spiral (Fig. 5) suggests that design is not simply a linear process and integrates opportunities to continually re-visit prior stages. The spiral expands upon Ledewitz's complex intellectual activity model (1985) by "reframing the problem" within the Distill Stage and translates the design challenge into biological terms. The Evaluate stage within the design spiral is based upon selection criteria (Life's Principles) and is meant to occur at both conceptual and post-design stages, so it is an amalgamation of both the concept-test model and the complex intellectual activity model.

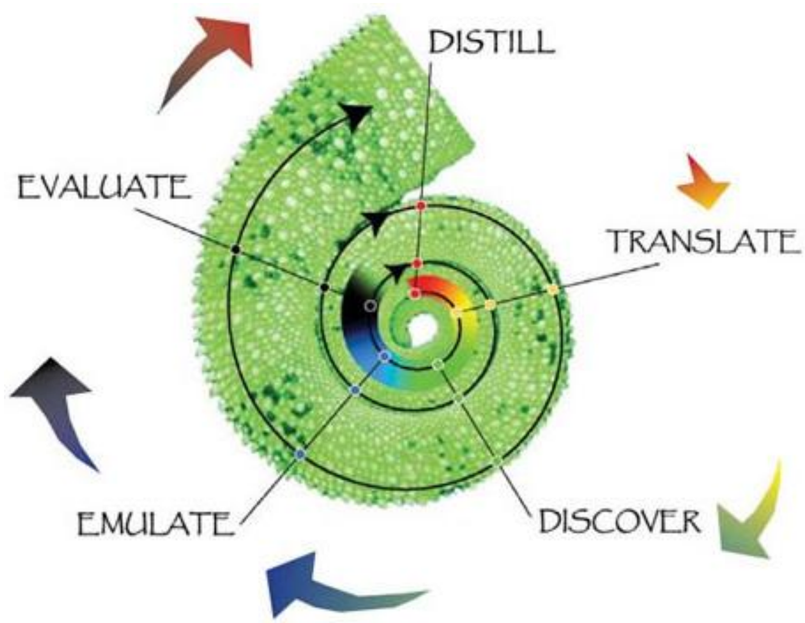

Figure 5 Design Spiral (Biomimicry Institute 2008)

The final model that serves as inspiration for a biomimicry design process model is that of an ecosystem model. An ecosystem behaves in a cyclical fashion transitioning between four stages that include: conserve, release, reorganize, and exploit (Gunderson 2002, Fig.6). Release occurs in nature after death or a natural disaster, as all of nature is broken into its most basic components. Ledewitz's (1985) suggestion to deconstruct the "problem into parts" mirrors this ecosystem stage. The design spiral's Distill and Translate stage divide the design challenge into functions. Reorganization begins to take these simple parts and begins to rebuild an ecosystem. Ledewitz's (1985) design model begins to assemble research into more refined parts determined by their interconnections. The design spiral's next stage aims to "discover" a breadth of organism strategies. Exploitation occurs when new species begin to emerge and the successful ones are those that find respective niches. During this stage, concepts emerge as satisfying a niche or being innovative, and increase the proposed design's chance of being successful. Conservation correlates to a system that has used all of its resources, subsequently returning to the Release stage. In a design process this equates to the point at which all research culminates in a conceptual design. This stage should not be looked at as an end of life stage, but rather an opportunity stage to re-assess the design. A sustainable species or design will continue through the cycle and emerge at the other end time and again. However, a solution that meets obstacles at this stage needs further refining in order to be sustainable, and must go through the cycle again.

A certain linear quality often exists as a result of planning and construction processes, although a circular or spiral model better reflects the incorporation of evaluation feedback loops (Tunstall 2006) that are integral to the complex intellectual activity model (Ledewitz 1985), the design spiral (Biomimicry Institute 2008) and the ecosystem cycle (Gunderson & Holling 2002). The primary difference between the ecosystem cycle and the design spiral is that the spiral proposes one can revisit early stages at any given time throughout the process while the cycle suggests that one must proceed in a certain order before one can revisit or re-assess a stage.

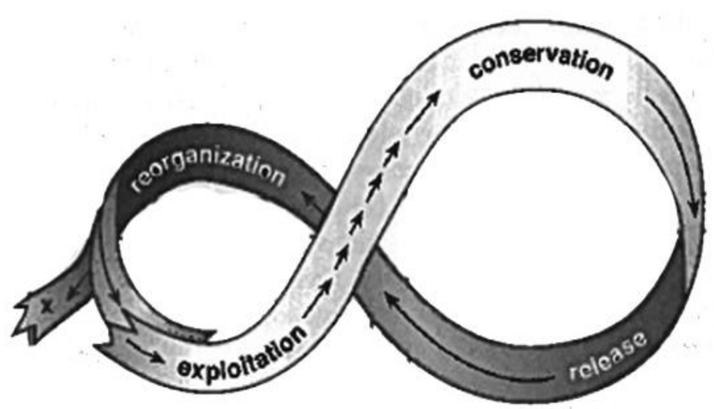

Figure 6 The Ecosystem Functional Loop (Gunderson 2002)

Biomimicry "Living" Design Process Model

The cyclic design process model proposed in this paper is an amalgamation of the various models aforementioned (Fig. 7). This model proposes that the design process itself is "living," and is based upon the ecosystem functional model. Attempts are made to use consistent biomimicry terminology in order to serve as an iterative of the design spiral.

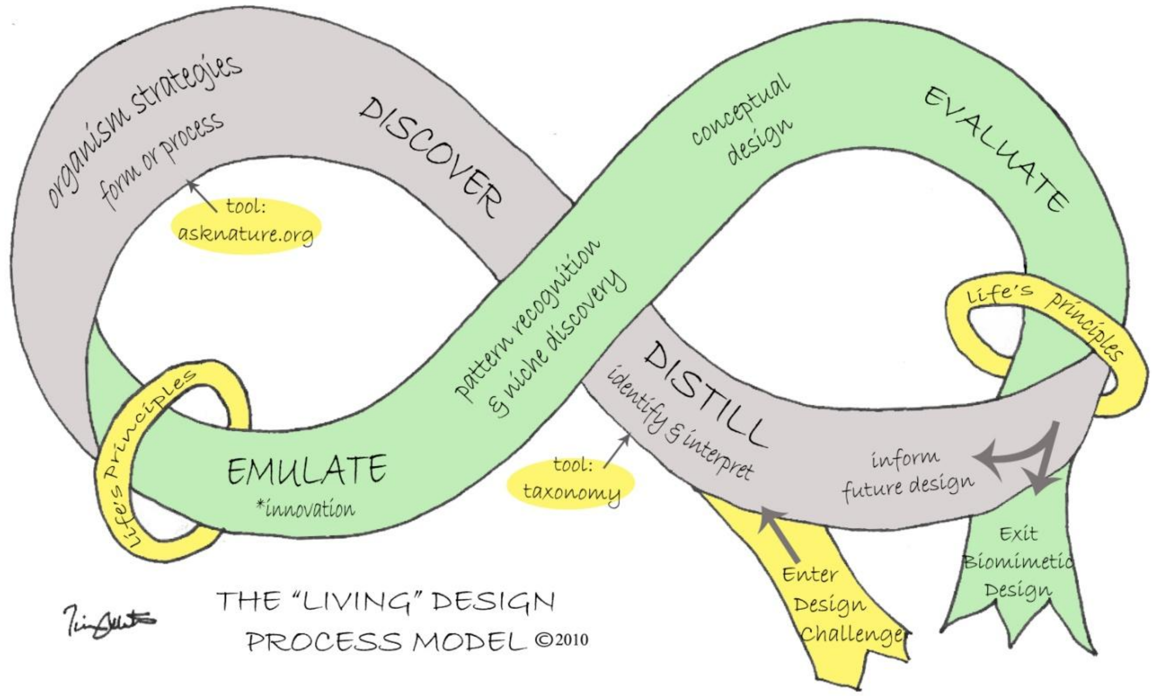

Figure 7 Living Design Process Model

Each of the four stages of the model will be discussed briefly to illustrate the ways each stage has been informed by previous models and to establish the relationships between these stages within the proposed model. The Distill stage picks up at the release stage within the ecosystem cycle and serves as the starting point within a design challenge. In order to integrate a human element into the process, this stage incorporates Schon's (Milburn & Brown 2003, p. 50) "projection of old ideas to new problems" in order to UNDERSTAND and/or justify past design decisions through an environmental and social history assessment. This stage further seeks to IDENTIFY components and INTERPRET functions consistent with the Ledewitz (Milburn & Brown 2003) and design spiral (Biomimicry Institute 2008) model. The Discover stage is consistent with the design spiral's aim to compile a breadth of LIFE'S STRATEGIES in response to the distilled functions and is consistent with Ledewitz's (Milburn & Brown 2003) proposal to assemble research into more refined parts determined by their interconnections. The first of two LIFE'S PRINCIPLES (Fig. 8) checklists serve as selection criteria and sum up the breadth of organisms selected in more identifiable patterns that will form the basis of the conceptual design in the subsequent stage. The Emulate stage recognizes PATTERNS within prior stages in order to discover NICHES that will inform the CONCEPTUAL DESIGN. The Evaluate stage ensures that the conceptual design is appropriate and functional by re-visiting the LIFE'S PRINCIPLES (Fig. 8) checklist. This stage is also relevant through post-construction as one may inform future projects through this feedback loop, as was suggested within Ledewitz's (Milburn & Brown 2003) model.

Depending on the project, either one of or both discrete and holistic approaches to problem solving are possible. A holistic approach supports a cognitive and emotive translation into a conceptual design and is most relevant when the "idea" of biomimicry is desired and a "loose" analysis is more feasible. There is still tremendous strength in the biomimicry process through the distillation of the design challenge and the incorporation of life's principles;

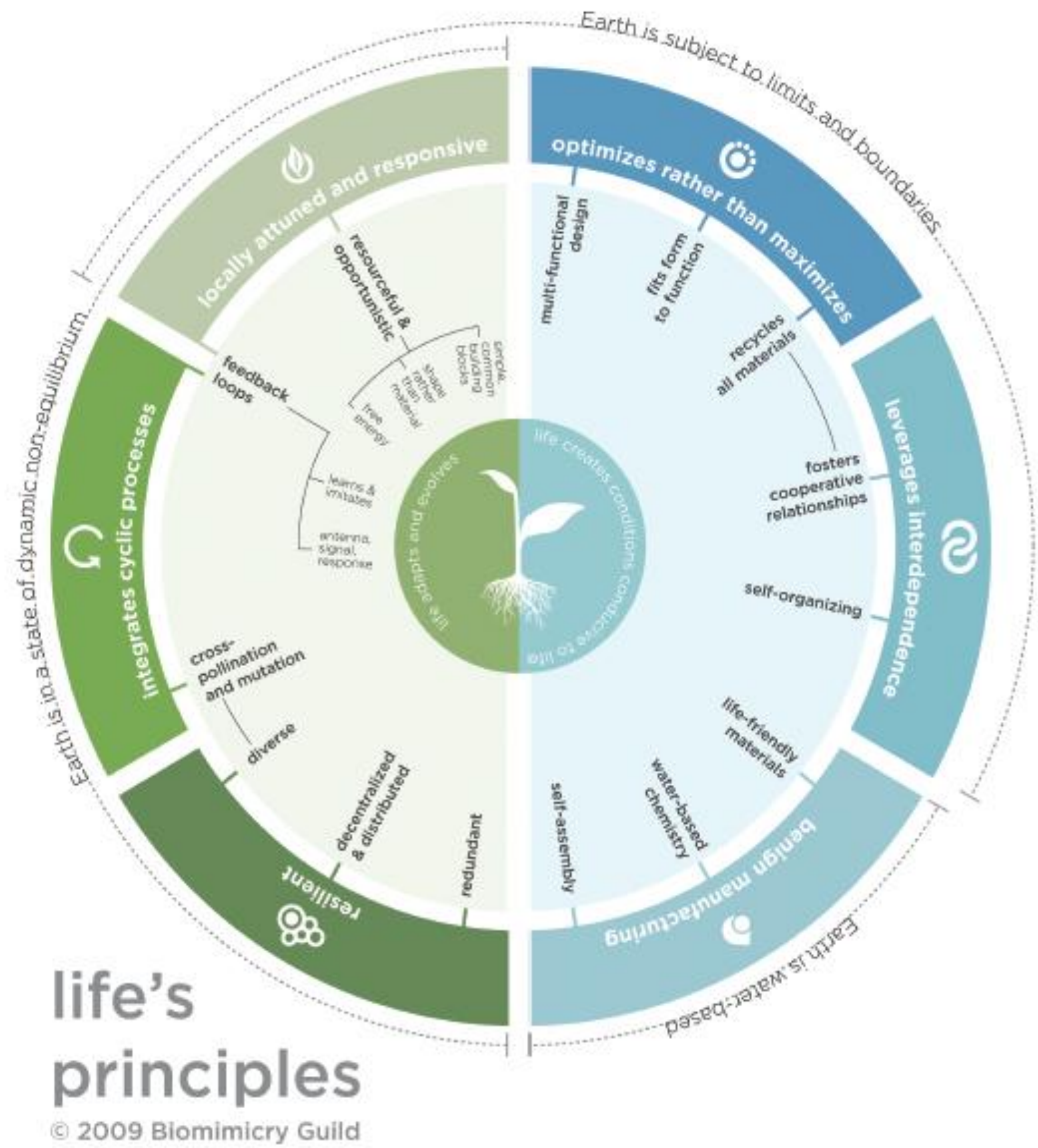

Figure 8 Life's Principles

however, as biomimicry seeks to "function" as nature does, a discrete approach is ultimately desired as a designer can directly translate components into an engineered design or product. Time constraints ultimately are a hindrance to the process, as the built industry typically requires a product within a specified timeline. Ledewitz's (Milburn & Brown 2003) process model supports biomimicry as a design process for the built environment as it proceeds through to construction of the concept and utilizes feedback loops in order to inform future projects, which is a missing feedback loop within the current biomimicry design spiral, and can be linked to research and development organizations. The proposed design process includes four stages, named distill, discover, emulate and evaluate. The process has been named the "Living " Design Process Model to emphasize that a sustainable human design process should mimic that of a natural process.

Distill

The distillation stage serves as the starting point in a design challenge. The main goals of this stage are first, to understand the problem, second to IDENTIFY components by deconstructing the design challenge, and third to INTERPRET the design challenge into functions that can be translated into biological terminology in a later stage. The first goal of deconstructing the design challenge into components begins with the identification of social indicators, environmental responses and performance factors. A multi-disciplinary team is essential in order to provide discrete responses through current human designs and processes that seek to distill patterns of past successes and failures, and identify where future markets might play a role.

Patterns are assessed within the discussions in order to offer objectives and opportunities that can be translated into functional objectives performed by nature. Although biomimicry can offer strategies that support sustainability in a socially responsible manner, an evaluation of cultural patterns and behaviors are equally important in order to suggest how a certain culture might adapt and evolve with the integration of a new technology, as well as benefit from a deeper sociologic perspective. Also, some human functions do not translate easily into natural functions. For this reason, the Biomimicry Institute has created a taxonomy tool that assists in the identification and translation of human design functions into biological functions (Fig. 9) by asking "how would nature" perform the respective design challenge (Biomimicry, taxonomy 2008). The ultimate goal is to eliminate extraneous variables that influence why humans design as they do, and get to the heart of a design challenge.

Discover

This stage seeks to discover ORGANISM STRATEGIES (case studies) in nature regarded as champions for a particular function, and then suggest whether the market translation might either be a FORM or a PROCESS. LPs are then cross-referenced against the current industry standard and the organism strategy being proposed in order to ensure that additional levels of sustainability are attainable.

Organism Strategies

Breadth is more important than depth during the ORGANISM STRATEGY search, although credibility or practicality might be an issue unless the strategy has been heavily researched. Valuable resources include scholarly journals and databases, biology textbooks and the Biomimicry Institute's wiki-style organism

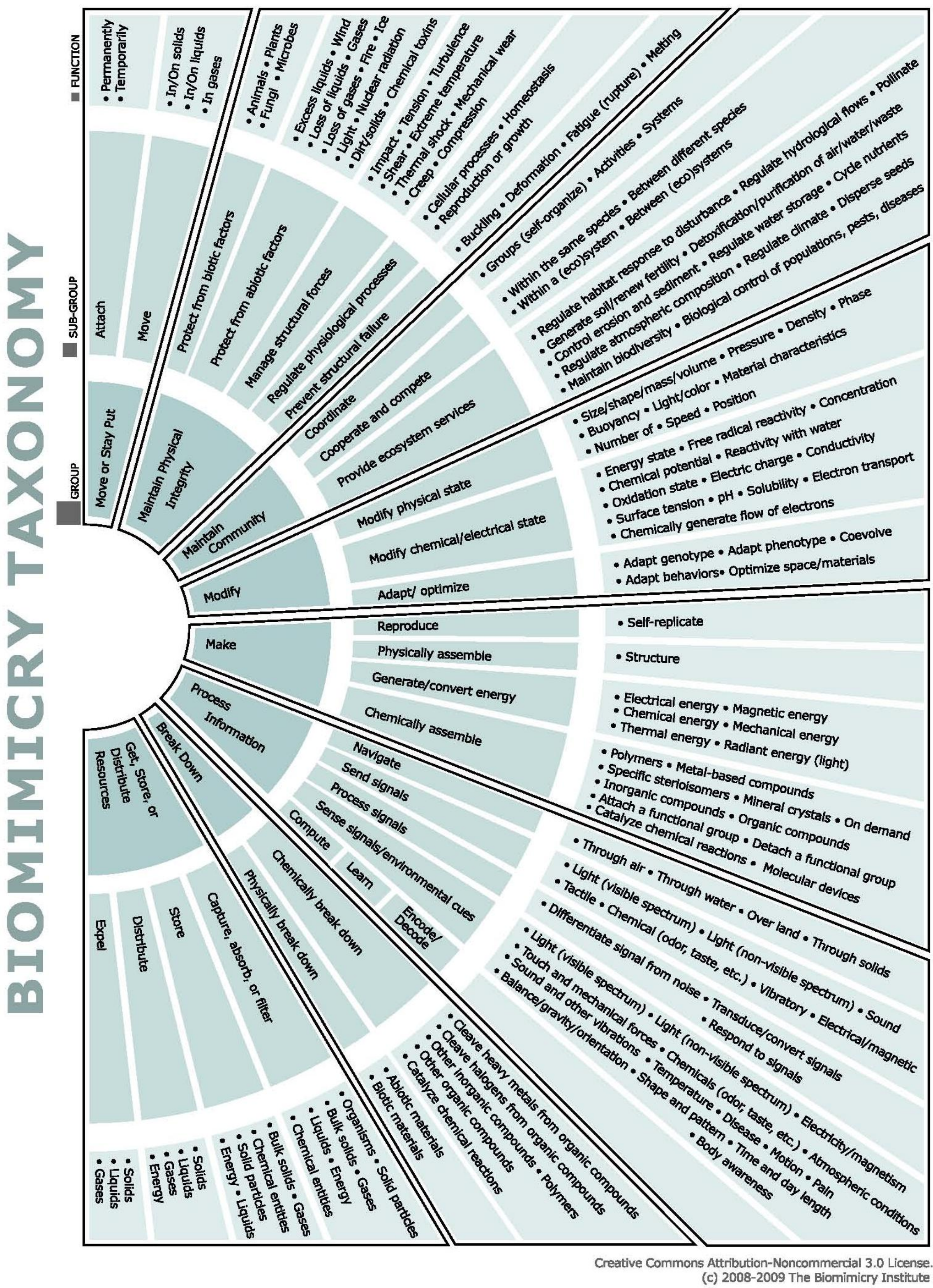

Figure 9 Biomimicry Taxonomy (Biomimicry Institute 2009)

database located at www.asknature.org. This resource is free to the public and created by academics and industry professionals for students, teachers, designers, engineers, architects, and biologists to have access to over 12,000 organism strategies, photos and scholarly references. This concise database provides a quick abstract of organisms that are accomplished at the function under consideration (as mentioned in the distillation stage).

Some faults within the current built environment are attributed to a poor "fit" into the ecosystem. The Biomimicry Guild has created a product called Ecosystem Performance Standards intended to support the creation of entire cities that perform at least as well as the native ecosystem. As each species has its own respective niche or responsibility, so does each constituent of the built environment. Within this analysis, the ecosystem is defined, such as temperate deciduous forest, chaparral, savanna or desert, while assessing variables that include carbon sequestration, water budgets and biodiversity. In addition to the determination of ecosystem specific factors, the discover stage also serves to seek out organisms that might be considered champion adapters in a respective ecosystem. For example, the most likely place to find an organism that excels at "conserving" water is the desert, not the ocean.

Once a compilation of organisms is created, it can be determined whether the strategy is a FORM or PROCESS that will translate into a human innovation. A FORM strategy translates directly into a tangible design while a PROCESS infers mimicking a phenomenon, such as a chemical reaction or establishing a certain relationship with an ecosystem.

Life's Principles

The use of Life's Principles (LPs) (Fig. 8) occurs twice in the proposed Biomimicry Living Design Process Model. The second occurrence serves to "Evaluate" the human innovation in order to ensure its sustainability as a product while the LPs within the Discover stage serve to overlay patterns of unsustainability within the current industry in order to determine where the organism strategies can serve a much needed niche.

Life's Principles acknowledge that the earth is subject to limits and boundaries on elements such as resources, earth (as water-based and in a state of dynamic non-equilibrium), and seasonal weather patterns. The LPs state that life creates conditions conducive to life, and life adapts and evolves. Some principles overlap and reinforce each other as they are applied to respective design projects. The primary principles for discussion are benign manufacturing, resilience, the integration of cyclic processes, being locally attuned and responsive, optimizing rather than maximizing, and leveraging interdependence.

Although there is great strength in extracting these principles from nature and suggesting they will support a sustainable product, several criticisms exist. For one, some critics believe that it is impossible to extract general principles, such as these, because they appear self-contradictory; biological nature is too diverse to generalize (Marshall 2009) and depending on the project, some are more apparent than others (Tsui 1999). Also, without insisting all LPs be incorporated into a design, the product can lack respect for nature, and support an anthropocentric agenda (Marshall 2009). For example, a product such as

Velcro has often been credited as being inspired by nature through its hook and burr system (mimicking form) and might prove to be ingenious in that it allows endless attachment opportunities; however, this product considers only a few of Life's Principles, and is dependent upon fossil fuels (plastic).

The Biomimicry Guild (the Guild) asserts that a comprehensive approach to the incorporation of LPs is the ultimate goal for sustainability. In cases where it is not feasible to accomplish all LPs immediately, the Guild develops long-term plans with companies in order to achieve sustainability. One of the Biomimicry Guild's clients, Interface FLOR, has based an entire marketing campaign on this stance, called Mission Zero. Mission Zero illustrates how an increase in LPs has indeed made the business more sustainable. For instance, Interface FLOR (Interface 2008) set goals to recycle all carpet in order to keep it out of landfills (LP: recycling all materials), and since have set the goal of eliminating their dependence on fossil fuels in all facets of their company (LP: using benign manufacturing).

Within the Discover stage, determining the pertinence of an organism's strategies to respective Life's Principles is an intuitive process. The more apparent principles for each respective strategy are the ones that will support pattern recognition within the conceptual design (Emulate stage). These principles are neither mutually exclusive nor all encompassing, and the format of these principles is merely organizational.

Emulate

Patterns and Niches

Pattern recognition can assist with determining commonalities between the current human design process and organism strategies. Commonalities between all organism strategies suggest niche opportunities when the current built environment example performs in an opposing manner. Pattern recognition might occur throughout the categories assessed within the DISCOVER stage and can often serve as a starting point for the conceptual design.

Conceptual Design

The conceptual design assembles research together from the pattern recognition and niche discovery exercise in order to brainstorm multiple concepts and solutions. This stage can continue to translate in a discrete manner if a design solution seeks to directly mimic a form or process. However, a designer may leave an organism's functions, systemic ecosystem relationships and the integration of Life's Principles to an intuitive thought process in order to inform the design.

Evaluate

The EVALUATION stage seeks to provide additional feedback loops in order to predict in what ways and to what extent the proposed design will be successful. One such evaluation approach might include a pre-feasibility analysis, which includes budget and technological constraints. Full life cycle analyses can be performed for embodied energy considerations such as extraction, production, distribution, consumption, and disposal. In addition to analyses that contribute to healthy ecosystems, social justice parameters need to be assessed, such as fair trade issues and ultimately, who might be the end user. For instance, if the design might be used in warfare then the potential user might be deemed not "creating conditions conducive to life," and thereby the design would be counter to the overall goal of biomimicry to provide sustainable solutions. If it is deemed that the design needs further tweaking, then one can journey back through the design loop to re-assess the design challenge, and proceed to the DISCOVER stage in order to further explore other organism strategies, or attempt to incorporate more Life's Principles in order to remediate any shortcomings.

The next section provides an illustration of the process discussed above by exploring the design of hydro-infrastructure in the Las Vegas Valley. It identifies patterns among the functions, structures, and characteristics of past and present human hydro-infrastructure in order to propose an alternative and sustainable hydro-infrastructure based on principles of biomimicry. This discussion will highlight attempts by human societies to design hydro-infrastructures that respect nature, and instances in which human benefits alone were the primary consideration.

CHAPTER 3

DISTILL HYDRO-INFRASTRUCTURE

The distillation stage serves as the starting point within the design challenge. This section will attempt to UNDERSTAND the challenge through the identification of social indicators, environmental responses and performance factors. The IDENTIFICATION OF COMPONENTS will deconstruct the design challenge by assessing patterns within current goals and objectives that can be interpreted into functional objectives performed throughout nature. Lastly, the components will be INTERPRETED INTO FUNCTIONS that can be translated into biological terminology at the discover stage.

Understand the Challenge

This section will attempt to UNDERSTAND the problem through a historical analysis of hydro-infrastructure and culminates with an overview of modern concerns. Due to time constraints, this paper limits its search to literature, scholarly journals and databases, and government reports, but it is suggested that a multi-disciplinary team be assembled in order to provide discrete responses for most biomimicry-led design processes.

History of Hydro-infrastructure

The availability and proximity of water resources transitioned from being desirable to being essential through the agricultural revolution due to a combination of factors (Bronson 1977). There was a shift to farming and herding to overcome periodic food scarcities (Hassan 2003). Water collection and distribution techniques were developed in response to growing populations, and the agricultural revolution reinforced trends such as subsistence, settlement, group size, economy, and social organization (Hassan 1977). Regional clusters resulted in increased populations within communities and the potential for sedentary life (Hassan 2003). Collectively, stationary agricultural resources placed a further demand for infrastructure that would reinforce this feedback loop (see figure 10).

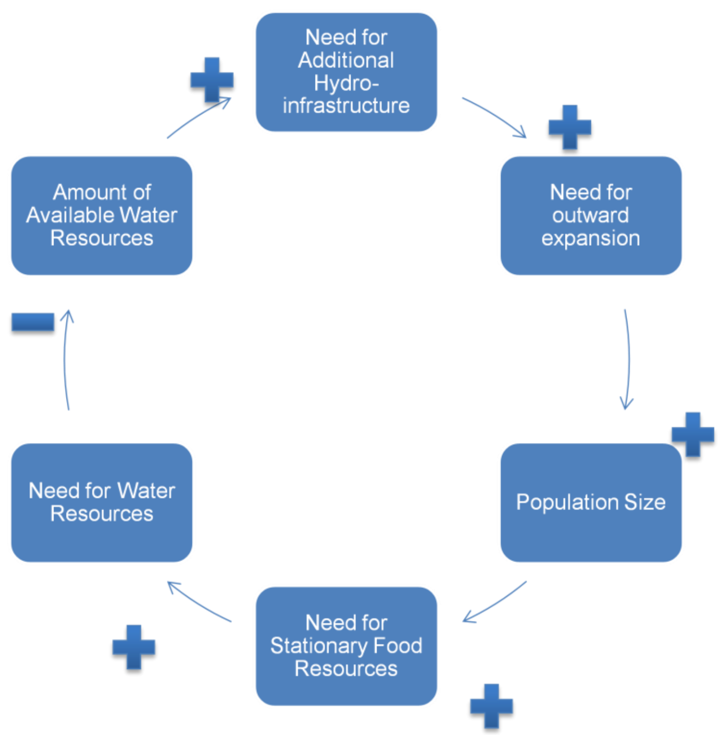

Figure 7 Social Hydro-infrastructure Feedback Loop

Pre-industrial Hydro-infrastructures

Water distribution systems began to emerge independently from 4000 to 1000 BCE. River communities, such as adjacent to the Tigris (Mesopotamia) and Indus (Mohenjo-Daro-Modern day Pakistan) Rivers, show evidence of primitive pipe systems and attempts to handle wastes by transporting them to local river streams. The Minoans were among the first to incorporate infrastructure comparable to that of modern day cities (Mays 2002). Minoan collection strategies included saving rainwater in rooftop reservoirs and cisterns while distribution was handled via aqueducts and tubular conduits, mostly consisting of terra cotta pipes (Mays 2002). Romans used gravity to distribute surface and groundwater stored in cisterns at higher elevations within the city and utilized both terra cotta and lead pipes (Mays 2002; Cech 2005). Archeologists credit Rome as the first city to develop concrete in order to further reinforce piping systems (Mays 2002).

Vitruvius and Frontius are the first to have documented strategic plans for abundant drinking water and sanitation infrastructures (Mays 2002). In Rome, Vitruvius suggested a hierarchical distribution by function via three uses: fountains and pools, baths, and drinking. In Pompeii and Nimes, Frontius was credited with designing layouts for distribution based on geography (Mays 2002). The typical Roman water distribution system (Fig. 11) included two steps: one being gravitational which served to collect water from surrounding ground and surface water sources; and, a pressure system which was used to distribute to the community. Drinking water was a byproduct of the aqueducts as the real purpose was to supply water for baths (Hauck 1988 in Mays 2002).

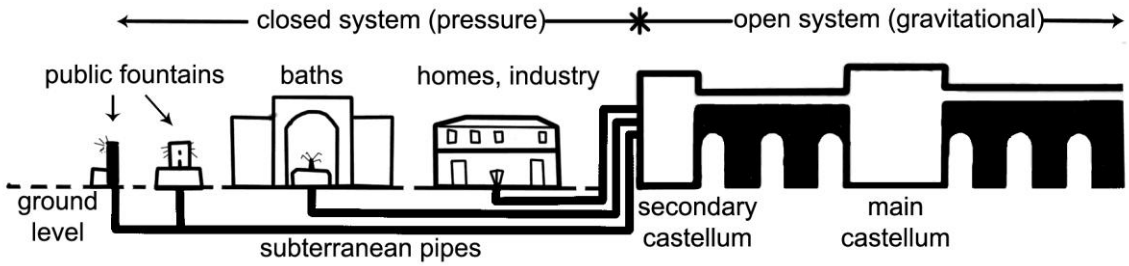

Figure 8 Roman Urban Water Distribution System (adapted from Mays 2002)

Diseases associated with human waste-contaminated drinking water were how nature controlled population growth, and a civilization's sophistication was judged by how it disposed of sewage (Cech 2005). Egyptians may have used the first chemical process for water treatment via alum, a white mineral salt, while Hindus in India boiled foul water to improve taste and clarity (Cech 2005). Hippocrates in Greece, in the first treatise on public hygiene, considered cyclic processes within the surrounding geography while promoting the concept of "healthy" drinking water via a cloth bag filter coined the "Hippocratic Sleeve" (Baker 1981), while Romans developed techniques such as sedimentation tanks, sand filters, and open aqueducts that allow ultraviolet (UV) rays to disinfect water (Cech 2005). Overflow water was used to flush drainage systems (Hodge 1992 in Mays 2002). The sewer systems in Rome were first created to control floods, and it was an afterthought to add sewage to these same pipes (Falkenmark 2004). Sanitation was largely forgotten throughout the Middle Ages as sewage was routinely dumped into streets and the Plague became rampant. In subsequent years Rome utilized open sewer systems down the center of its roadways and installed a vaulted sewer. Sanitary conditions in Paris remained intolerable until the mid-nineteenth century (Cech 2005).

Post-Industrial Hydro-infrastructure

Although modern municipal delivery systems are more elaborate than historic hydro-infrastructure, similar feats are accomplished by utilizing gravity to transport water whenever possible, maintaining reserves, and in general, returning wastewater to rivers downstream of the water supply areas (Cech 2005). In 1804, the first citywide, municipal water treatment plant was installed in Scotland and was instrumental in providing clean water to everyone (Cech 2005). Initial sewer systems in London and Paris were primarily designed to handle storm water runoff, although Cholera epidemics throughout the 1850s forced sanitary sewage to be added soon thereafter (Cech 2005).

In the mid-nineteenth century, social drivers were in place for welfare-related infrastructure such as irrigation, sanitation, and flood control. Soon, these concerns expanded to include new water services such as protecting health, cleaning public streets, and fighting fires, thus requiring further infrastructure development (Meyer 1996). Science furthered technologies in water sanitation throughout subsequent decades while policy has furthered hydro-infrastructure development in recent years. In 1972 the U.S. Clean Water Act demanded all

U.S. cities have their own water treatment facility and in 1974, the U.S. Safe Water Act set the first regulations for providing drinkable water to everybody (U.S. EPA, Clean Water 2002). These standards created a political infrastructure for the regulation of water used by the public and are credited with the present-day structure of water and wastewater infrastructures (Cech 2005; Mays 2002).

Hydro-infrastructure Concerns

As mentioned above, many social, political, environmental and technological factors informed the hydro-infrastructure that exists today. Although human civilizations are more adept at managing water and wastewater today than at any other point in time, many concerns still plague the future of hydro-infrastructure including the availability of quality water, implications of the energy-water nexus and the overall operation and maintenance of current and future hydro-infrastructure.

Water Availability

Over one billion people lack reliable potable water, and over two billion people lack adequate sanitation (NWRI 2009). Supplying water to these people is cost prohibitive and today's model requires massive energy inputs from fossil fuels (WHO 2000). In 2002, half of the continental US experienced drought conditions that triggered water restrictions (U.S. EPA, Growing 2006). Even places across the country that had abundant rainfall faced water shortages (U.S. EPA, Growing 2006). Groundwater aquifers are being pumped down faster than they are naturally replenished in India, China, and the US (Pacific Institute 2002). A multitude of factors contribute to the availability of water, although population growth is often the primary culprit as it affects the costs of water infrastructure, the demand for water, and the efficiency of water delivery (U.S. EPA, Growing 2006).

As a response to concerns regarding drought related to population growth, humans adapt their consumption and conservation patterns. Hydro-infrastructure allows populations to be less aware of water consumption requirements for human activities as they were no longer required to migrate in order to subsist. In times of water scarcity conservation is often the leading prescription, and is achieved through a reduction in usage or need via efficiency measures, usually accomplished through the integration of technological innovations, water re-use programs and policy strategies (U.S. EPA, Growing 2006).

Incentives and policies attempt to regulate water consumption by determining direct end-user groups. Agriculture is responsible for 70% of water consumption worldwide, whereas the residential sector consumes approximately 10% of available water; however, the government considers the residential sector as providing the largest opportunity for reducing water usage as government subsidies give farmers little incentive to conserve (Kalogirou 2005). Water consumption issues often require state-to-state coordination as upstream water usage has consequences for those downstream in regards to quantity and quality. For over fifteen years, water rights have caused heated debates between states such as Alabama, Georgia and Florida, and states and provinces bordering the Great Lakes (EPA, Growth 2006). States dependent upon the Colorado River for water receive an established allotment according to the 1922

Colorado Compact. Arguments against this agreement maintain that it is outdated, and allotment numbers need to be readjusted to modern day population requirements. California maintains that their agriculture has depended on an allotment in excess of the Compact for decades, and so refused to concede to other Colorado Compact states. Subsequently, Arizona and Nevada have negotiated a bi-state share agreement that allows Nevada to pay the same rates as cities within Arizona and use surplus water that Arizona has banked (Mulroy).

Water Pollution

Over 40% of water bodies are considered to be polluted due to runoff from nonpoint sources, such as farm lands, construction sites and mining and timber operations, and from storm sewer overflows (Clarke 2002; U.S. EPA, Protecting 2004). Other pollution occurs simply through chemical deposits into the waste stream that are not processed via treatment plants, such as some pharmaceuticals and personal care products. For example, low levels of endocrine disrupting compounds (EDCs) from pharmaceuticals affect the human reproductive cycle, so more complete removal methods are required as they have been detected in surface water, drinking water, and influents and effluents of sewage treatment plants (Zhang 2008). Many pollution sources come from within the very hydro-infrastructure that was made to supply water to its consumers and include the addition of chemicals required to bring polluted water to satisfy quality standards (U.S. EPA, Protecting 2004; U.S. EPA Growing 2006). In order to counteract the effects of disinfectant chemicals on aquatic wildlife, further chemicals must be added, compounding further environmental and economic costs (MacCrehan 2005).

Water-Energy Nexus

Energy and water use are intrinsically linked as the reduction in consumption of one will result in a decrease of demand in the other (Thirstwell 2007; NRDC). However, additional resources reinforce the water and energy nexus through further water intensive processes, such as the quest for oil shale in order to secure independence from external suppliers of energy (Water Education Foundation 2009). The amount of energy consumed by the water and wastewater systems in the United States is equivalent to the entire residential energy demand for the state of California (NRDC). The Electric Power Research Institute acknowledges that water may be a limiting factor in providing access to electricity to over 2 billion people, and points to the coupling of water and energy as the most promising area for increasing water efficiency (EPRI, Power Production 2002). Other impacts of excessive water and energy consumption include water pollution, air pollution and global climate change (NRDC). These two variables, water and energy, often inform policy development as is evidenced by Leadership in Energy and Environmental Design (LEED) which promotes an improved building performance by focusing on variables that include energy savings and water efficiency (USGBC).

Operation and Maintenance

Although the last century has witnessed a wide range of technological improvements and strong clean water policies, human hydro-infrastructure in the

United States is reaching the end of its useful life and must be rehabilitated or replaced to sustain our commitments to clean water goals (Mays 2002, AWWA 2001). Sustainability agendas require an evaluation of current challenges within the existing infrastructure in order to create new alternative designs in order to replace or update current infrastructures. Drinking Water Utilities can expect to spend two trillion dollars over the next 20 years for building, operating, and maintaining wastewater and drinking facilities (USEPA Growing 2006). A great deal of this total investment focuses on current technology.

Alternative Hydro-infrastructure Approaches

The Pacific Institute suggests two paths can be taken in order to overhaul the current system: a hard path and a soft path (Pacific Institute 2002). The hard path is the current centralized design and the soft path is a hybrid of the hard complimented with decentralized facilities, efficient technologies, and human capital (Pacific Institute 2002). Decades of growth have allowed existing infrastructure to simply expand as funds permit and growth demands (Pacific Institute 1999). However, this gradualist approach usually further compounds leakage and breaks resulting in further water losses and increased costs (EPA, Growing 2006).

An alternative to the gradualist approach is a holistic approach. This soft path seeks to improve overall productivity of water rather than seek endless sources of new supply (Pacific Institute 2002). A soft path refers to nonstructural components of a comprehensive approach, including equitable access to water, incentives for efficient use, and public participation (Pacific Institute 2002).

Holistic technological strategies are critical to adopting sustainable hydro-infrastructure (UNEP 2008). Environmentally Sound Technologies (ESTs) are technologies that have significant potential over existing (UNEP 2008). Evaluation principles for these technologies include whether they “protect the environment, are less polluting, use resources in a sustainable manner, recycle or handle their wastes and products in a more environmentally way” (UNEP 2008, p. ???). These technologies are based on specific needs, and focus not just on individual technologies, but on whole systems, and provide centralized and decentralized processes as a basis (UNEP).

A watershed approach creates alliances between local, state, and federal levels by establishing ecological limits and boundaries instead of arbitrary political boundaries (EPA, Sustainable Infrastructure web page). It is then possible to establish a green infrastructure that addresses the connectivity between environmental, economic, and human health benefits (EPA, Sustainable Infrastructure web page). Strategies include source water management, water quality trading, onsite/decentralized wastewater management and smart growth strategies. Also considered are wet weather management strategies, such as Low Impact Development (LID) which include rain gardens, green roofs, bioswales and permeable paving (EPA, Green Infrastructure web page). Smart growth principles consider direct and indirect impacts on the environment and those that affect hydro-infrastructure include compact development, reduced impervious surfaces and improved water detention (EPA, Smart Growth web page).

Desalination of seawater, which refers to the removal of salt in order to make water drinkable, is becoming popular as many view the sea as an abundant resource (Ayhan 2010). However, conventional seawater desalination techniques such as reverse osmosis, thermal distillation, and electro-dialysis consume a large quantity of energy and thus are quite expensive (Ayhan 2010). Renewable technologies are rapidly emerging in order to support desalination efforts at larger scales and with reduced economic costs (Kalogirou 2005; Lopez 2008).

Future municipal hydro-infrastructure design decisions will undoubtedly consider adaptability to population growth, technological change over time, and cost limitations through an effective and efficient delivery of quality water. The next section will further distill comprehensive goals from several international plans that seek to develop sustainable hydro-infrastructures. These goals will be IDENTIFIED according to basic human components (or functions) in order to be INTERPRETED into biological functions.

Identify the Components

Humanity's primary requirement for water is for the same reason as any other organism: thirst. Other uses become secondary, or indirect, and include bathing, flushing of waste, and aesthetics. Historically, water has been seen as an abundant resource, so concerns often are not about running out of it, but rather simply, how to provide access to it. Population surges over recent decades, compounded with climate change issues, have brought the concern of water availability to the forefront, suggesting that prior hydro-infrastructure designs might not provide sustainable solutions for humans, freshwater species and ecosystems (Richter 2003).

Several international development plans have proposed goals that are dependent upon the creation of sustainable hydro-infrastructure. Managing water as a resource is no easy task, but water management requires a neutral organization with well-defined goals based on the well-being of all of humankind. Such plans can inspire individual countries, states, and municipalities to develop their own inclusive, humane plan, instead of pursuing self-interested plans that do not address common water problems. The following plans serve as the basis for determining water goals for human civilization.

The United Nation's Development Goals seek to halve the number of people that are without safe water supply (currently at 1.1 billion people), and halve the number of people without appropriate sanitation (currently at 2.4 billion), by 2015 (UNEP 2008). This organization sets forth the following guiding principles in order to accomplish this mission: acknowledge water as a finite resource, acknowledge the importance of public participation, require women to play a key role in provisioning, and acknowledge that water has economic value (UNEP 2008). In order to further support the United Nations (UN), the Netherlands established the Ministerial Declaration of The Hague on Water Security in the 21st Century (Pacific Institute 2002). This plan provides blueprints for how respective countries can satisfy the goals of the UN by addressing criteria that are relevant to their country (Pacific Institute 2002). These criteria include meeting basic water needs, securing the food supply, protecting ecosystems, sharing water resources, managing risks, valuing water, and governing water wisely (Pacific Institute 2002).

The success of ecological sustainability is dependent upon ecological considerations being at the forefront when determining water management goals rather than being treated as compliance factors (Richter 2003). Thus, the overarching goal for human society at all levels should be to develop plans for ensuring clean, safe, reliable water supplies for increasing populations while protecting fragile ecosystems (Cech 2005). Translating these design challenges into more distilled functions might include the following (at a minimum):

- Collect water
- Distribute water
- Process and treat water and waste-water

These human hydro-infrastructure components (functions) will now be expanded upon in more detail.

Collect Water

Human hydro-infrastructures rely on the collection of a dependable quantity of quality water throughout the year via rain and snowfall via streams and rivers and their respective reservoirs, groundwater sources, salt-water sources and water re-use opportunities (addressed as a conservation strategy). Managing water resources such as these has become difficult as climate change issues affect predictable supplies of water. Also, insufficient knowledge in translating urban stressors impact sustainable design and planning solutions (Van den Berg 2007). Water collection is addressed through hydro-infrastructure through centralized and decentralized systems while innovative technologies continue to improve and allow the collection of water from sources that were not previously feasible, such as the desalination of sea water.

Centralized systems are typically municipality-controlled and unique to human systems and consist of the collection of potable water, storm water, and wastewater. These systems are processed primarily through one central collection basin and are typically intended to prevent flooding. They contribute to an infrastructure that serves Combined Sewer Outlets (CSOs) where the sewage infrastructures combine and empty into a river downstream (Grigg 1986). Advantages are mostly associated with economies of scale as they allow water to be routed hundreds of miles in order to be treated, and then re-routed back to the community for use (Lens, Lettinga & Zeeman 2001).

Decentralized systems suggest smaller scale solutions in order to support resilience, as the failure of one piece is less likely to collapse the entire system. Site analyses can provide metrics in regards to the amount of water available for collection and dictate how a site is developed (LaGro 2008). For example, rainwater might be collected and stored via cisterns, other water sources might be distributed evenly instead of into one central bank, or else groundwater might be recharged. Decentralized hydro-infrastructure examples include green roofs, rainwater harvesting, redevelopment, porous pavement, rain gardens, and vegetated swales. Environmental benefits include filtering air pollutants, reducing energy demands, mitigating urban heat islands, and sequestering carbon while providing communities with aesthetic and natural resource benefits (EPA, Green Infrastructure web page).

Distribute Water

Civilizations once subsisted solely within the vicinity of a respective water source, but hydro-infrastructures have allowed the built environment to flourish just about anywhere as extensive distribution systems focus on the movement of water long distances to point source discharges. Although gravity and pressure-fed systems are consistent with natural systems and human hydro-infrastructure, modern hydro-infrastructure often includes pumps that require energy. This action has interrupted important hydrological functions and been detrimental to ecosystems that are dependent on groundwater, such as freshwater fish habitats (Pacific Institute 2002).

The repercussions of urban design practices on hydro-infrastructure are certain to be addressed in future developments. One study illustrates that infrastructure and pumping costs are more sensitive to lot size than any other factor (U.S. EPA, Growing 2006), meaning that population densities have a direct effect on the amount of water and energy consumed. Also, it is difficult to protect the quantity and quality of water supplies due to highly dispersed development that results in the conversion of woodland, meadowland and wetland to impermeable surfaces (U.S. EPA, Protecting 2004). Low density requires longer pipes resulting in leakage and higher transmission costs in addition to higher operation and maintenance investment (U.S. EPA, Growing 2006). Two factors determining leakage are system pressure and length, both of which are required in low density communities (U.S. EPA, Growing 2006). Increasing development densities also allows current infrastructures to be upgraded instead of expanding already out of date piping systems. Collectively, these urban design patterns argue the elimination of large lots and dispersed planning and favor decentralized and dense communities.

Process and Treat Water and Waste-water

Potable water and wastewater is processed in order to eliminate transmission of disease and reduce contaminants to acceptable levels. The drinking water process includes protecting raw water at the source, creating intakes that capture the water to be processed, and subsequent sedimentation, filtration and chemical treatments, at which point the water is distributed back to the consumers (Cech 2005). Waste-water treatment plants typically utilize a three step process (Fig. 12) in order to eliminate contaminants that, generally, utilize gravity by being located at strategically placed geographic points within the city (Cech 2005). Collectively, these mandated designs dictate the incorporation of a centralized treatment system. Problems or concerns with any of these processes include high energy requirements, the use of toxic chemicals that are subsequently released into streams, the creation of waste in sludge that is often placed in landfills, and aging sewer lines that yield high volumes of storm-water that must be managed to prevent overflows of raw wastewater onto city streets (U.S. EPA, NPDES Wet Weather 2004).

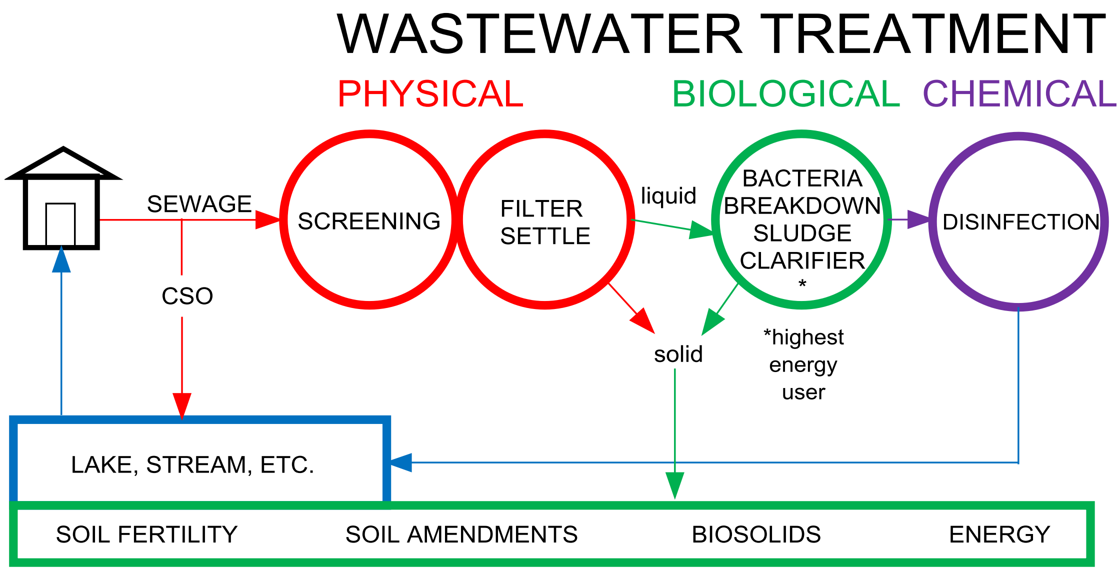

Figure 9 Conventional Wastewater Treatment Process

Modern sewage systems are moving away from the centralized design that has dominated the last century in preference for decentralized designs (Van Roon 2007). Decentralization refers to a system whose components are not located exclusively together. This strategy increases resilience as the collapse of one system does have as large an impact on other systems. One example of a decentralized design occurs within a constructed wetland which naturally breaks down molecules into common parts (Campbell 1999). Major advantages of this method are overcoming the intense chemical inputs, amount of energy required, and subsequent high costs of the current model. Additionally, these wetlands can offer tremendous value to those developments that do not have access to existing wastewater treatment facilities or those that require upgrading from septic tanks. Regardless, some communities have little choice in selecting a decentralized solution over the existing centralized infrastructure (Campbell 1999). Constructed wetlands achieve multi-functionality as they not only treat water, but offer aesthetics, support wildlife habitat and deter measures that otherwise might contribute to global warming (Campbell 1999). Perhaps, the largest challenges for these "wetlands" are operation and maintenance as they require a level of expertise over a typical "flush everything down the drain" system. Many installments have witnessed short-lived successes because of operation and maintenance failures.

Decentralized approaches often suggest the re-use of water (grey-water) for non-potable uses, such as toilet flushing or irrigation (Nolde 2000). This water may be obtained from low pollution sources such as washing machines or bath tubs and poses a minimal health risk (Nolde 2000). Black-water is also a re-use option although it has further health and social challenges. Social concerns regarding "healthy" water are diminishing as grey-water recycling plants have proven their efficiency and applicability in recent years. Hydro-infrastructure that is able to distinguish between high quality water for drinking and lower quality water for other purposes will have significant benefits (Nolde 2000).

The biological step (Fig. 12) illustrates that a tremendous amount of energy is required in order to break down sewage. Alternatives include energy recovery from wastewater, which turn organic matter into energy instead of simply being placed in landfills. One approach generates reliable electricity and power from biogas from anaerobic digesters through combined heat and power (CHP) (U.S. EPA, Energy and Water web page). Another technology occurs via

Microbial Fuel Cells (MFCs). This technology literally turns wastewater plants into power plants, and can create desalination plants without additional energy inputs. The energy available in wastewater is almost equal to the energy currently used for water infrastructure (Logan 2008).

The chemical step (Fig. 12) currently requires a tremendous amount of chemicals that are both toxic and costly. Green chemistry is a field receiving a great deal attention within the chemical product industry and the consumers who use them (U.S. EPA, green chemistry web page). The concept of green chemistry eliminates the use of hazardous reactants (potential water pollutants), conserves water and increases both the quality and quantity of pure water. Other factors include the use of benign chemicals at lower levels, unique catalysts, and the creation of closed-loop systems (National Academy of Sciences 2004).

The Las Vegas Valley Hydro-infrastructure System

Las Vegas must address similar conerns to those identified through the historical analysis of hydro-infrastructure such as explosive population growth, a prolonged drought, competition for the Colorado River's limited supplies with other basin states, and climate change (Pacific Institute 2007). Since Las Vegas's centralized design collects, distributes, and processes water and wastewater predominately in one central system, it is assumed in this paper that it succumbs to many of the problems aforementioned, such as high energy, chemical and water use necessary in order to treat its water.

One central organization, the Southern Nevada Water Authority (SNWA), manages and operates all facilities that pump, treat and deliver Colorado River water from Lake Mead to the Las Vegas Valley (WRA 2006). Ninety percent of Las Vegas' water comes from the Colorado River and ten percent comes from groundwater aquifers (WRA 2006). Las Vegas is limited to 300,000 acre-feet (AF) per year in consumptive use from the Colorado River due to the Colorado Compact, so it depends on return flow credits in order have access to surplus water (SNWA 2009; WRA 2006). The SNWA reclaims all of its wastewater through return flow credits or direct reuse (SNWA 2009). The SNWA is pursuing both ground and surface water supplies across the state that could potentially provide an additional 200,000 AF (SNWA 2009; WRA 2006).

The City of Las Vegas operates its own wastewater agency, participates in regional planning activities related to flood control, prevention of erosion, and the preservation of wetlands along the Las Vegas Wash (City of Las Vegas 2005). The City of Las Vegas supports the use of the municipal sewer system over private septic systems for fear of groundwater contamination (City of Las Vegas 2005). However, the City provides direct reuse water through several facilities throughout the valley that support power plants and golf courses. One of the most recent reuse facilities is capable of providing over 10,000 acre-feet/year (AFY) (City of Las Vegas 2005). The city is obligated to provide an extensive network of wastewater collection lines to all new subdivisions (City of Las Vegas 2005).

Historically, storm water run-off was handled via dispersed washes throughout the valley that culminated at Lake Mead (City of Las Vegas 2005). Development throughout the 1970s began to take a toll on these washes, and over 300 miles of storm drains and 60 detention basins have been installed (City of Las Vegas 2005). Over the next 25 years these numbers are expected to double in order to support growth (City of Las Vegas 2005). The purpose of these basins is to manage storm runoff using predetermined flow rates (City of Las Vegas 2005). A problem with Las Vegas' hydro-infrastructure occurs through its combined sewer outlets (CSOs). These have a limited capacity during seasonal floods and allow waste to be diluted during intense storm events instead of processed. In flood conditions, the sewage is released downstream, further contaminating the ecosystem.

The Pacific Institute (2007) states that water agencies have placed too much emphasis on return flow credits over indoor efficiency measures and have sacrificed the following opportunities:

- Reducing energy and chemical costs associated with pumping, treating, and transporting water and wastewater.
- Reducing energy-related greenhouse gas emissions.
- Saving the customer money over the life of those improvements through reductions in energy, water, and wastewater bills.
- Permitting more people to be served with the same volume of water, without affecting return flows.

• Reducing dependence on water sources vulnerable to drought and political conflict.

• Delaying or eliminating the need for significant capital investment to expand conveyance and treatment infrastructure.

The efforts of this biomimicry process model seek to address Las Vegas' water needs within the Las Vegas watershed in order to eliminate the need to tap into water sources that extend hundreds of miles away, as is being proposed by the SNWA. This thesis seeks to offer innovative designs that contribute to the overall management of water and waste-water. The water components (functions) of collect, distribute and process/treat will now be interpreted into biological functions according to the taxonomy chart provided by the Biomimicry Institute.

Interpret Functions

The UNDERSTAND stage provided a general overview of historical approaches towards hydro-infrastructure design, and compiled modern concerns and alternative approaches. The IDENTIFY stage distilled patterns among sustainable hydro-infrastructure goals and proposed several basic components (functions) that are required in order to achieve respective goals. The INTERPRET stage seeks to interpret these functions into biological functions.

The Biomimicry Institute's taxonomy tool assists in the identification and translation of human design functions into biological functions (Fig. 9) by asking "how would nature do this?" The ultimate goal is to move away from any predetermined ideas of what a design is supposed to do, and get to the heart of the design challenge. Some human functions may not translate easily into nature. In this case the designer must determine whether they are asking the right question. Perhaps either the function needs to be distilled further into subsets of functions, or nature may not perform that function in the same manner as humans. If a collection of biological functions are required to achieve a goal, then the designer might be required to assemble multiple strategies into a more complex design.

To use the taxonomy chart, first ask what the design needs to do. Try to extract functional words in the form of verbs and extend them outward within the chart. A successful query will undoubtedly expedite future stages throughout this process, although an unsuccessful query does not mean the designer will not find organism strategies within Ask Nature or other searches. These functions should be considered interdependent and cooperative.

Table 2 utilizes the taxonomy chart in order to interpret the pre-determined components (functions) of the previous step. It can be seen that “collect and distribute water” translate seamlessly, however the “wastewater” component results in a large number of possible interpretations. Two possible conclusions can be drawn from this result: one, that nature does not “treat” water or waste-water in the same manner as humans do; and/or; two, the component requires further research through the distillation process. The next stage compares human and organism functional strategies against Life’s Principles and will provide further insight as to how “waste-water” should be addressed by the biomimicry process.

Table 2 Taxonomy Interpretation

IDENTIFIED COMPONENT	INTERPRETED FUNCTION (via taxonomy chart)
Collect water	Capture liquid
Distribute water	Distribute liquid
Process and treat water/waste-water	Chemically break down compounds
	Physically break down abiotic and biotic materials
	Provide ecosystem services: regulate hydrological flows, generate soil/renew fertility, detoxify/purify water/waste, control sediment, regulate water storage, cycle nutrients
	Protect from abiotic/biotic factors

CHAPTER 4

DISCOVER ORGANISM STRATEGIES

The DISCOVER step suggests that the designer compile an extensive list of possible organisms to be used as references for inspiration. Additional intuitive analyses are performed on each strategy according to potential applications within the built environment and to determine underlying Life's Principles within each respective strategy. Life's Principles identification is not intended to be an arduous process, but merely an organizing strategy to help discover patterns at a later stage.

The Biomimicry Institute's Ask Nature website and scholarly journal databases were used to compile a breadth of organisms. Evaluation criteria had to be developed to distinguish the most relevant organisms, and these criteria are design challenge dependent. For example, a wide array of organism collection strategies exists for the collection of water as vapor, or humidity. It was deemed that as novel as these may be, was most likely not pertinent to this design challenge. The INTERPRETED functions serve as a starting point for keyword searches, but intuition and literature review are encouraged as part of relevant searches.

Collect and Distribute Water

The over-riding goal for the design challenge is to "ensure clean, safe, reliable water supplies" and this translates into "collecting" and "distributing" water. The function "store water" has been found to offer added depth to the organism strategy search, and has been included within the Discover Organism

Strategy Grid (Appendix A). Interconnected functions such as these are expected, so intuition is encouraged when compiling organism strategies. Storage is often represented as the repercussion of collection, and is most pertinent in climates, such as the desert, where one must conserve water. Distribution is purely how to get water from point “A” to “B,” although ultimately it assumes collection and other functions as well.

Appendix A compiles a comprehensive list of organism strategies related to the collection and distribution of water juxtaposed against the current human hydro-infrastructure (within the first row). Ask Nature is fairly thorough in providing information that can be transferred to this grid, such as assessing the ecosystem in which the organism resides and the specific strategy the organism performs. Noting the ecosystem sometimes helps deduce patterns, but is not always essential. The second set of columns support the initial brainstorm of a conceptual design. It is determined whether a form or process was utilized by the organism, and how this strategy might translate into the built environment, whether as a product or part of a system.

Appendix B provides a chance to brainstorm to what degree each organism strategy accomplishes each respective LP. The LPs that begin to receive the most checks illustrate organism strategies that offer strengths to a conceptual design. The goal of a thorough analysis is to deduce LPs within the current human hydro-infrastructure that have compiled negative marks and spot organism strategies that have positive marks. These are the niche opportunities which will be discussed in greater detail in the EMULATE stage, which culminates in conceptual design.

“Waste” Water

The current human hydro-infrastructure that consists of the treatment of water and wastewater is dissimilar to anything in nature, as “waste equals food” in nature. The omission of the word “waste” from nature’s vocabulary illustrates a tremendous disconnect between how humans and nature design. A further analysis of all the parts within water and wastewater treatment would be essential to a complete analysis. In this manner, the Las Vegas water system also requires a much more thorough analysis in regards to its processing and treating of water and waste-water. Options in this case are to continue through the process and propose an alternative hydro-infrastructure that manages waste water as a wetland does, and how that might integrate within the existing hydro-infrastructure of Las Vegas. Also, a more thorough analysis could distill further individual components and propose biomimetic designs that could be assembled as a system in order to co-exist with the current hydro-infrastructure.

A further distillation IDENTIFYs some of the challenges within water treatment to include (Fig. 12):

1. How to reduce the amount of energy used
2. How to reduce the use of toxic chemicals

A further distillation in order to INTERPRET these challenges into functions might include:

1. How is nature energy efficient? Or how does nature mix liquid?

2. How does nature filter? Or how does nature self-clean?

Ask Nature provides some existing biomimicry technologies for these functions that are already on the market within the water treatment industry. One example includes a water mixer produced by Pax that mimics the spiral shape of bull kelp (Fig. 13). This efficient shape mixes water in a manner that reduces the amount of chemical inputs while using less energy.

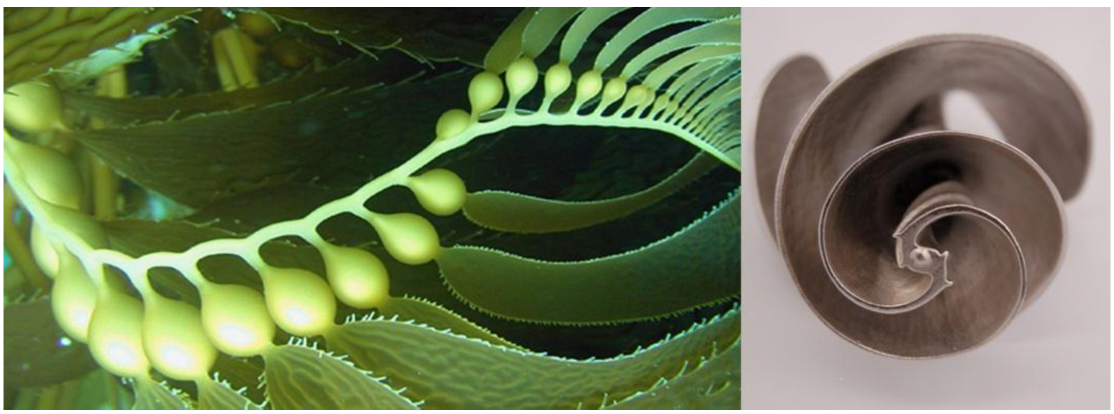

Figure 10 Kelp Spiral Flow (Menjou 2008) & Pax Mixer (Pax 2008)

This next section recognizes patterns between both human hydro-infrastructure and organism strategies in order to discover niches. These niches will become the basis for the conceptual design which will propose an amalgamation of water collection, distribution, and treatment systems based on how nature would design.

CHAPTER 5

EMULATE

The Emulate stage seeks to recognize PATTERNS within the organism strategy grid (Appendix A & B) in order to determine NICHES that will become the basis of the CONCEPTUAL DESIGN. Niches will be cross-referenced with relevant functions and various scales of application. The niches might either require a conceptual design in order to envision possible applications, be products that are currently being developed, or already exist on the market.

Patterns

Patterns to note are LPs that received a “No” within the “current human hydro-infrastructure row” (Appendix B). One can now proceed down those columns and ascertain what organism strategies, if any, achieve that respective LP. The primary LPs that cross-reference between the hydro-infrastructure and organism strategies include DECENTRALIZED AND DISTRIBUTED, FREE ENERGY, AND BENIGN MANUFACTURING (Appendix B & C).

- DECENTRALIZED AND DISTRIBUTED: As deduced in the hydro-infrastructure analysis, most municipal water systems, including the Las Vegas system, are centralized, meaning all collection, distribution and processing predominately depends on one central processing center. For this reason, the dominant underlying principle within the conceptual design will be a DECENTRALIZED AND DISTRIBUTED model, consistent with nature’s ecosystem models of peat lands and wetlands.

- FREE ENERGY AND BENIGN MANUFACTURING: Both energy and the use of expensive and toxic chemicals have been illustrated as concerns within the water and wastewater treatment industry. These same systems release a byproduct of their process that includes high level nutrient and chemical effluent and sludge that could be captured as an energy source. Nature's examples do not harm any life in the process, do not require toxic substances, and do not require high energy inputs.

In order to address the above mentioned LPs, how organisms utilize the respective LP while accomplishing a respective function is of interest. This can be categorized by either form or process (Appendices A and C). Forms include grooves, channels, hinges, root-like functions, high surface to volume ratios, logarithmic spiral shapes, and a lack of right angles. Processes include capillary action, water adhesion properties, hydrophilic/hydrophobic reactions, and electro-osmotic flow. The aforementioned forms and processes will now be applied at various scales relevant to Las Vegas' hydro-infrastructure.

Niches

Niches can now be suggested according to recognized patterns. In order to support a decentralized and distributed conceptual design, a combination of forms and processes will be assembled in various manners at different scales. Scales to be addressed include small, community and large (Fig. 14). Small scale refers to a design that can stand on its own, perhaps as an element that might be integrated within a single building or site. The community scale suggests either the integration of multiple strategies, or a single strategy that seeks to address multiple families or structures. Large scale seeks to support the whole of a municipality, city or state through a comprehensive system strategy.

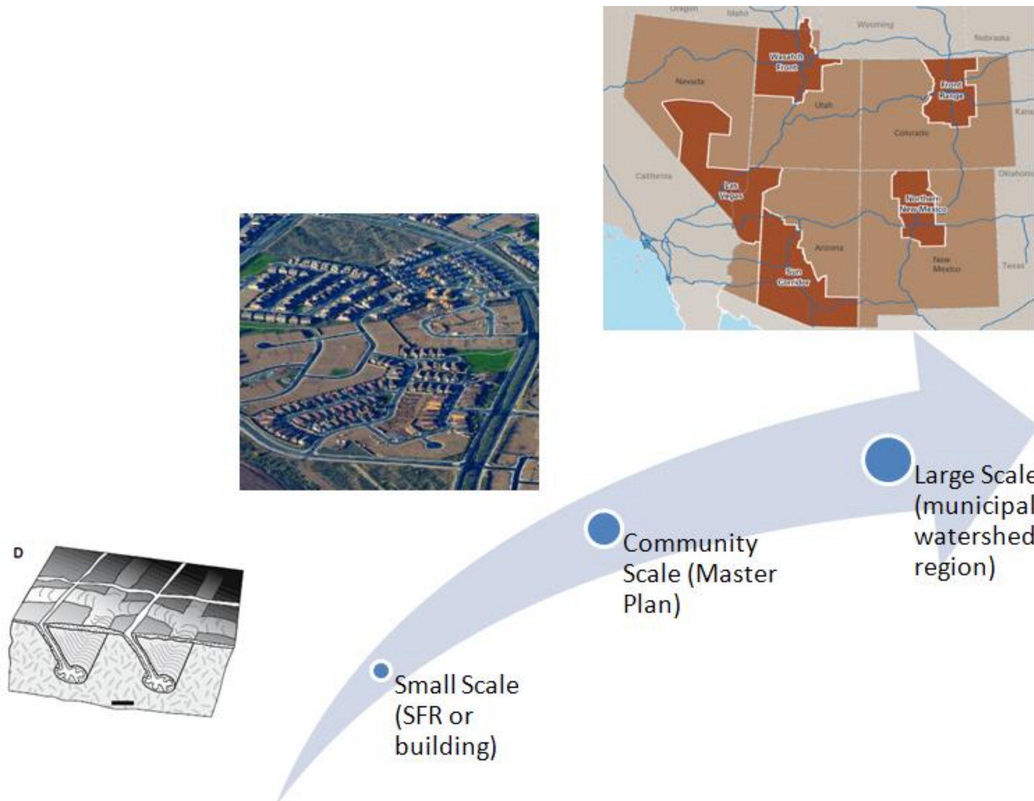

Figure 11 Scale Integration (Sherbrooke 2007, Brookings Institution 2008)

Conceptual Design

This analysis determines that the current centralized system must transition to a decentralized and distributed model. A combination of existing sustainable alternative hydro-infrastructure strategies, such as a constructed wetland and existing biomimetic products, can be considered for this transition (Appendix C). The conceptual design might inspire future products by expanding upon “discovered” organism strategies such as the horned lizard’s form and the processes it uses to collect and distribute water (Fig. 15). Image D of Figure 15 can be translated into a direct engineered product that collects and distributes water using capillary action (free energy).

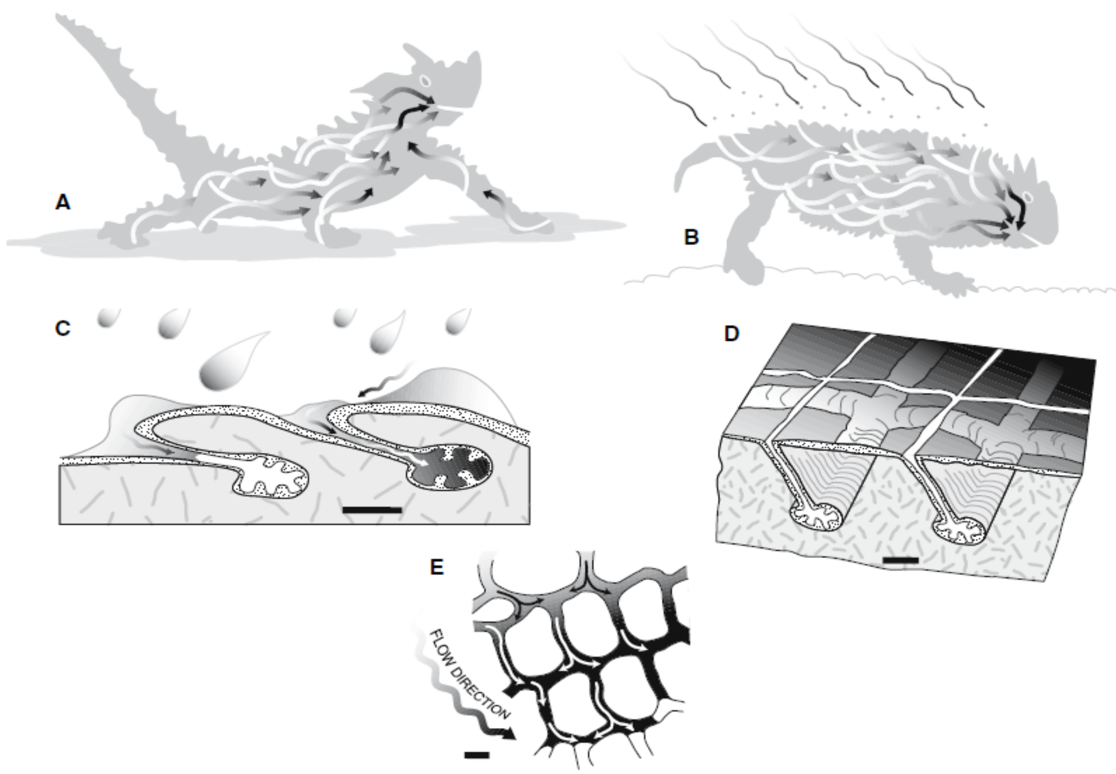

Figure 12 Horned Lizard Water Collection and Distribution (Sherbrooke 2007)

A combination of such products can be utilized to support a decentralized and distributed model while being integrating into an existing centralized system. Figure 16 illustrates that a six thousand square foot constructed wetland could feasibly support two hundred and eighty single family residential units (SFRs). A large-scale model might support an inter-connected network system throughout the Las Vegas Valley.

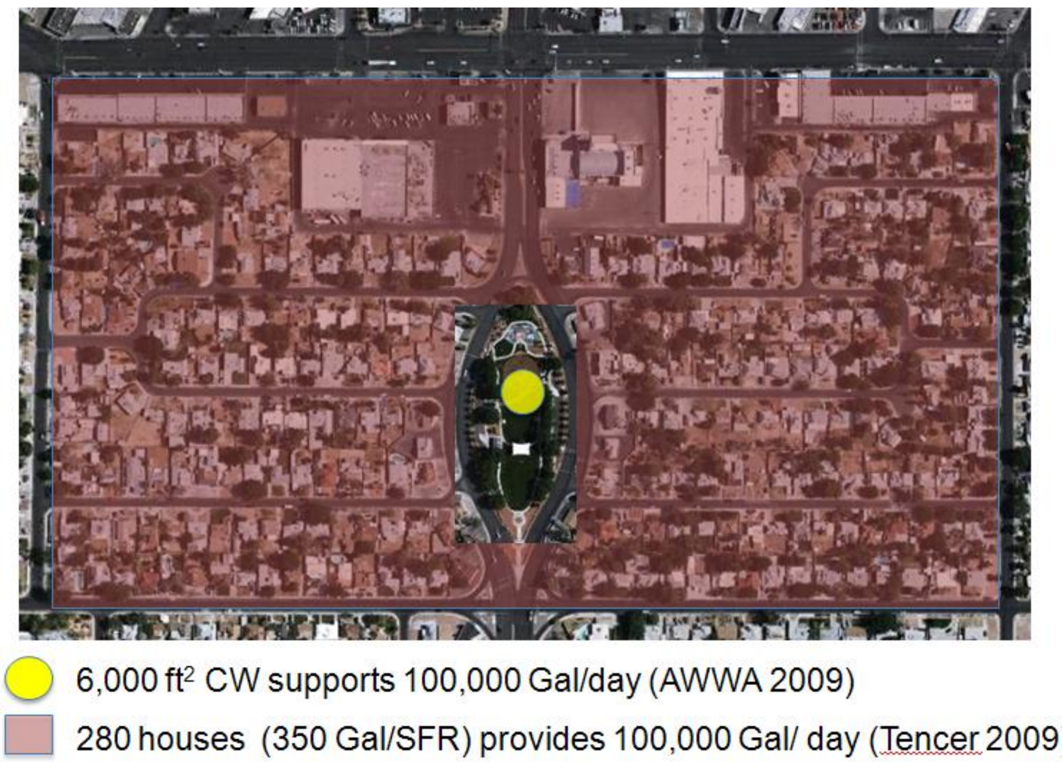

Figure 13 Circle Park, Las Vegas, NV (Google Earth 2009)

In order to accomplish the goal of creating a sustainable alternative hydro-infrastructure, additional Life's Principles must also be considered and are included under the umbrella principles “life adapts and evolves” and “life creates conditions conducive to life” (Appendix B and Figure 10). “Adapt and evolve” requires feedback loops that respond to disturbances, as “life is in a constant state of non-equilibrium.” The response is resilient as other principles translate into operational simplicity and redundancy.

The conceptual design will “create conditions to life” by not expanding the footprint of the existing infrastructure (optimize not maximize), and fostering cooperative relationships by simply being a good neighbor. These strategies might include increasing feedback loops by considering the implications of any proposed design on the community through public participation and education.

CHAPTER 6

EVALUATE

The evaluation stage establishes a feedback loop in the design process model in order to re-assess criteria within the initial design challenge that is relevant to the conceptual design. Additional passes through the design model might provide insight into the improvements offered by the proposed design (over the existing conditions or approach), whether it is more or less harmful than current practices, and whether the incorporation of more LPs could strengthen the concept and improve the level of sustainability. A pre-feasibility analysis is not pertinent at this time as this is a hypothetical exercise, but one can see where factors such as budget, and technological and social constraints can inform decisions to move forward with the conceptual design into either further research or production. Various development stages might include the design stage, an engineering stage (if development of a product is being attempted), a construction stage and a post-construction evaluation stage.

CHAPTER 7

CONCLUSION

Biomimicry offers a new approach to the integration of nature into design by directly mimicking organism functional strategies that are grounded in sustainable principles. This paper demonstrates how a “living” design process model based upon an ecosystem functional cycle and principles of biomimicry can support the built environment design process. This “living” design process model is illustrated through an alternative proposal to the existing hydro-infrastructure system within the Las Vegas Valley.

The historical analysis revealed that throughout time humans have sought safe, clean and plentiful water. Although technology has improved, the world still struggles to achieve these water goals, and will continue to do so over the coming decades due to concerns related to climate change and population growth. Several sustainable alternative approaches to achieving sustainable water goals have been proposed that seek both social and environmental sustainability. These goals serve as the foundation for establishing goals and distilling individual components necessary to support Las Vegas’ hydro-infrastructure. These basic components (functions) translated into the collection, distribution and processing or treating of water and waste-water.

The applied design process demonstrated that the overall design of the Las Vegas Valley hydro-infrastructure is not consistent with how nature would manage water. Nature is decentralized and distributed where the current system is centralized. Two approaches have been suggested in order to offer an alternative to the existing hydro-infrastructure system: an integrated decentralized master plan of the Valley; and individual biomimicry-inspired components. The organisms strategies discovered illustrate how this sustainable model requires minimal energy and chemical inputs, adapts and evolves along with population growth, and supports biodiversity. Future research could expand upon the “City As An Organism” conceptual design by performing density studies that relate building capacities to available land (parks, parking lots, etc.) and by further conceptualizing collection, distribution and water processing hybrids.

Obstacles that stand in the way of the built environment achieving sustainability through the integration of nature-based innovations include “fit” within a current machine-based model, overcoming preconceived mindsets (such as prioritizing population growth at all costs), and progressing past an idea to application. Janine Benyus (1997) mentions that even biologists need to re-educate themselves, as they have been previously taught to extract from nature, not learn from nature. Further research might further expand upon the design process model that was proposed in this paper in order for it to adapt and evolve, to further challenge the validity of LPs and biomimicry as a science and further explore manners to increase feedback loops within the industry. Ideally, ideas would not be considered proprietary, but rather communal in order to create further sustainable projects. Ask Nature has been one incredible step in this direction, but requires the continuing input of researchers and professionals in order to be successful.

Implications of this research extend across political and technological boundaries. Biomimicry shows how one can learn "from" nature in order to propose both ecological and technological solutions to human problems. Technology can assist the distillation at the front end in order to move beyond preconceived notions of a design challenge through urban ecology-based research that assesses patterns between social and environmental data sets (Pickett 2001). An increase in research and development can be expected to support human innovations at the nanoscale, the scale at which nature predominately designs. Innovations that have risen out of nanoscale technology include self-cleaning films that mimic the lotus leaf (Biomimicry Institute 2008). Perhaps the most important area requiring effort to further a sustainability agenda based on nature's principles is instituting a mindset shift (Meadows 2004). Current mindsets suggest that technology alone will solve current design concerns (Van der Ryn and Cowan 1996). One way to combat this predominately anthropocentric view might be to point out the failures of the current system and place people with the new paradigm in places of public visibility and power.

APPENDIX A

DISCOVER ORGANISMS

Function								
Organism	Context/ Ecosystem	Strategy	Form	Process	Strategy translated to Built Environment	standalone PRODUCT	part of a SYSTEM	on the MARKET?
Manage Water								
Current Human Hydro-infrastructure	Las Vegas Valley	To provide a high quantity of quality water	Closed loop system	YES	Create a system that can collect, process, distribute, and further process water via one centralized process.	NO	YES	YES
Collect Water								
Thorny Devil Lizard & Texas Horned Lizard[1, 2]	Desert	Microscopic structure of scales enable capillary action that moves water from feet or chest to mouth. The key is the hinges and channels within the scales.	Grooves, Channels, & Hinges	water hydrogen bonds & capillary action	collection and delivery of water from multiple sources, deployable structures, irrigation	YES	YES	NO
Marsh Crab[3]	Near water	Tufts on legs draw water from mud by hydrophilic setae	Root-like, high S/V ratio	Hydrophilic setae	Drawing water from mud	YES	YES	NO
Plants[4]	Desert & other	Roots extract water from soil	Roots, high S/V ratio	Negative pressure/high surface area	low energy water removal	YES	YES	NO
Earthworm[5]	Moist Soil	Negative charge forms on body and attracts postive charged water molecules where friction would be greatest.	High S/V ratio	electro-osmotic flow for lubrication	collect water from soil into a layer that creates anti-adhering surfaces	YES	YES	NO
Bromeliads[6]		Capture water in a storage tank via hydrophobic leaf surfaces & hydrophilic hairs	Rosette channels water	hydrophobic/ hydrophilic interactions	Water capture on buildings	YES	YES	NO
Cloud Forests[7] (dense track of evergreens)		comb water from clouds onto needles (fog drip)	Height & Canopy	NO	increase water yield & restoring ecosystem services	NO	YES	NO
Peatlands, Wetlands[8]		Act as shallow reservoirs, attenuate water in wet conditions, & release in dry conditions	Structure	NO	Absorb periodic flood waters	YES	YES	NO
Amponotus Colbopsis ant[9]		Carries water droplets that adhere to body	Hairs, high S/V ratio	adhesion & the act of removal	Flood control/water removal	YES	YES	NO
Lotus (plant)[10]	Muddy habitats	Extensive folding and a roughened microscale surface deter solids from adhering while repelling water to rinse	nanoscale bumps	super hydrophobic	Self cleaning surfaces that route water	YES	YES	Lotus Clay Roofing Tiles
Venus Flower Basket (Sponge)		water adheres to sponge walls (water cohesivenss)	Water through hollow cylinder	adhesion & removal	flood control/water removal	YES	YES	NO

Store Water									
Ice plant[11]		Epidermal Bladder Cells (Surface cells) store water within photosynthetically active tissues	NO	Ion exchange	Surface collector & storage of water while collecting solar	YES	YES	NO
Hottentot bread plant[12]		store water in a large, underground corky tuber (swollen roots)	YES	NO	underground storage and pipes that resist leaks	YES	YES	NO
Saguaro Cactus (collection)	Desert	Specialized cells activate in presence of water and allow for rapid root growth and extend laterally inches from ground surface	YES	YES	2-way irrigation systems (collection & dispersal), rain sensor - collection devices that disperse according to rain events, ribs expand for storage	YES	YES	NO
Distribute Water									
xylem/phloem (vascular bundle)[13, 14]	Circulatory system inside plants	conduits in plants transport water from soil to leaves through a pulling force when water evaporate at the surface of leaves/ also mechanical strength	YES	Capillary action/ negative pressure gradient	leak proof membrane	siphon/ pump	power generation, water utilities	NO
aortic valve (heart)[15]	Circulatory system inside animals	tissue (valve) expands under high pressures having elastic properties	YES	NO	backflow-built in resilience	valve	YES, as a component	NO
blood vessels[16]	Circulatory system inside animals	branching patterns allow less direct connections to heart, create primary/secondary vessels...Also, elastic walls support smooth pumping by expanding upon pressure, placing a smaller load on the heart	YES	NO	plumbing systems to increase resilience, less demand on system	pipe design	yes	NO
Clams[17]	Water	Siphons inhale and exhale due to their flexibility & extensibility	YES	NO	flexible pipes resist leakage/bursting, manage stormwater overflow in sewer systems	pipe design	yes	NO
Earthworm[17]	Moist Soil	Flexible cylinders-allow considerable volume of body to pass through small space	YES	NO	flexible piping	pipe design	yes	NO

APPENDIX B

EVALUATE LIFE'S PRINCIPLES

		Life Adapts and Evolves &									Creates Conditions Conducive to Life							
		Simple Common Building Blocks	Shape Rather than Material	Free Energy	Learns and Imitates	Antenna, Signal, Response	Cross-pollination and Mutation	Diverse	Decentralized and Distributed	Redundant	Multi-functional Design	Fits Form to Function	Recycles all Materials	Fosters Cooperative Relationships	Self-organizing	Life-friendly materials	Water-based Chemistry	Self-assembly
Function		Locally Attuned & Responsive;Resourceful &			Integrates cyclic processes; Feedback			Resilient			Optimizes Rather than Maximizes			Leverages Interdependence		Benign Manufacturing		
Organism	**Strategy**																	
Manage Water																		
Current Human Hydro-infrastructure	To provide a high quantity of quality water			N					N				N			N	N	N
Collect Water																		
Thorny Devil Lizard & Texas Horned Lizard[1, 2]	Microscopic structure of scales enable capillary action that moves water from feet or chest to mouth. The key is the hinges and channels within the scales.		Y	Y		Y				Y	Y	Y				Y	Y	
Marsh Crab[3]	Tufts on legs draw water from mud by hydrophilic setae			Y		Y				Y	Y	Y				Y	Y	
Plants[4]	Roots extract water from soil			Y		Y				Y	Y	Y				Y	Y	
Earthworm[5]	Negative charge forms on body and attracts postive charged water molecules where friction would be greatest.			Y		Y				Y	Y	Y				Y	Y	
Bromeliads[6]	Capture water in a storage tank via hydrophobic leaf surfaces & hydrophilic hairs		Y	Y		Y				Y	Y	Y		Y		Y	Y	
Cloud Forests[7] (dense track of evergreens)	comb water from clouds onto needles (fog drip)		Y	Y		Y			Y	Y	Y	Y		Y	Y	Y	Y	
Peatlands, Wetlands[8]	Act as shallow reservoirs, attenuate water in wet conditions, & release in dry conditions					Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	
Amponotus Colbopsis ant[9]	Carries water droplets that adhere to body			Y		Y				Y	Y	Y				Y	Y	
Lotus (plant)[10]	Extensive folding and a roughened microscale surface deter solids from adhering while repelling water to rinse			Y					Y	Y	Y	Y				Y	Y	
Venus Flower Basket (Sponge)	water adheres to sponge walls (water cohesivenss)		Y	Y						Y	Y	Y				Y	Y	
Store Water																		
Ice plant[11]	Epidermal Bladder Cells (Surface cells) store water within photosynthetically active tissues			Y		Y				Y	Y	Y				Y	Y	

Hottentot bread plant[12]	store water in a large, underground corky tuber (swollen roots)			Y		Y				Y	Y	Y				Y	Y	
Saguaro Cactus (collection)	Specialized cells activate in presence of water and allow for rapid root growth and extend laterally inches from ground surface			Y		Y				Y	Y	Y				Y	Y	
	Distribute Water																	
xylem/phloem (vascular bundle)[13, 14]	conduits in plants transport water from soil to leaves through a pulling force when water evaporate at the surface of leaves/ also mechanical strength			Y		Y				Y	Y	Y				Y	Y	
aortic valve (heart)[15]	tissue (valve) expands under high pressures having elastic properties			Y		Y						Y				Y	Y	
blood vessels[16]	branching patterns allow less direct connections to heart, create primary/secondary vessels...Also, elastic walls support smooth pumping by expanding upon pressure, placing a smaller load on the heart		Y	Y		Y				Y	Y	Y			Y	Y	Y	
Clams[17]	Siphons inhale and exhale due to their flexibility & extensibility		Y	Y		Y						Y				Y	Y	
Earthworm[17]	Flexible cylinders-allow considerable volume of body to pass through small space		Y	Y		Y						Y				Y	Y	

REFERENCES FOR APPENDIX B

1 Sherbrooke, W. C. (2004). Integumental water movement and rate of water ingestion during rain harvesting in the Texas horned lizard, Phrynosoma cornutum. *Amphibia-Reptilia, 25(1),* 29-39.

2 Sherbrooke, W. C., Scardino, A. J., de Nys, R., & Schwarzkopf, L. (2007). Functional morphology of scale hinges used to transport water: convergent drinking adaptations in desert lizards (Moloch horridus and Phrynosoma cornutum). *Zoomorphology, 126(2),* 89-102.

3 Hogarth, P. J. (1999). The biology of mangroves. *Oxford University Press, 228*.

4 Vogel, Steven. (2003). Comparative Biomechanics: Life's Physical World. Princeton: Princeton University Press.

5 Zu, Y. Q., Yan, Y. Y. (2006). Numerical simulation of electroosmotic flow near earthworm surface. *Journal of Bionic Engineering, 3*, 179-186.

6 Pierce, S., Maxwell, K., Griffiths, H., & Winter, K. (2001). Hydrophobic trichome layers and epicuticular wax powders in Bromeliaceae. *American Journal of Botany, 88(8)*, 1371-1389.

7 Baskin, Y. (1997). *The Work of Nature: How The Diversity Of Life Sustains Us*. Island Press.

8 Rydin, H, & Jeglum, J. K. (2006). *The Biology of Peatlands.* Oxford University Press.

9 Federle, W., Maschwitz, U.,& Fiala, B. (1998). The two-partner ant-plant system of Camponotus (Colobopsis) sp.1 and Macaranga puncticulata (Euphorbiaceae): Natural history of the exceptional ant partner. *Insectes Soc.,* 45 (1), 1-16.

10 Neinhuis, C., & Barthlott, W. (1997). Characterization and distribution of water- repellent, self-cleaning plant surfaces. *Annals of Botany, 79(6),* 667-677.

11 Agarie S, Shimoda T, Shimizu Y, Baumann K, Sunagawa H, Kondo A, Ueno O, Nakahara T, Nose A, & Cushman JC. (2007). Salt tolerance, salt accumulation, and ionic homeostasis in an epidermal bladder-cell-less mutant of the common ice plant Mesembryanthemum crystallinum. *Journal of Experimental Biology. 58(8),* 1957-1967.

12 Attenborough, D. (1995). *The Private Life of Plants: A Natural History of Plant Behavior.* London: BBC Books.

13 Tyree, Melvin T. (2003). Plant hydraulics: The ascent of water. *Nature. 423(6943),* 923-923.

14 Cutler, DF. (2005). Design in plants. In Collins, MW, Atherton, MA, & Bryant, JA (Eds.), *Nature and Design, 95-124.* Southampton, Boston: WIT Press.

15 Bellhouse, B. J., & Bellhouse, F. H. (1968). Mechanism of closure of the aortic valve. *Nature, 217(5123),* 86-87.

16 Chalmers, G. W. G., Gosline, J. M., & Lillie, M. A. (1999). The hydrophobicity of vertebrate elastins. *Journal of Experimental Biology, 202(3),* 301-314.

17 Foy, Sally, & Oxford Scientific Films. (1982). *The Grand Design: Form and Colour in Animals.* Lingfield, Surrey, U.K.: BLA Publishing Limited for J.M.Dent & Sons Ltd, Aldine House, London.

APPENDIX C

PATTERN RECOGNITION AND NICHE DISCOVERY

Patterns		
LPs not meant by hydro-infrastructure	Organism strategies that accomplish these LPs by function	
Free Energy - Gravity is often utilized; however, a tremendous amount of energy is required in processing and pumping	Forms:	Grooves, channels, hinges, root-like function, high surface to volume ratio, logarithmic spiral shape, processes line inner side of hollow cylinder, gradual transitions (reducing friction),
	Processes:	Capillary action, Natural water adhesion properties, hydrophobic/hydrophillic rxns, electro-osmotic flow
Benign Manufacturing	This category is, generally, inherent in all organisms as nature does not produce waste. Nature produces and uses toxins locally and in small quantities that doesn't harm food & water supplies.	
Decentralized & Distributed	Form and Process work together and are benefitted by a diversity of organisms within the ecosystem	
Redundancy	Supports resiliency through many forms and processes performing the same function.	

	Niches			
	Organism mechanisms that might be further explored into the conceptual design in order to support decentralized systems that incorporate into the existing hydro-infrastructure			
	Small Scale	Small Scale	Community Scale	Large Scale
Collect	Roof tops can be designed to route water through grooves much like the desert lizard does. Gravity can be utilized on rooftops as water is routed into a mini-wetland processor*.	A weed-fabric like membrane place under landscape rock can also be designed as water collector which through micro-tubules (horned lizard) and can either route water against gravity via capillary pressure or utilizing gravity to the mini-wetland processor*.	The incorporation of constructed wetlands throughout the valley, increase the amount of neighborhood parks, increase biodiversity	Storm water basins include root like forms that increase S/V ratio and include materials that adhere water, thus slowing down flooding & requiring less footprint. (Marsh Crab Setae, roots)
Distribute	rain sensor activates 2-way irrigation systems that switch from distributing water to collecting	Branching piping systems (increase resilience during breaks) and lessen pressure (circulatory systems)	An underlying membrane on sports fields that has extensive microtubules that can remove water	Pipes that resist leaks by swelling (tubers)
Store	Storage tanks that expand to make room for water storage during rain events (Saguaro)	Photosynthetic water bladder cells for heating water, or collecting energy while collecting water (EBC in ice plant)	The CWs are decentralized and distributed with other CWs for storage purposes and serve to provide a balanced water supply for respective neighborhoods	Increase resilience by reducing the demand on the Colorado River (all states)
Process	Self cleaning roof tiles in place of asphalt shingles- product currently on market (lotus leaf)	*A mini-wetland processor suggest a living machine of sorts that uses natural filtering strategies while ensuring high quality water with no added chemical, no energy inputs.	Decentralized constructed wetlands might support determined neighborhood scales & be located within local parks or parking lots.	Take the capacity load off of the existing centralized treatment plant reducing the amount of energy & chemical inputs

REFERENCES

American Institute of Architects. (2009). *The architecture student's handbook of professional practice (14th ed.).* Hoboken, N.J.: Wiley.

American Water Works Association. (2001). *Dawn of the replacement era: Reinvesting in drinking water infrastructure.* Retrieved from http://www.eweb.org/Public/documents/water/awwaReplacement.pdf

American Water Works Association. (2009). *Water Use Statistics.* Retrieved from http://www.drinktap.org/consumerdnn/Home/WaterInformation/Conservation/WaterUseStatistics/tabid/85/ Default.aspx

Ayhan, T., & Al Madani, H. (2010). Feasibilty study of renewable energy powered seawater desalination technology using natural vacuum technique. *Renewable Energy, 35*(2), 506-514.

Baker, M. N., & Taras, M. J. (1981). *The quest for pure water: The history of water purification from the earliest records to the twentieth century* (2nd ed.). American Water Works Association.

Benyus, J. M. (1997). *Biomimicry : Innovation inspired by nature* (1st ed.). New York: Morrow.

The Biomimicry Institute. (2008). *The Biomimicry Approach*. Retrieved from http://www.biomimicryinstitute.org/downloads/BiomimicryApproachVennv1.pdf

---. (2008). *Biomimicry Curricula*. Retrieved from http://www.biomimicryinstitute.org/education/university/curricula.html

---. (2008). *Biomimicry Taxonomy*. Retrieved from http://www.asknature.org/article/view/biomimicry_taxonomy

---. (2008). *Design Spiral*. Retrieved from http://www.biomimicryinstitute.org/downloads/DesignSpirals.pdf

---. (2008). *Entry Portal*. Retrieved from http://www.biomimicry.net

---. (2008). *Life's Principles*. Retrieved from http://www.biomimicryinstitute.org/downloads/LP_list.pdf

Biswas, A. K. (1970). *History of hydrology*. Amsterdam: North-Holland Pub. Co.

Boyd, Charles W., & Chairman of the Water Service Committee, City of Frederick. (2004). *"Got water?" presentation to the 7th annual southeast* *watershed roundtable, Nashville, Tennessee* (October 30). Retrieved from http://www.watershed-assistance.net/pdf/resources/boyd.pdf

Brandon, Peter S., P.L. Lombardi, & V. Bentivegna (Eds.). (1997). *Evaluation of the built environment for sustainability.* London; New York: E & FN Spon.

Bronson, Bennet. (1977). The Earliest Farming: Demography as Cause and Consequence. *Origins of Agriculture.* Ed. Charles A. Reed. The Hague: Mouton, 23-48.

Brookings Institution. (2008). *Mountain Megas: America's Newest Metropolitan Places and a Federal Partnership to Help Them Prosper.* Washington: Brookings Institution. Retrieved from http://www.brookings.edu/reports/2008/0720_mountainmegas_sarzynski.aspx

Campbell, C. S., & Ogden, M. (1999). *Constructed wetlands in the sustainable landscape*. New York: Wiley.

Cech, T. V. (2005). *Principles of water resources: History, development, management, and policy* (2nd ed.). Hoboken, NJ: John Wiley & Sons.

City of Las Vegas. (2005). *The City of Las Vegas Water Element of the Las Vegas 2020 Master Plan.* Retrieved from http://www.lasvegasnevada.gov/files/Water_Element.pdf

Clarke, E. L. (2002). *Water resources: Issues and perspectives*. Hauppauge, N.Y.: Nova Science Publishers.

Cromwell, John E. and Joel B. Smith and Roberts S. Arucher. (2007). *Implications of Climate Change for Urban Water Utilities*. Washington: Association of Metropolitan Water Agencies.

Edwards, P.N. in Misa, T. J., Brey, P., & Feenberg, A. (2003). *Modernity and technology*. Cambridge, Mass.: MIT Press.

EPRI. (2002). *Water and sustainability: U.S. electricity consumption for water supply and treatment -- the next half century (Vol. 4).* Retrieved from http://mydocs.epri.com/docs/public/000000000001006787.pdf.

---. (2002). *Water & Sustainability: U.S. Water Consumption for Power Production - The Next Half Century (Vol. 3, 2002)*. Concord, CA: EPRI. Retrieved from http://mydocs.epri.com/docs/public/000000000001006786.pdf.

Falkenmark, M., & Rockstrom, J. (2004). *Balancing water for humans and nature :The new approach in ecohydrology*. London; Sterling, VA: Earthscan.

Grant, J. (2006). *Planning the good community: New urbanism in theory and practice*. London; New York: Routledge.

Gruber, P. (2007). The signs of life in architecture. *Comparative Biochemistry and Physiology - Part A: Molecular & Integrative Physiology, 146(4, Supplement 1), S136.* Retrieved from http://stacks.iop.org/1748-3190/3/023001

Gunderson, L. H., & Holling, C. S. (2002). *Panarchy: Understanding transformations in human and natural systems*. Washington, DC: Island Press.

Hassan, Fekri A. (1977). The Dynamics of Agricultural Origins in Palestine: A Theoretical Model. In Reed, Charles A. (Ed.), *Origins of Agriculture.* The Hague: Mouton, 589-609.

---. (2003). Water for Peace: A Cultural Strategy. *History and Future of Shared Resources.* UNESCO, Divison of Water Sciences. Retrieved from http://unesdoc.unesco.org/images/0013/001332/133286e.pdf.

Interface. (2008). *Biomimicry.* Retrieved from http://www.interfaceglobal.com/Sustainability/Sustainability-in-Action/Biomimicry.aspx

Kalogirou, S. A. (2005). Seawater desalination using renewable energy sources. *Progress in Energy and Combustion Science, 31*(3), 242-281.

Kellert, S. R., Heerwagen, J., & Mador, M. (2008). *Biophilic design :The theory, science, and practice of bringing buildings to life*. Hoboken, N.J.: Wiley.

LaGro, J. A. (2008). *Site analysis :A contextual approach to sustainable land planning and site design (2nd ed.).* Hoboken, N.J.: John Wiley & Sons.

Leedy, P. D., & Ormrod, J. E. (2005). *Practical research: Planning and design (8th ed.).* Upper Saddle River, N.J.: Prentice Hall.

Lens, Piet, Lettinga, Gatze, & Zeeman, Grietje. (2001). *Decentralised Sanitation and Reuse: Concepts, systems and implementation.* London: IWA Publishing.

Logan, B.E., Call, D., Cheng, S., Hamelers, H.V.M., Sleutels, T.H.J.A., Jeremiasse, A.W., & Rozendal, R. A. (2008). Microbial electrolysis cells for high yield hydrogen gas production from organic matter. *Environ. Sci. Technol, 42*, 8630.

Lopez-Gunn, Elena, & Llamas, Manuel Ramon. (2008). Re-thinking water scarcity: Can science and technology solve the global water crisis? *Natural Resources Forum,* 32(3), 228-238.

MacCrehan, W. A., Bedner, M., & Helz, G. R. (2005). Making chlorine greener: Performance of alternative dechlorination agents in wastewater. *Chemosphere, 60*(3), 381-388.

MacNeish, R. S. (1992). *The origins of agriculture and settled life* (1st ed.). Norman: University of Oklahoma Press.

Mays, L. W. (2002). *Urban water supply handbook*. New York: McGraw-Hill.

McClelland, P. D. (1997). *Sowing modernity: America's first agricultural revolution*. Ithaca, N.Y.: Cornell University Press.

McHarg, I. L., & American Museum of Natural History. (1971). *Design with Nature*. Garden City, N.Y.: Published for the American Museum of Natural History by the Natural History Press.

Menjou, Chris. (2008). *Kelp Spiral Flow.* Retrieved from http://www.asknature.org/media/image/174

Meyer, W. B. (1996). *Human impact on the earth*. Cambridge; New York: Cambridge University Press.

Milburn, Lee-Anne S., & Brown, Robert D. (2003). The Relationship between Research and Design in Landscape Architecture. *Landscape and Urban Planning,* 64.1-2, 47-66.

Mulroy, Pat. (2008). *Diving in the Deep End:Help Water Agencies Address Climate Change. March 12, 2010.* http://www.brookings.edu/papers/2008/0207_climate_change_mulroy_opp08.aspx

Mulroy, Pat. (2007)."Overcoming the Traditions That Divide Us - Tomorrow's Reliable Water Supply Dependent Upon Partnerships." WRCA's California Colloquium on Water lecture series (May 1, 2007). Retrieved from <http://blogs.lib.berkeley.edu/wrca.php/2007/05/14/pat_mulory_video_california_colloquium_o>.

National Resources Defense Council. (2009). *Energy Down the Drain: The Hidden Costs of California’s Water Supply.* Retrieved from http://www.nrdc.org/water/conservation/edrain/execsum.asp

National Water Research Institute. (2009). *The 2009 Clark Laureate Lecture.* Retrieved from www.nwri-usa.org/pdfs/2009ClarkeLecture.pdf

Nolde, E. (2000). Greywater Reuse Systems for Toilet Flushing in Multi-Storey Buildings – Over Ten Years Experience in Berlin. *Urban Water, 1*(4), 275-284.

Orr, H. A. (1998). The population genetics of adaptation: The distribution of factors fixed during adaptive evolution. *Evolution, 52*(4), 935-949. Retrieved from http://www.jstor.org/stable/2411226

Pacific Institute. (2007). *Hidden Oasis: Water Conservation and Efficiency in Las Vegas.* Retrieved from http://www.pacinst.org/reports/las_vegas/hidden_oasis.pdf

Pacific Institute for Studies in Development, Environment, and Security. (2002). *The World's Water: The Biennial Report on Freshwater Resources.* Washington, D.C.: Island Press.

Pax Scientific. (2008). *Pax Mixing Impeller.* Retrieved from http://www.asknature.org/product/gallery/1a119e978284900963298a0aac59a120

Pickett, S. T. A., Cadenasso, M.L., Grove, J. M., Nilon, C.H., Pouyat, R. V., Zipperer, W.C., and Costanza, R. (2001). Urban Ecological Systems: Linking Terrestrial Ecological,Physical, and Socioeconomic Components of Metropolitan Areas. *Annual Review of Ecology and Systematics,* 32, 127–157

Reed, C. A. (1977). *Origins of agriculture*. The Hague: Mouton.

Richter, B. D., Mathews, R., Harrison, D. L., & Wigington, R. (2003). Ecologically sustainable water management: Managing river flows for ecological integrity. *Ecological Applications, 13*(1), 206-224. Retrieved from http://www.jstor.org/stable/3099960

Roseland, M. (2000). Sustainable community development: integrating environmental, economic and social objectives. *Progress in Planning,* 54, 73–132.

Sherbrooke, W. C. and Scardino, A. J., de Nys, R., Schwarzkopf, L. (2007). Functional morphology of scale hinges used to transport water: convergent drinking adaptations in desert lizards. *Zoomorphology.* 126(2), 89-102.

Southern Nevada Water Authority (SNWA). (2009). *The SNWA Water Resource Portfolio.* Retrieved from http://www.snwa.com/assets/pdf/wr_plan_chapter2.pdf

Stokes, J.R., and A. Horvath. (2009). Energy and air emission effects of water supply. *Environmental Science Technology, 43*, 2680.

Tencer, Yoram (2009). Establishment of a constructed wetland in extreme dryland. *Environmental Science and Pollution Research*, 16(7), 862-875.

Thirstwell, Gweneth M. and Chandra A. Madramootoo and Isobel W. Heathcote. (2007). Energy-water Nexus: Energy Use in the Municipal, Industrial, and Agricultural Water Sectors (October 2, 2007). Washington D.C.: Canada-US Water Conference, sponsored by Policy Research Initiative of Canada and the Woodrow Wilson Institute. Retrieved from http://www.policyresearch.gc.ca/doclib/Thirlwell_energy_water_nexus.pdf.

Thirlwell, Gweneth M., Madramootoo, Chandra A., & Heathcote, Isobel W. (2007). Retrieved from http://www.policyresearch.gc.ca/doclib/Thirlwell_energy_water_nexus.pdf

Tsui, E. (1999). *Evolutionary architecture: Nature as a basis for design*. New York: John Wiley.

Tunstall, G. (2006). *Managing the building design process* (2nd ed.). Amsterdam; Boston: Butterworth-Heinemann, an imprint of Elsevier.

U. S. Environmental Protection Agency (EPA). (2002). *The Clean Water and Drinking Water Infrastructure Gap Analysis,* EPA-816-R-02-020. Retrieved from http://epa.gov/waterinfrastructure/pdfs/report_si_infrastructuregap.pdf.

---. (2009). *Environmental Benefits of Smart Growth.* Retrieved from http://www.epa.gov/smartgrowth/topics/eb.htm

---. (2009). *Managing Wet Weather with Green Infrastructure.* Retrieved from http://cfpub.epa.gov/npdes/greeninfrastructure/technology.cfm.

---. (2009). *Green Chemistry.* Retrieved from http://www.epa.gov/greenchemistry/pubs/basic_info.html.

---. (2006). *Growing Toward More Efficient Water use: Linking Development, Infrastructure, and Drinking Water Policies. EPA's Development, Community, and Environment Division (DCED).* Retrieved from http://www.epa.gov/dced/pdf/growing_water_use_efficiency.pdf.

---. (2007). *National Pollutant Discharge Elimination System (NPDES): Watershed-Based NPDES Permitting.* Retrieved from http://cfpub.epa.gov/npdes/wqbasedpermitting/wspermitting.cfm.

---. (2007). *National Pollutant Discharge Elimination System (NPDES): Wet Weather Discharges.* Retrieved from http://cfpub.epa.gov/npdes/wetweather.cfm?program_id=0.

---. (2004). *Protecting Water Resources with Smart Growth.* EPA's National Center for Environmental Publications. Retrieved from http://www.epa.gov/dced/pdf/waterresources_with_sg.pdf.

---. (2009). *Sustainable Infrastructure for Water and Wastewater: Energy and Water.* Retrieved from http://www.epa.gov/waterinfrastructure/bettermanagement_energy.html#basicone.

---. (2009). *Sustainable Infrastructure for Water and Wastewater: Watershed Approaches.* Retrieved from http://www.epa.gov/waterinfrastructure/watershedapproaches.html.

United States Green Building Council (USGBC). (2009). *What LEED is.* Retrieved from http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1988.

United Nations Environment Programme (UNEP). *(*2008). *Every drop counts.* Retrieved from http://www.unep.or.jp/ietc/publications/water_sanitation/everydropcounts/index.asp

University of Arizona. (1996). *Consumers Increasingly Use Bottled Water, Home Water Treatment Systems to Avoid Direct Tap Water.* Retrieved from http://ag.arizona.edu/AZWATER/arroyo/081botle.html.

Van Bueren, Ellen and Jitske de Jong. (2007). Establishing sustainability: policy successes and failures. *Building Research & Information*, 35(5), 543–55.

Van den Berg, AE, and T Hartig, H Staats. (2007). Preference for Nature in Urbanized Societies: Stress, Restoration, and the Pursuit of Sustainability. *Journal of Social Issues,* 63(1), 79-96.

Van der Ryn, Sim, & Cowan, Stuart. (1996). *Ecological design*. Washington, D.C.: Island Press.

Van Roon, M. (2007). Water localisation and reclamation: Steps towards low impact urban design and development. *Journal of Environmental Management, 83(4),* 437-447.

Water Education Foundation. (2009). *Colorado River Report: The Water-Energy Nexus in the Colorado River Basin.* Retrieved from http://www.watereducation.org/userfiles/RiverReport_Summer09_WEB.pdf

Water Infrastructure Network (WIN). (2001). *Water infrastructure now: Recommendations for clean and safe water in the 21st century*. Washington, D.C.: Water Infrastructure Network.

Webb, R. H. (2009). *The mojave desert :Ecosystem processes and sustainability*. Reno: University of Nevada Press.

Western Resource Advocates (WRA). (2006). *Water in the Urban Southwest: An Updated Analysis of Water Use in Albuquerque, Las Vegas and Tuscon.* Retrieved from http://www.westernresourceadvocates.org/media/pdf/FINAL%203%20City.pdf

World Health Organization (WHO) and United Nations Children's Fund (UNICEF). (2000). *Global Water Supply and Sanitation Assessment 2000 Report.* Retrieved from http://www.who.int/water_sanitation_health/monitoring/jmp2000.pdf.

Wunsche , Isabel. (2003). *Biological Metaphors in 20^{th}-Century Art and Design, YLEM: Artists Using Science & Technology, 8/23 (2003),* 4-10. Retrieved from <http://ylem.blueparticles.com/Journal/2003Iss08vol23.pdf>.

Yanarella, Ernest J., Levine, Richard S., Lancaster, Robert W. (2009). Green versus Sustainability. *Sustainability: The Journal of Record*, 2(5): 296-302.

Yeang, K. (1995). *Designing with nature :The ecological basis for architectural design*. New York: McGraw-Hill.

Zhang, Y., & Zhou, J. L. (2008). Occurrence and removal of endocrine disrupting chemicals in wastewater. *Chemosphere, 73*(5), 848-853.

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