BIOMIMICRY AND WETLANDS

P Dama-Fakir. A Dower, C Janisch, C O'Connor, D Otto, P Welz

WATER RESEARCH COMMISSION

TT 679/18

Biomimicry and Wetlands

Report to the
WATER RESEARCH COMMISSION

by

P DAMA-FAKIR, A DOWER, C JANISCH, C O'CONNOR, D OTTO and P WELZ
Golder Associates Africa
Biomimicry Institute of South Africa
Digby Wells Environmental
Cape Peninsula University of Technology

WRC Report No. TT 679/18

ISBN 978-0-6392-0037-8

August 2018

Obtainable from
Water Research Commission
Private Bag X03
GEZINA, 0031

orders@wrc.org.za or download from www.wrc.org.za

This report emanates from a project entitled *Biomimicry and Wetlands* (WRC project No K5/2096)

Printed in the Republic of South Africa

ACKNOWLEDGEMENTS

The authors would like to thank the Water Research Commission for the funding and their involvement in the project. We would also like to thank the Reference Group of the WRC Project K5/2096 for the assistance and the constructive discussions during the duration of the project. The committee consisted of the following:

Dr Valerie Naidoo	*Water Research Commission*
Dr John Zvimba	*Water Research Commission*
Mr Bonani Madikizela	*Water Research Commission*
Dr Stanley Liphadzi	*Water Research Commission*
Mr Craig Sheridan	*University of Witwatersrand*
Ms Ritva Mahlbauer	*BHP Billiton Energy Coal South Africa*
Ms Bernelle Verster	*Biomimicry South Africa*
Mr John Dini	*South Africa National Biodiversity Institute*
Mr Clifford LW Jones	*Rhodes University*
Mr Gary Marneweck	*Wetland Consulting Services*
Prof Chris Buckley	*University of KwaZulu-Natal*
Dr J A Wilsenach	*Virtual Consulting Engineers*
Dr Liz Day	*The Freshwater Consulting Group CC*
Mr Anton Linstrom	*Wet Earth*
Mr Donovan Kotze	*University of KwaZulu-Natal*

In addition to the members of the reference group, we would to thank Prof Stephanie Burton for her initial involvement and continued mentorship of staff at CPUT.

We would also like to thank the greater wetlands community, including SanParks, Working with Wetlands, Wetland Consulting services, Enviross and Spatial Ecological Consulting for their enthusiasm and sharing their experiences with the project team.

This page was deliberately left blank

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION AND OBJECTIVES

Biomimicry is defined as the learning from and subsequent emulation of nature to solve human problems, resulting in more sustainable designs. Natural wetlands provide ecosystem services including flood attenuation and water purification/waste treatment through nutrient absorption; this process has been emulated to some extent with constructed wetlands.

The purpose of the study is to demonstrate the Biomimicry methodology and apply it to water and wastewater treatment. This document includes an introduction to Biomimicry and a review of both constructed and natural wetlands.

2 APPROACH AND METHODOLOGY

The approach taken was as follows:

- Compile a review providing an introduction to Biomimicry and a review on existing knowledge on natural and constructed wetlands;
- Carry out a gap analysis, identifying areas of focus or applying the Biomimicry methodology;
- Encourage discussion sessions with multi-disciplinary teams in order to develop novel approaches to constructed wetland design and operations;
- Explore the feasibility of applying key biomimicry concepts in the design of constructed wetland and in natural wetland rehabilitation, through discussion sessions and workshops;
- Identify examples in nature that can be mimicked for water treatment applications (water treatment champions). Use the Biomimicry methodology to extract relevant information on these examples and publish this information in a user-friendly information tool;
- Reporting on findings of the post graduate investigations; and
- Recommending further investigations on innovative water treatment options identified during the course of the study.

3 BIOMIMICRY

3.1 What is Biomimicry?

Biomimicry is an inter-disciplinary approach to solving design challenges. Engineers, designers and architects work with biologists and ecologists to understand and emulate natural forms, processes and ecosystems.

Developing further bio-inspired products, processes and polices requires research and investment to move forward on areas of critical concern. Water treatment/purification is one such area of concern, and is the focus of this report. This report outlines the biomimicry process as developed by The Biomimicry Institute and The Biomimicry Guild and how it can be used to research water purification strategies, focussing on wetlands, in order to translate these ideas into potential water purification processes and systems. The aim is to use this process, together with research on natural wetlands and constructed wetlands to provide insight on opportunities for improving the design and performance of constructed wetlands for wastewater treatment.

3.2 The Biomimicry methodology

Whilst nature's models have been emulated by humans for centuries, the Biomimicry institute has formalised the methodology. The methodology presented here was summarised from the Biomimicry Guild website (Biomimicry 3.8, 2011) and compared to conventional engineering design methodology.

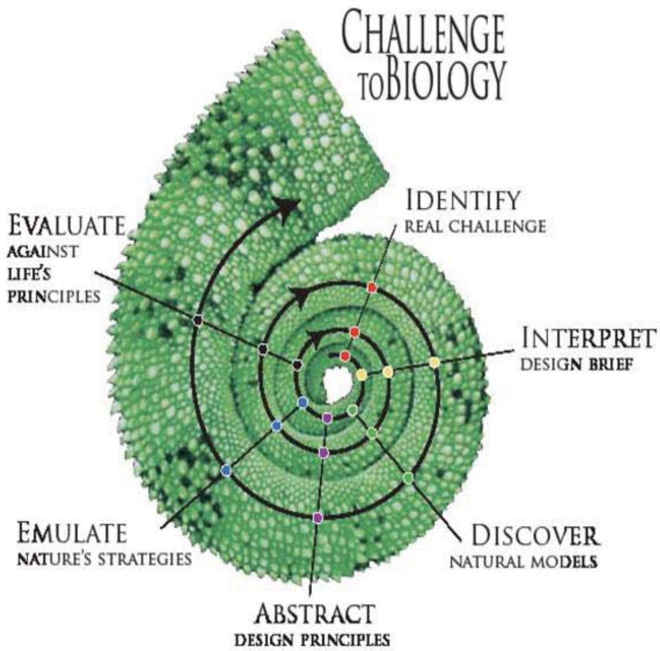


Figure 1: Representation of a design methodology (2009, Biomimicry Guild)

Table 1: Comparison between Biomimicry methodology and conventional design methodology

Step	Conventional Design	Biomimicry Methodology (2009, Biomimicry Guild)

IDENTIFY	• Scope of Work
	    ○ Design Brief
	• Basis of design
	    ○ Identifying inputs and outputs
		• Key questions:
		    ○ What are the core problems?
		    ○ What function do you need to accomplish?
		    ○ What do you want your design to do? (Not what do you want to design!!!)
		    ○ Why do you want your design to do that?
		• Specific to :
		    ○ Target market; and
		    ○ Location

INTERPRET	• Confirm Basis of design
	• Identify external factors influencing decision
	    ○ Long term effects;
	    ○ Project boundaries;
	    ○ Project limitations; and
	    ○ Legislation.
		• Biologize the question – translate design brief into “How does nature do this function?”
		• Or “How does nature NOT do this function?”
		• Habitat/location:
		    ○ Climatic conditions;
		    ○ Nutrient conditions;
		    ○ Social conditions; and
		    ○ Temporal conditions
		• Context:
		    ○ Project boundaries;
		    ○ Legislative requirements; and
		    ○ Project limitations

DISCOVER	• Available technologies:
	    ○ Proven technologies;
	    ○ Same / similar applications;
	    ○ Emerging technologies; and
	    ○ Discussions with suppliers and consumers.
		• Identify natures models which meet the functions identified;
		• Select champions – whose survival depends on this?
		• Look at habitat extremes; and
		• Brainstorm between engineers and biologists.

Step	Conventional Design	Biomimicry Methodology (2009, Biomimicry Guild)

ABSTRACT	• Short list options:
	  ○ Must meet with BoD requirements; and
	  ○ Consideration of context:
	    ▪ Skilled labour;
	    ▪ Access to chemicals, spares, etc.;
	    ▪ Climatic effects;
	    ▪ Land availability;
	    ▪ Legislative requirements; and
	    ▪ Budgetary constraints
		• Create taxonomy of life's challenges;
		• Select most relevant champions to meet design challenge; and
		• Abstract repeating successes and principles that achieve this success.

EMULATE	• Conceptual design:
	  ○ Equipment selection;
	  ○ Process flow diagram;
	  ○ Equipment sizing; and
	  ○ Cost estimates:
	    ▪ Capital; and
	    ▪ Operational.
		• Develop concepts and ideas;
		• Apply lessons learnt from natures teachers;
		• Mimic form:
		  ○ understand morphology (form and structure)
		• Mimic function:
		  ○ Understand biological processes
		• Mimic ecosystems:
		  ○ Understand interactions between organisms

EVALUAT	• Compare options:
	  ○ Legislative and environmental compliance;
	  ○ Reliability;
	  ○ Social impacts; and
	  ○ Operational and capital costs.
		• Evaluate against Life's Principles;
		• Restructure design brief if required; and
		• Identify further ways to improve design.

It can be concluded that while several similarities exist between the conventional and biomimicry design approaches, the fundamental difference is looking to nature's models for a solution to the design challenge. Another key aspect is ensuring that the design team focuses on the function that needs to be achieved rather than “What needs to be designed.” This requires a fundamental change in the way a designer approaches a problem.

The key to success is ensuring that the biologists and engineers are able to communicate in a language that they all understand and being able to translate principles observed in nature to applications that can be mimicked. This is a skill that is achieved with practice. Illustrations and models are often used in the biomimicry methodology to facilitate the communication process.

3.3 Biomimicry Life’s Principles

Life’s Principles are what biomimics use to drive and evaluate the sustainability and appropriateness of their designs. The Biomimicry Guild and The Biomimicry Institute, along with many partners, have studied, compiled, and distilled scientific research to create a collection of fundamental biological principles now known in biomimicry as Life’s Principles. Life’s Principles are intended to represent nature’s strategies for sustainability and resilience, that is, how nature has adapted and evolved to sustain life on earth for 3.85 billion years. They represent the overarching principles identified in all species surviving and thriving on Earth. Humans live and function within the same operating conditions as the other creatures living on Earth, so Life’s Principles provide important insights for us for resilience and sustainability. Life’s Principles also provide ***aspiration ideals*** and ***sustainable benchmarks*** (The Biomimicry Group, January 2011).

Life integrates and optimises these principles as a system to create conditions conducive to life. While one can apply or emulate each principle on its own, it is the *inclusion of all of them* in designs that fosters truly sustainable and resilient design.

Life’s Principles List and definitions (The Biomimicry Group, January 2011)

- **Be Resource (Material and Energy) Efficient:** Skillfully & conservatively take advantage of local resources & opportunities.
    - Use Multi-functional Design: Meet multiple needs with one elegant solution.
    - Use Low Energy Processes: Minimize energy consumption by reducing requisite temperatures, pressures, and/ or time for reactions.
    - Recycle All Materials: Keep all materials in a closed loop.
    - Fit Form to Function: Select for shape or pattern based on need.
- **Use Life friendly Chemistry:** Use chemistry that supports life processes.
    - Build Selectively with a Small Subset of Elements: Assemble relatively few elements in elegant ways.

Life's Principles List and definitions (The Biomimicry Group, January 2011)

  - Break Down Products into Benign Constituents: Use chemistry in which decomposition results in no harmful by-products.
  - Do Chemistry in Water: Use water as solvent.
- **Integrate Development with Growth:** Invest optimally in strategies that promote both development and growth.
  - Combine Modular and Nested Components: Fit multiple units within each other progressively from simple to complex.
  - Build from the Bottom Up: Assemble components one unit at a time.
  - Self-organize: Create conditions to allow components to interact in concert to move towards an enriched system.
- **Be Locally Attuned and Responsive:** Fit into and integrate with the surrounding environment.
  - Use Readily Available Materials and Energy: Build with abundant, accessible materials while harnessing freely available energy.
  - Cultivate Cooperative Relationships: Find value through win- win interactions.
  - Leverage Cyclic Processes: Take advantage of phenomena that repeat themselves.
  - Use Feedback Loops: Engage in cyclic information flows to modify a reaction appropriately.
- **Adapt to Changing Conditions:** Appropriately respond to dynamic contexts.
  - Maintain Integrity through Self-renewal: Persist by constantly adding energy and matter to heal and improve the system.
  - Embody Resilience through Variation, Redundancy and Decentralization: Maintain function following disturbance by incorporating a variety of duplicate forms, processes or systems that are not located exclusively together.
  - Incorporate Diversity: Include multiple forms, processes or systems to meet a functional need.
- **Evolve to Survive:** Continually incorporate and embody information to ensure enduring performance.
  - Replicate Strategies that Work: Repeat successful approaches.
  - Integrate the Unexpected: Incorporate mistakes in ways that can lead to new forms and functions.
  - Reshuffle Information: Exchange and alter information to create new options.

Whilst achieving all of the above principles may not be practically possible, the principles provide an excellent evaluation tool that can be used to highlight improvements, possible design flaws and identify potential improvements to the design. The project team used these principles to identify processes in nature that can be successfully mimicked.

3.4 Discussion

The success/failure of a constructed wetland design inspired by biomimicry will depend on a range of variables – the understanding and successful mimicry of key functions and design principles, as well as consideration of context, are just some of the important factors. Context refers to the external factors influencing the wetland, i.e. location, topography, climate, etc.

The biomimicry framework provides a robust process for ensuring that nature is incorporated as both model and measure, by looking to biology in the scoping, creating and evaluation phases of the design. The use of evaluation tools like Life's Principles enables a further test on the resilience and sustainability of the design.

In the case of constructed wetlands, the biomimicry process can be used in a range of different ways, but deep biomimicry requires a comprehensive understanding of aspects such as the wetland system, functions, critical components and interdependence of the various components. It requires interdisciplinary experienced teams with a thorough understanding of the ecological and engineering complexities to be able to successfully mimic natural wetlands in a constructed wetland. Each locality and application will have unique features that will need to be considered. However, it is very likely that there are a set of key principles for the successful functioning of wetlands within specific contexts that can be abstracted and can help to inform the design process with a greater likelihood of success. Many constructed wetlands have been implemented successfully to meet the required functions. Some may still require significant maintenance, energy input, or otherwise. Can a design be emulated that enables a self-regulating constructed wetland that runs on minimal resource input by relying more on abstracted design principles from natural processes? Are there some key principles for the success of a complex ecosystem that can be abstracted and applied to the improvement of constructed wetlands? How can the biomimicry process assist in improving the design of constructed wetlands? How can the biomimicry process assist in identifying other potential opportunities for wastewater treatment?

4 BIOMIMICRY FOR WASTEWATER TREATMENT

IDENTIFY

At its most basic the challenge presented asks: "How does life provide safe clean water for reuse (i.e. safe for drinking, bathing, irrigation or release to environment in general)?" This indicates a need for water that has limited chemical (organic/inorganic) or biological contamination.

INTERPRET

For this stage we assume an initial contaminated body of water that needs to be made safe for drinking/bathing/irrigation/return to aquatic ecosystems. It is assumed that there are three main types of wastewaters to be treated –

i. Organic contamination (e.g. sewage, industrial – farming, food processing, paper)
ii. Inorganic contamination (e.g. industrial/mining wastewater)
iii. Biological – pathogens and toxins (e.g. sewage, industrial wastewater, medical waste)

DISCOVER

All life needs safe water to live and thrive. Contaminated water supplies have negative impacts on organisms that depend on water for life. Over millions of years organisms have evolved and adapted to specific challenges to obtain safe water. As a result, there is an infinite variety of potential avenues to investigate for water purification and the removal of various contaminants. However, when adaptation is not possible there are a few general ways that organisms use for creating safer drinking water. For the purpose of this literature review we have summarised these as: ecosystem technologies (which include wetlands), flow technologies and filtering technologies. A decision was taken not to focus on specific contaminants at this stage.

The review focused on the following:

- Ecosystem technologies;
- Filtration technologies; and
- Flow management technologies.

Similarly, this type of review can be done for other key water treatment functions for critical wastewaters/contaminated waters in South Africa.

5 CASE STUDIES

This section includes an overview of existing relevant biomimicry research and existing biomimetic water treatment products, processes and systems – from ecosystem technologies (including constructed wetlands) to other filtration technologies and also flow technologies. Examples and case studies are included to provide an indication of the success of these biomimicry technologies. Some of these are already being used in constructed wetland applications. Others may have key principles that can be abstracted for mimicking, such as the aquaporin example described in Table 3.

5.1 Ecosystem Technologies

This review begins with ecosystem technologies as these encompass constructed wetlands that are the main focus area for this research. Organisms within an ecosystem are reliant on water sources within that ecosystem for drinking water. Various components of the ecosystem are responsible for ensuring that this water is contained and purified for the purpose of consumption by the organisms. Thus animals in nature rely on the work of a diversity of plants, trees, algae, fungi and bacteria to capture rain water, filter sediments and toxins, and store water in leaves, lakes, ponds, underground, etc. Recreating these ecosystems is possible on a smaller scale.

<u>EXISTING BIOMIMETIC ECOSYSTEM TECHNOLOGIES</u>

Research into relevant biomimetic ecosystem technologies identified a number of existing biomimetic water treatment technologies on the market. The following sections list and compare some examples. These examples are described as case studies in more detail in Appendix A.

Table 2: Examples of Existing Biomimetic Ecosystem Technologies

Company	*Biolytix*	*Floating Island International, Bright Water Company*	*Eco Machines, John Todd Ecological*	*Natural Systems Utilities, Naturally Wallace Consulting, Whole Water Systems*
What's being mimicked:	*Forest litter decomposition*	*Wetlands*	*Wetlands*	*Wetlands*
Product/ Process Resulting:	*Biolytix wastewater treatment system*	*Biohaven Wild Floating Islands, Bright Water Company floating islands*	*Living Machines/ EcoMachines*	*Natural Systems*
Website:	www.biolytix.co.za	http://www.floatingislandinternational.com , http://www.brightwatercompany.nl/lang/eng	http://www.livingmachines.com, http://www.toddecological.com	http://www.natsyssolutions.com , http://naturallywallace.com , http://wholewater.com/H2OTREATMENT
Availability:	*On the market (incl. South Africa).*	*On the market (incl. South Africa). Test cases in, e.g. Du Noon township, 15 km North of Cape Town.*	*On the market (USA, UK, Australia, China, Ghana).* The patents for *living machine* systems are now owned by companies affiliated with Worrell Water Technologies, LLC.	*On the market (USA).* *Similar systems in SA being developed by, e.g. Peoples Power Africa (Mark Wells)*

Company	*Biolytix*	*Floating Island International, Bright Water Company*	*Eco Machines, John Todd Ecological*	*Natural Systems Utilities, Naturally Wallace Consulting, Whole Water Systems*
Description:	Dean Cameron invented the Biolytix Biopod, a compact biological reactor that treats sewage, wastewater and food wastewater to a quality suitable for irrigation. The system emulates how forest litter decomposes and mimics the natural conditions which fuel the decomposition of debris on a river's edge.	Bruce Kania of Floating Island International has created these man-made floating islands that filter nutrients and pollutants from water by mimicking the way in which wetlands perform the same role. Possible applications include livestock ponds, golf courses and wildlife habitat areas.	The Living Machine/Eco-Machine, invented by Dr. John Todd, is a form of wastewater treatment inspired by aquatic ecosystems that accelerate nature's water purification process. They incorporate bacteria, fungi, plants, snails, clams and fish that thrive by breaking down and digesting organic pollutants.	A biomimicry approach, that integrates on-site treatment, reuse and natural systems, that can provide sustainable solutions for municipal, commercial, and industrial wastewater treatment and water reuse developments.

Case studies on the examples presented in Table 1 can be found in Appendix A. In addition, Appendix A includes specific case studies of the applications of Floating Islands and Living Machines for specific problem wastewaters in different locations.

In practical application, ecosystem technologies are self-contained treatment systems designed to treat a specific waste stream using the principles of ecological engineering. They achieve this by using diverse communities of bacteria and other microorganisms, and some combination of algae, plants, trees, snails, fish and other living creatures.

Biolytix systems mimic forest ecosystems water treatment principles, employing relevant organisms and design principles and applied to sewage treatment. The Biolytix system contains the solid wastes from the water and then selected worms, beetles and microscopic organisms convert the waste into structured humus, which acts as a filter to turn the wastewater into water suitable for garden irrigation.

Floating islands mimic wetland systems and other aquatic ecosystems. The core of each island is a cushioning polymer batting, made from recycled material that is stacked in layers that are buoyant and can be shaped. Plants are then inserted into pre-cut pockets. The layers allow the plants' roots to reach the water. As the plants grow and microbes begin clinging to the island, they take excess nutrients out of the water. In natural wetlands floating plants perform this function eliminating the need for a polymer batting. The floating is primarily achieve as a result of the leaves or root system containing air-pockets

Living machines/eco-machines are modular designs consisting of a series of tanks/islands/reactors that are connected as a system, each with their own "ecosystem" design specialising in a particular phase of decomposition and breakdown of organic and/or inorganic matter in the water. Instead of using chemicals as cleaning agents, aquatic living creatures like snails and small fishes as well as different species of plants and vegetation are utilised in different combinations to suit the relevant context (such as location, wastewater content and available space). This approach transforms high-strength industrial wastewater and sewage into water clean enough to be recycled for reuse in some cases (Cantona, 2010).

In warm climates living machine systems can be outdoors as the temperature will sustain sufficient biological activity throughout the winter. In temperate climates, a greenhouse is used to keep water temperatures warm to prevent plants from being damaged by frost and snow. Biological processes occurring in the units result in heat generated within the green houses. In cold climates supplemental heating may also be necessary. Living machine systems use screens, biofilters, plumbing, large plastic tanks, reed beds, rocks, fans, pumps and other mechanical devices. Every system is tailored to the volume and makeup of the wastewater. Some are within stand-alone greenhouses, while others are built into larger buildings or outdoors. The system often includes an anaerobic pre-treatment component, flow equalization, aerobic tanks as the primary treatment approach followed by a final polishing step, either utilizing Ecological Fluidized Beds or a small constructed wetland. The size requirements are entirely dependent on the waste flow. The Eco-Machine functions similarly to a facultative pond with both aerobic and anoxic treatment zones, only instead of a body of water, the process occurs within individual tanks, creating independent treatment zones. Each system is designed to handle a certain volume of water per day, but the system is also tailored for the qualities of the specific influent. For example, if the influent contains high levels of metals, the living machine must be designed to include the proper biota to accumulate the metals (Todd N. J., 2005). The principles for design of living machines that have been researched and developed by Todd *et al*., 1993 are included in Figure 1 on relevant ecosystems biomimicry research.

Ecosystem technologies can also be integral to creating whole-system approaches to water management in general that encompasses a biomimicry approach of *decentralised, sustainable* systems for an expanding range of wastewater treatment and reuse options. Technologies and systems that *optimise the entire water solution* to deliver productivity gains and water conservation, by integrating on-site treatment, reuse, and natural systems, can provide sustainable solutions for municipal, commercial and industrial wastewater treatment and water reuse developments. This is taking ecosystem mimicry up to the next level where integrated closed-loop food webs are mimicked as whole systems and where water treatment is one component of the whole.

These whole-system solutions can adapt or intensify ecosystem principles to meet the needs of a land-constrained context or to augment existing systems to optimise their longevity. These solutions are modelled on: natural processes and distributed systems; restoration of water health and balance; reduction of energy, carbon, and costs required for water treatment and transport; and regeneration of water resources, habitats, and biodiversity. The most effective solutions integrate water, energy and biological efficiencies (Equilibrium Capital Group, 2010).

Table 1 includes Natural Systems Utilities (NSU), John Todd Ecological Design, Whole Water Systems and Naturally Wallace Consulting as examples of companies focused on designing, building and/or operating biomimetic combined water and wastewater systems. These alternatives incorporate natural or biomimetic wastewater treatment systems, such as combinations of bio-regenerative wetlands and biomembrane technologies, and integrate with onsite rainwater capture, stormwater management and water reuse systems to meet various community demands for water with appropriate supplies.

*Rethinking infrastructure is a key component of biomimicry applications for water treatment: moving away from centralised facilities, towards **decentralised water-wastewater supply, treatment, and reuse systems.*** In response to the high cost of transporting and treating water in conventional centralised facilities, and the lack of capacity in many municipal systems, biomimicry systems move to more efficient distributed and scalable water treatment and reuse systems. Decentralisation is also one of Life's Principles. Technologies and processes that conserve and reuse water also provide numerous environmental benefits including: more efficient water delivery and use: reduced energy demands associated with transporting and treating water supplies; reduced agricultural production costs (energy, transmission, fertilisers); and benefits to aquatic and other natural habitats (Equilibrium Capital Group, November 2010).

This approach to biomimicry also has the potential to unlock new business models and revenue streams: reclamation; residual value and local redistribution creating economic value in water treatment and reuse. With this approach grey water and stormwater can be seen as valuable commodities. Energy capture of the waste can enable the wastewater to be energy self-sufficient and become a power generator back to the grid. By-products of heat, non-potable water and nutrients can generate new cash flows that can make water a lucrative industry. The local design solutions by People's Power Africa (Peoples Power Africa, 2008) based in South Africa indicate that there is significant potential for this whole-systems integrated water, energy and materials (nutrients) biomimicry approach, rather than a single focus on water and wastewater treatment alone.

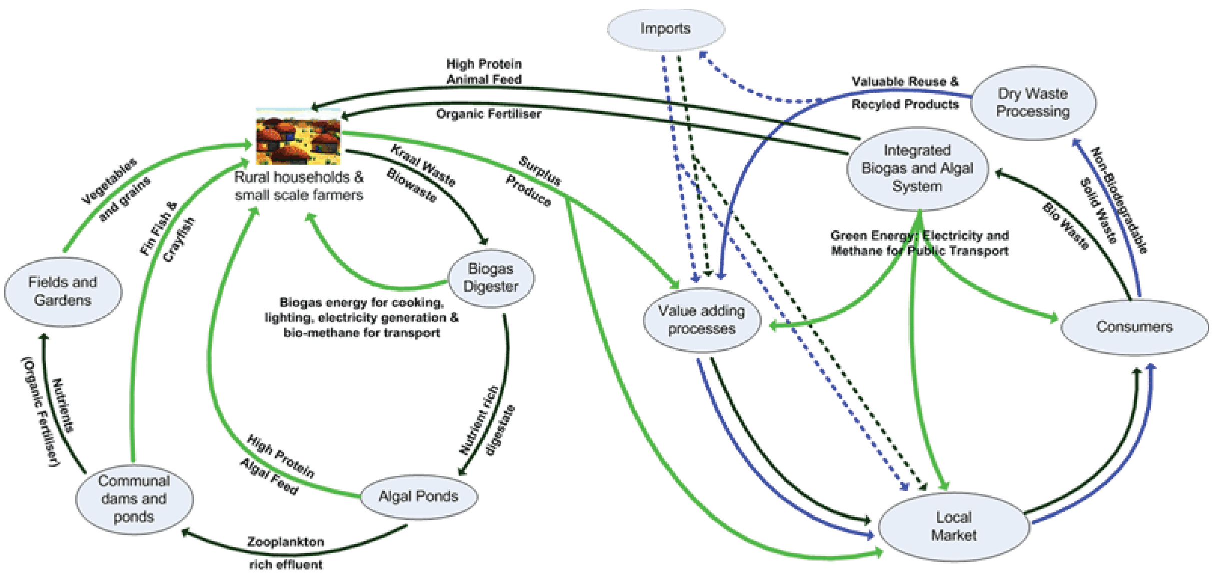


Figure 2: Closing the loop in an urban/rural zero waste economy (Peoples Power Africa, 2008)

Although only applied at a small scale in South Africa (PPA/Mark Wells), the successful results indicate that this whole-systems approach to biomimicry definitely warrants further research. Public-private partnership (PPP) opportunities may provide an enabling environment for companies who could reduce water and energy demand by 30-50%, reduce operational costs significantly, meet water quality discharge standards and improve habitats and biodiversity.

5.1.1 Biomimetic Ecosystem Technologies Research & Development

Research into ecosystem technologies has revealed general criteria relevant to the successful function of these systems. Such research is valuable for the applications in biomimetic constructed wetlands.

Section 5.2 below provides an overview of the key design principles of some of the wetland biomimicry systems included in Table 2. These offer a point of comparison to constructed wetlands and could inform how applying the biomimicry methodology could improve the operation of constructed wetlands. In each system described briefly in Table 2 the understanding of the relevant ecological principles for each case (such as forest/ wetland), combined with an understanding of the individual components in context, is required to emulate their functions in human applications.

Ecological systems have resilient, self-organising and effective mechanisms leading to the purification of water. These mechanisms have been applied in large scale waste treatment facilities and also in smaller batch processes. The research in this area focuses on understanding the elements needed to purify the contaminated water and the systems perspective to gain a high performance product/process/system. The following section includes insights from a paper written by John Todd – one of the world's leading designers of biomimetic constructed wetlands, with over 35 years' experience of deep ecological engineering practice. It provides a good starting point for considering the implications of biomimicry applied to ecological engineering and specifically for constructed wetlands (Todd & Josephson, 1996).

According to (Todd & Josephson, 1996), ecological technologies have attributes that separate them from conventional technologies. Ecological technologies are unique in that they include a wide range of selected life forms in their design. Ecological engineers select the initial species, initial and operational conditions and nature does the rest. Re-creating models of natural systems in laboratory settings has advanced considerably over the years.

Practitioners in ecology, design and the fields of complexity and chaos dynamics have cooperated in the design of ecosystem technologies and this has significantly benefited ecosystem engineering. Todd (1996) notes how studies into self-organisation generated in nature, ranging in scale from the molecular level to large ecosystems, can be applied to technological settings. Attempts have been made to discover what propels a living system towards chaos or a balanced state in order to understand why an ecomachine works. The process involves establishing diverse life forms in new combinations of species within artificial settings for specific processes, such as water purification. The theory is based on the concept of *criticality*. Organic forms may reach a state of *supracriticality* where they are able to generate new molecular combinations or species arrangements. Diverse ecosystems may have this property of supracriticality. *Subcritical* systems lack adaptiveness because they lack the critical diversity or the ability to support this diversity. According to this theory, life at the level of the *individual*, from bacteria to higher organisms, is *subcritical*. Ideally, ecosystem engineers would like to develop ecosystem technologies that are *supracritical*, capable of self-design and self-regulation.

Todd *et al*. (1996) argue that if complex ecological systems with diverse enzymatic pathways and complex surfaces for the exchanges of gases and nutrients, such as are found in the micro-anatomy of plants, will enable the design of ecosystem technologies with the potential of several orders of magnitude greater efficiency than contemporary mechanical and chemical technologies. If so, it may be possible to reduce pollution and its negative impact on the environment to a small fraction of existing levels (Todd & Josephson, The design of Living Technologies for waste treatment, 1996)

Ecosystem technologies for treating water are designed along the principles evolved by nature for building and regulating ecologies of forests, lakes, estuaries and wetlands whose primary energy source is sunlight. Like natural ecosystems, ecosystem technologies have hydrological and mineral cycles. To create an ecosystem technology such as a living machine, organisms are collected and reassembled in unique ways depending on the purpose of the project. Appropriate assembly, depending on context is based on knowledge of the specific organisms that make up the components of the system, and on an understanding of the relative ecological context and ways to combine the individual components to achieve the desired function (Todd & Todd, 1993).

This list of nine fundamental principles for the design of ecosystem technologies or living machines was developed by John Todd, based on his experience which extends over 35 years. The principles for ecological engineering are set out in in the information box below.

1. ***Microbial communities***: The primary ecological foundations of living machines are based on diverse microbial communities obtained from a wide range of aquatic (marine and/or freshwater) and terrestrial environments. In addition, organisms from chemically and thermally highly stressed environments are critical.
2. ***Photosynthetic Communities***: Sunlight-powered photosynthesis is the primary driving force of these systems. Anaerobic phototropic microbes, cyanobacteria, algae and higher plants must be linked in a dynamic balance with the heterotrophic microbial communities.
3. ***Linked Ecosystems and the Law of the Minimum***: At least three distinct types of ecological systems need to be linked together to carry out self-design and self-repair through time. Such systems have the theoretical ability to span centuries and possibly millennia.
4. ***Pulsed Exchanges:*** Nature works in short-/long-term pulses which are both regular and irregular. This pulsing is a critical design force and helps maintain diversity and robustness. Pulses need to be intrinsic in design. The background of pulse creates the resilience, agility and vigour for the systems to recover from external shocks.
5. ***Nutrient and Micronutrient Reservoirs:*** Carbon/Nitrogen/Phosphorous ratios need to be regulated and maintained. A full complement of macro and trace elements needs to be in the system so that complex food matrices can be established and allowed to “explore” a variety of successional strategies over time. This will support biological diversity.
6. ***Geological Diversity and Mineral Complexity:*** Living machines can simulate a rapid ecological history by having within them minerals from a diversity of strata and ages. The geological materials can be incorporated into the sub-ecosystems relatively quickly by being introduced as ultrafine powders which can be solubilised over short time frames. Alternatively crushed stones from diverse relevant mineral substrates can form the substrate of the constructed system.
7. ***Steep Gradients:*** Steep gradients are required within and between the sub-elements of the system. These include redox, pH, humic materials and ligand or metal-based gradients. These gradients help develop the high efficiencies that have been predicted for living machines.
8. ***Phylogenic Diversity:*** In a well-engineered ecosystem all phylogenic levels from bacteria to vertebrates should be included. System regulators and internal designers are often unusual and unpredictable organisms. The development of various phyla has arisen to a large extent from the strategic exploration of the total global systems over a vast period of time. This time can be compressed with the consequences of this evolution.
9. ***The Microcosm as a Mirror Image of the Macrocosm:*** This applies to ecological design and engineering as much as possible. Global design should be miniaturised in terms of gas, mineral and biological cycles. The big system relationships need to be maintained in the living machine.

Eco machine systems fall within the emerging discipline of ecological engineering and many similar systems are built in Europe and the US without being called “Eco Machines.” Whole system solutions take the eco machines concept further by creating integrated systems that not only clean water but manage water and wastes in closed loops. These systems are modelled on: natural processes and distributed systems; restoration of water health and balance; reduction of energy, carbon, and costs required for water treatment and transport; and regeneration of water resources, habitats, and biodiversity. These system designs include a range of innovative sustainable technologies and systems that optimise the entire water solution to deliver productivity gains and water conservation.

Research required to improve Ecosystem Technologies

In a 2000 report to the US EPA (Environmental Protection Agency) on a South Burlington, Vermont, living machine, Ocean Arks International outlined key areas which could shape the future of this field (Todd J. , 2008). The report identifies the "foremost possible breakthrough area" as the ongoing ***classification of species*** by the biochemical, biological and ecological roles they play and how those roles affect other species under the context of wastewater treatment. According to the report the breakthrough would be to study the function of organisms in hopes of being able to more readily and successfully manage overall ecosystem functions.

Another key area identified in the report is trophic management – a management technique that exploits the close interconnections of the food web, trophic cascade to influence entire systems by selective predation. It is based on diagnosing an imbalance and analysing the web of ecosystem classifications, roles and relationships. This technique will require research to advance understanding of the conditions in the ecosystem and modelling the dynamic relationships down the trophic cascade.

5.2 Biomimetic Filtering Technologies

Filtering technologies rely on membranes with pores of various sizes, shapes, filaments and charges to allow transport of water but not contaminant from one side of the membrane to another. Classic examples in nature are the human kidney that filters 190 litres of blood a day, or the mangrove forests that use ultra-filtration to separate fresh water from salt water. The primary molecular mechanism in all of these involves aquaporins. Aquaporins are a class of proteins that enable membrane transport of water, essentially acting as a filter for fresh clean water. Research in the area of understanding and applying aquaporins is just emerging as a leading field. This literature research into relevant biomimetic filtering technologies identified some existing biomimetic filtering technologies as well as additional relevant research, and a number of inspiring organisms that could yield further fruitful research.

5.2.1 Existing Biomimicry Filtering Technologies

Table 3: Examples of Existing Biomimetic Filtering Technologies

Company	**Baleen filters**	**Aquaporin and AquaZ**
What's being mimicked:	Baleen whales	Aquaporins
Product/Process Resulting:	Baleen whales	Aquaporin membrane technology
Website:	www.baleenfilters.com	http://www.aquaporin.dk/, www.aquaz.dk
Availability:	Available on market in Australia.	Aquaporing.dk: The main goal of Aquaporin is to develop the Aquaporin Inside™ technology. Commercial success will be reached through completion of these three main phases: • Development and proof of the technological concept; • Development of a prototype and further development thereof into a final membrane technology; and • Marketing, sales and out licensing of the final membrane technology expected in 2016. AquaZ – under development of membrane technology incorporating aquaporins, not available on the market at this stage.
Description:	The Baleen Filter emulates the Baleen whale filtering mechanism which is a combination of a sweeping action of the tongue and the reversing of the water flows which enable them to capture and strain food, then clean their baleen. The Baleen Filter design does this by using a	Aquaporin.dk is developing the Aquaporin membrane technology capable of separating and purifying water from all other compounds. Primary market focus includes ultrapure water (UPW) used in extreme applications such as medicinal, biotech, production of semiconductors and flat panels and other industrial

Company	Baleen filters	Aquaporin and AquaZ
	double-act of high pressure, low volume sprays – one which dislodges material caught by the filter media or screen, whilst the other sweeps the material away for collection. This non-pressurized self-cleaning separation technology filters to 25 microns without chemical assistance. By using flocculation techniques, it is possible to filter to 3 microns.	purposes. Secondary market focus includes desalination of seawater and pressure retarded osmosis applications. The Company's goal is to use aquaporins in water filtering devices to be employed in industrial and household water filtration and purification. AquaZ.dk is developing technology based on Danfoss AquaZ membrane concept with a layer of redundant Nano Membranes with incorporated Aquaporins.
Further info:		Refer to Appendix A for a case study on aquaporins

The Baleen filter was originally patented by the University of South Australia based on studies of filter-feeding whales. The baleen is a filter mechanism that enables filter-feeding whales to collect plankton, small fish and other marine organisms from the water during feeding. The combination of a sweeping action of the tongue and the reversing of the water flows as the whales dive and re-surface during feeding, enable them to capture and strain food, then clean their baleen prior to the next dive. The Baleen filter technology is an adaptation of this natural technique used by whales to keep their baleen clean and free from long-term deposits.

The Baleen Filter emulates the whale filtering mechanisms by using high pressure, low volume sprays in two ways: one to dislodge material caught by the filter media or screen, whilst the other to sweep the material away for collection, thereby removing constituents such as grit, suspended and fibrous matter, grease and oil from water, without blocking the filter, to enable smooth continuous operation. It was designed to overcome problems with traditional systems of treating industrial and municipal wastewaters, which typically involve segregation of contaminants by less effective settling or flotation methods, which can create adverse effects like increased odours, and significant maintenance issues, such as sludge handling. The Baleen Filter serves as a primary (load reduction) and secondary (solids dewatering, polishing) treatment system. The Baleen Filter offers several advantages over conventional systems including:

- Realisation of value-added by-product recovery opportunities and associated markets. For example composting, biogas generation, soil conditioners, vermiculture, nutrient and minerals reclamation, farm feeds, tallow and protein recovery;
- Increased water recycling or re-use; and
- Can be readily adapted to mobile clean-up systems and emergency pollution response (such as for oil spills and land remediation) due to its innovative, enhanced separation capability.

The Baleen filter technology is already on the market (based in Australia) and illustrates the success of mimicking filtration mechanisms of specific organisms for specific applications. A list of many other biological organisms that could similarly yield further fruitful research and development of innovative filtration technologies is included at the end of this section.

Aquaporin membrane biomimetic technology included inTable 3 is still under development and research into this area is discussed below.

5.2.2 Biomimetic filtering technologies – Research and development

Membranes are ubiquitous in nature and the technology for producing inexpensive and high performance membranes is still an important area of development. Current membrane processes result in high operational costs as a result of the high pressures required to achieve the desired water recoveries. Traditional membrane technologies – Reverse Osmosis and Nanofilters – sort water impurities by size, requiring high pressures and hence energy to treat brackish and sea water. Due to the higher salinity and levels of dissolved solids, sea water is far more expensive to treat than brackish water.

Creating high performance membranes that are inexpensive and perform at operating pressures that are closer to atmospheric conditions will likely take a concerted effort of research and development. Carbon nanotubes have recently gained momentum as a feedstock for developing inexpensive pores for filtration. In addition to carbon nanotubes, understanding the principles of natural membranes in general has been a leading area of interest.

Nature provides a large number of highly effective membranes capable of highly selective vectorial transport of a large number of molecular species. It is therefore striking that the membrane industry has developed synthetic separation membrane processes in a very different way (Rios , Belleville, & Paolucci-Jeanjean, 2007). Most synthetic membranes may be broadly described as polymer sheets containing micro to nanometre sized holes. This is in stark contrast to the bewildering complexity of biological membranes. Despite dramatic progress over the last decades in the understanding of the molecular basis for biological membrane transport, this complexity remains a major obstacle. One way that may lead to a better understanding of membranes and membrane transport is to focus on a few of its components and features. This understanding is crucial in order to mimic nature's capability for selective membrane transport.

Living cells are enclosed by a lipid bilayer membrane, separating the cells from other cells and their extra-cellular medium. Lipid bilayer membranes are essentially impermeable to water, ions and other polar molecules; yet, in many instances such entities need to be rapidly and selectively transported across a membrane, often in response to an extra- or intracellular signal. The water-transporting task is accomplished by aquaporin water channel proteins. Aquaporins are crucial for life in any form and they are found in all organisms, from bacteria to plants and man.

Aquaporins operate at the thermodynamically lowest energy level for water purification. They isolate water molecules based on electrostatic physical recognition. This means that only water molecules are allowed to pass through the aquaporin channel leading to production of truly pure water. Smaller molecules, for instance nitrates, are restricted passage as their electrochemical properties do not "fit". Since the discovery of aquaporins in 1992 to date, an almost complete atomic-level understanding of aquaporin water channel function has been reached (Chakrabarti, Tajkhorshid, Roux, & Pommes, 2004), (Groot & Grubmuller , 2001). Research into water transport in various organisms and tissues by (Agre, Bonhivers, & Borgonia, 1998), revealed that aquaporins have a narrow pore preventing any large molecule, ions (salts) and even proton (H_3O^+) and hydroxyl ion (OH^-) flow while maintaining an extremely high water permeation rate: ~ 109 molecules H_2O per channel per second. The research indicates that the architecture of the aquaporin channel allows water molecules to pass only in single file while electrostatic tuning of the channel interior controls aquaporin selectivity against any charged species.

Engineering aquaporin-like pores in a wide variety of materials has been a leading interest in water purification research over the past several years. Two companies leading in the development of aquaporin membrane filtration technology are Aquaporin and AquaZ both based in Denmark. A case study on these is included in Appendix A. This type of biomimicry research and development is very valuable in the field of water treatment. It is useful not only in that specific applications could be very valuable, but in that the case study shows the value of abstracting design principles from specific biological mechanisms that can be applied to water treatment (rather than using the organisms themselves, e.g. in constructed wetland ecosystem technologies).

5.2.3 Overview of biological filtering examples for potential research into biomimicry applications for wastewater treatment

In filtration there are a wide range of organisms that perform bulk filtration from water for feeding. These filter feeding organisms have evolved superior filtration technologies out of simple, lightweight, common materials. Oganisms that can filter water include those which occur in natural wetlands and which are used in constructed wetlands. The opportunities for further research lie in identifying for which applications these organisms may be used (in ecosystem mimicry) or for which applications key principles (for example membrane mechanisms or materials) may be mimicked and applied to water treatment.

The section to follow includes an overview of organisms in nature that fulfil the function of water filtration using a variety of different strategies. This information can be used as a basis for further research to identify specific biomimetic innovations for wastewater treatment. Alternatively, this information could be used for identifying important components in a biomimetic ecosystem technology (for example a constructed wetland requiring specific filtration requirements).

Filtration → Macrofiltration Biological Examples → Using keratinous filaments

- **Baleen Whales (krill > 2 mm's):** Baleen Whales have no teeth; instead they have developed a keratinous row of fibres known as a baleen. The keratin sheath of each plate encapsulates hair like strands that become evident as the sheath is worn down and splits open. Upon closing its mouth the lower jaw distends creating pressure of water against the baleen, this forces water through the keratin fibres but retains all organic material. Once all water is forced out the tongue rises and sweeps all organic material off the baleen which is then swallowed (Croll, 2008), (Brodie & Vikingsson, 2009). The principles of Baleen Whale filtration have been emulated in the existing biomimetic technology called Baleen Filters, discussed in earlier chapters of the document. This is an indication of the type of biomimicry that could evolve from the organisms listed below.

- **Basking Sharks (plankton > 1 mm):** The basking shark is the second largest living shark, after the whale shark. It is a slow moving and generally harmless filter feeder. It has anatomical adaptations to filter feeding, such as a greatly enlarged mouth and highly developed gill rakers (Sims, 1999); (Biomimicry Institute, 2011).
- **Flamingos (crustaceans, algae > 0.5 mm):** Flamingoes are gregarious wading birds in the genus Phoenicopterus. The bill is lined with numerous complex rows of lamellae, which filter the various small crustaceans, algae and unicellular organisms on which flamingos feed. The feeding process requires a series of tongue movements and opening and closing of the beak, which allows food items to be filtered by the lamellae and eventual ingestion. Unwanted items such as mud and saltwater are pushed out by the tongue (Biomimicry institute, 2010); (Jenkin, 1957).

Filtration → Macrofiltration Biological Examples → Using a partial vacuum

- **Bladder Wort (water fleas to small fish 1 µm-1 mm):** Bladder Worts are water plants found in wetlands in many parts of the world. Their traps, the bladders from which they get their name, are tiny transparent capsules. Glands on the inner surface of these are able to absorb water, and in doing so create a partial vacuum within. Each has a tiny door fringed with sensitive bristles. If a small water creature, such as a mosquito larva, touches one of these, the bristle acts as a lever, slightly distorting the edge of the door so that it no longer fits tightly on the rim. Water rushes in, sweeping the door inwards and with it the little organism. The swirl of water within the capsule pushes the door back again and the prey is imprisoned. The whole action is completed within a fraction of a second (Laakkonen, Jobson, & Albert, 2006).

Filtration → Macrofiltration Biological Examples →Using simple cilia:

- **Sea Squirts (plankton 1-100 µm):** Sea squirts are invertebrates in the class Ascidiacea, marine animals with some primitive vertebrate features. The body has an outer protective covering, the tunic. There are two large pores, one to guide water into the body cavity, the other serving as an exit. Water is propelled through the animal by pharyngeal cilia. Food and oxygen are taken from the water current as water passes through gill slits in the pharynx (Ask Nature, 2011).

- **Daphnia (algae 1-35 μm):** Daphnia are small, planktonic crustaceans, between 0.2 and 5 mm in length. Daphnia possess bristle-equipped appendages with which they swim, using them as paddles – with a lot of semi-stagnant water around each bristle an appendage can serve as a paddle. The creatures also use the appendages as rakes, filtering edible particles from the water around them. This requires the passage of water between the bristles.
- **Venus' Flower Basket (organic material <5 μm)**: Venus' flower baskets are deep-sea animals. They are known as glass sponges as their bodies are entirely composed of silica. The silica lattice of the sponge body acts as the primary filtering layer removing particles larger than 5 microns in size (fed upon by symbiotic shrimp), while it's form creates a drawing effect on water from outside to the inside of the sponge body. The water flows through the lattice toward the mouth of filtering choanocyte cells, and in doing so any particle still in solution will be filtered by small cilli at the collar of the cell opening and transported away to be fed upon (Risgard & Carsen, 2001).

Filtration → Macrofiltration Biological Examples → Using mucus lines appendages:

- **Salps (algae <1 mm):** Salps are small free-swimming marine creatures with gelatinous, semi-transparent bodies that move around by means of jet propulsion, drawing in water through an aperture at one end of the body, and then forcing it out through another aperture at the opposite end. Small food particles are gathered by a mucous net of varying complexity (depending on species) formed by a specialized gland. The net, or "house", is discarded when clogged with food, and a new one is quickly formed. An individual may produce up to 10 or more houses in a single day.
- **Peacock Worm** (detritus, bacteria, plankton 0.2-100 μm)**;** The Peacock worm is a marine polychaete worm. Tiny hair-like structures on the mucus lined tentacles known as 'cilia' filter suspended particles from the water. These particles are then sorted according to size; small ones are eaten, large ones are discarded and medium-sized particles are added to the top of the tube with mucus in order to increase its length. (Avant, 2002)
- **Sea Cucumber** (detritus, bacteria, plankton 0.2-10 μm)**;** they are marine animals with a leathery skin and an elongated body. Sea cucumbers are found on the sea floor worldwide. Sea cucumbers feed on deposited material by mechanical entrapment with the aid of sticky papillae on the tentacle buds. (Graham & Thompson, 2009); (Fankboner)

Filtration → Macrofiltration Biological Examples → Nanofiltration Biological Examples:

- **Human Kidneys:** Human Kidney is the primary filtration organ that maintains blood homeostasis in the body. Renal circulation is unique in that it has two capillary beds; the glomerular and peri-tubular capillaries. The actual removal of wastes occurs in tiny units inside the kidneys called nephrons. Each kidney has about a million nephrons. In the nephron, a glomerulus—which is a tiny blood vessel, or capillary—intertwines with a tiny urine-collecting tube called a tubule. The glomerulus acts as a filtering unit, or sieve, and keeps normal proteins and cells in the bloodstream, allowing extra fluid and wastes to pass through. (NKUIC); (Agre & Kozono, Aquoporin water channels: Molecular mechanisms for human disease, 2003)
- **Vampire Bats;** Vampire bats are bats whose food source is blood, a dietary trait called hematophagy. Bat stomachs can hold a volume of blood equal to 57 percent of their body mass, but they can't fly with this much extra weight. The problem is solved by rapidly getting rid of water and lightening their load before taking off. Within two minutes after a bat begins to feed, it begins to excrete a stream of very dilute urine.
- **Mangroves** (aquaporins for desalination – see aquaporin example in case studies)
- **Loons; Loons** (North America) or divers (UK/Ireland) are a group of aquatic birds found in many parts of North America and northern Eurasia. The marine species in this group of birds have the ability to generate a net gain of water with the ingestion of seawater. Ingestion is facilitated by large nasal glands for the elimination of excess salt and ultrastructural specialization of the kidneys. Such glands work by active transport via sodium-potassium pump that moves salt from the blood into the gland, where it can be excreted as a concentrated solution. Salt glands function to keep salt balance, and allow marine vertebrates to drink seawater.

5.2.4 Phyto-accumulation:

SOUTH AFRICAN EXAMPLES:

- **Potato** (Solanum tuberosum); the ubiquitous Potato is a herbaceous perennial plant and depending on its variety can have white, pink, blue, or purple flowers. Studies conducted in Europe have determined that the potato plant is a hyperaccumulator of aluminum. Accumulating this heavy metal in the roots, leaves, and tubers, the entire plant should be harvested.
- **Indian Mustard** (Brassica juncea); given its widespread habitat and ability to grow in poor soil conditions, this plant has been well researched for its hyperaccumulation capabilities. Indian mustard is a hyperaccumulator of lead, cadmium, selenium, nickel, zinc and chromium. Roots of B. juncea concentrated these metals.

- **Kenaf** (Hibiscus cannabius); Kenaf is an annual herbaceous plant of African origin. Although traditionally grown to make rope in Africa and Asia Kenaf leaves are edible and the woody stalks are often used for fuel. The economic and cultural importance of Kenaf to developing societies has sparked much research into the cultivation and potential uses for the plant. In Nigeria research is underway to determine the best methods for using Kenaf for the phyto-extraction of cadmium.
- **Water Hyasinth** (*Eichhornia crassipes*): Water hyacinth are the only large aquatic herb that can float on water unattached to the bottom. They float on bloated air-filled hollow leaf stalks with roots trailing underwater in a dense mat. Water hyacinth can take up and translocate 6 trace elements: arsenic, cadmium, chromium, copper, nickel and selenium. The highest levels of cadmium were in shoots and roots at 371 and 6,103 mg/kg dry weight. (wt), and those of chromium were 119 and 3,951 mg/kg dry wt. Cadmium, chromium, copper, nickel and arsenic were more highly accumulated in roots, whereas selenium accumulated more in shoots.
- **Duckweed** (*Lemna minor*): *Lemna minor*, sometimes commonly called lesser duckweed, is perhaps the most wide-spread of the duckweeds, being found throughout the world. Studies show duckweed strongly absorbs mercury from water and after 3 days contained 2,000 ppm of mercury by weight. When duckweed was kept in a solution containing copper at 8 ppm, the value of the metal concentration factor (i.e. the ratio of metals in the plant to the growth media) after 14 days was 51. However, in the presence of an equal concentration of iron the value of this factor was 27, indicating the influence of iron on the uptake rate of copper.

FOUND IN, BUT NOT ENDEMIC TO SOUTH AFRICA

- **Bush Morning Glory** (*Ipomoea carnea*): the Bush Morning Glory originated in the tropical Americas and is a shrub that grows 1.22 to 4.88 meters tall. The beauty of its pink flowers make it a choice ornamental plant. Having a strong alkaloid content the Bush Morning Glory is unpalatable to many herbivores and best left to grow rather than be eaten. It is a proven hyperaccumulator of the metal chromium.
- **Sunflower** (*Helianthus annuus L.*): the Sunflower is an annual plant native to the Americas. Reaching heights of 1.5 to 3.5 meters, it is best grown under full sun in fertile, well-drained soil. *Helianthus annuus L.* is not only beautiful but grown commercially for its seeds and extracted oil. Research into the hyperaccumulator properties of the Sunflower have shown it to be effective for the phytoextraction of arsenic, lead and uranium. Uranium concentration in water reduced from 21-874 ug/l to <20 ug/l by rhizofiltration.
- (Padmavathiamma & Li, 2007); (dos Dantos, 2010); (Ghosh & Singh, 2005); (Baghour, 2001)

OTHER:

- **Dung Beatle:** In New England studies showed dung beetles had the ability to dispose of 1 gram of dung per beetle per day. During parts of the year in India dung beetles bury an estimated forty to fifty thousand tons of human excrement each day.
- **Bacteria: (*Ralstonia metallidurans*):** *Ralstonia metallidurans* is a gram-negative microbe that does not form spores. It is unique in that it can flourish in millimolar concentrations of metals, such as gold, that are normally toxic to bacteria. Experiments showed that the ubiquitous *R. metallidurans* can pull dissolved gold (which is highly toxic to most life forms) out of solution and precipitate it as harmless particles of solid gold. The details of the process remain to be understood but in nature it enables the bacteria to live in toxic soils and to contribute to the creation of solid gold (Nature, Dissolved gold is precipitated: Bacteria, 2010).
- **Fungi:** Fungi have an amazing ability to degrade a variety of environmental pollutants. The fungi produce enzymes necessary for pollutant degradation just prior to the end of their growth cycle. For example the oyster mushroom can be grown on mats of oil saturated hair absorbing the oil in the process.
- **Hair:** Hair naturally absorbs oil. There are microscopic glands in the skin that give off a waxy and oily substance named sebum that lubricates the hair and skin of mammals. This oil waterproofs and protects the skin and hair by preventing them from becoming dry, brittle, dehydrated and cracked.
- **Banana:** Minced banana peel can quickly remove lead and copper from river water.
- **Grapefruit** and other citrus skins can remove metals like cobalt, cadmium, lead, copper, nickel and zinc

5.3 Biomimetic Flow Technology

Flow technologies rely on shape to move water in ways that dissipate or avoid the forces of friction. By creating different flow environments water is oxygenated, suspended particles are removed and nutrients are distributed. Literature research into existing biomimetic flow technologies identified two relevant existing technologies, some additional relevant research, and some inspiring organisms that could yield further fruitful research. Table 4 sets out some examples of flow technology solutions and these are described in more detail in the section to follow.

5.3.1 Existing Biomimetic Flow Technologies

Table 4: Examples of flow technology solutions

Company	***PAX Water Technologies***	***Watreco***	***Whale Power Inc.***
What's being mimicked:	Natural fluid flow dynamics	Natural vortex fluid flow	Humpback whale fin fluid flow dynamics
Product/Process Resulting:	Pax water mixer	Limeteq, Greenteq, REALice	Wind turbines & fans
Website:	http://www.paxwater.com	www.watreco.com	http://www.whalepower.com
Availability:	On the market	On the market	On the market
Description:	The PAX Water Mixer uses efficiencies of fluid flow to provide efficient mixing of drinking water in storage tanks. This eliminates stratification, keeps disinfectant residuals actively working to maintain drinking water safety, and prevents conditions favourable to nitrification.	Watreco's water treatment products use the patented Vortex Generator and the technology platform VPT (Vortex Process Technology) to create energy-efficient, low-cost solutions for several water treatment problems. The system essentially works by causing water to quickly swirl down an ever-tightening coil of channels. This forces contaminants and/or air bubbles (depending on the application) into a column in the center of the swirling water. At the end of the process a vacuum quickly sucks this column out, leaving water with the desired properties behind.	Tubercle technology was inspired by the tubercles found on humpback whale fins. The technology creates bumps on the leading edge of a flow surface that create vortices that enable a higher performance. The performance enhancements create an airfoil that exceeds all existing technologies with a stall angle of 31 degrees. When applied to renewable energy, tests have already shown a 20% increase in effective energy generation.

Inventor Jay Harman developed the Pax Lily impeller after studying fluid flow efficiencies in natural systems, such as air and ocean currents. He observed that nature never moves in a straight line, and instead tends to flow in a spiraling path he called nature's Streamlining Principle. PAX technology replicates nature's most energy-efficient and effective path of mixing fluids – spiral geometry. PAX Water Technologies provides active, submersible tank mixers for potable water storage tanks. By ensuring uniform temperature and disinfectant residual, the PAX Water Mixer reduces nitrification and disinfection byproducts and eliminates ice damage in tanks. The Lily takes advantage of nature's flow pattern – a low resistant and effective method of mixing fluids – to significantly improve the performance and energy usage of water mixing technology. The core of PAX Water's mixing technology is the Lily impeller – a biomimetic technology used to solve potable water challenges. With this natural design, the PAX Water Mixer can mix up to 38 000 m^3 of water with the same energy footprint as three 100 watt light bulbs.

The Watreco Vortex Generator was inspired by a trout's ability to hold steady in the current of a river or stream. Water rushing into a trout's mouth is forced into ever-tightening vortices as it passes through the gills and back into the current. This allows the trout to hold steady even in inconsistent or violent flows. The system essentially works by causing water to quickly swirl down an ever-tightening coil of channels. This forces contaminants and/or air bubbles (depending on the application) into a column in the centre of the swirling water. At the end of the process a vacuum quickly sucks this column out, leaving water with the desired properties behind. The Limeteq product uses the Vortex Generator to change the structure of the lime crystals in water from calcite to aragonite, causing significantly less limescale build-up leading to longer-lasting pipes and reduced usage of harmful cleaning chemicals. This technology can also be used to remove contaminants from water in an effective and energy-efficient way.

An examination of the properties of vortexed water was made in 2010 and 2011 by the Polymer Technology Group Eindhoven BV (PTG/e), an independent research and knowledge institute which is a part of the Eindhoven University of Technology (TU/e). Samples were taken from municipal water in Holland, before and after Vortex Process Technology (VPT) treatment. Water treatment was made with a standard Watreco vortex generator at a water pressure of 3.5 bar. It was found that the radial pressure gradient in the vortex chamber causes a strong subpressure along the vortex axis. When using water, this subpressure forces gas bubbles (undissolved gas) to move inward toward the vortex axis. If the pressure gradient is strong enough, cavitation occurs. The strong pressure gradient shifts chemical balances, giving rise to reactions that would not happen under normal flow conditions. The combination of pressure gradients and shear forces causes formation, aggregation or fragmentation of solid matter in the fluid under certain circumstances.

Tubercles on the leading edge of humpback whales evolved as an adaptation to allow for more effective maneuvering and tighter turns which is the humpbacks main means of catching prey. Although WhalePower is currently utilized for air-related applications, Dr. Fish's discovery from years of studying the humpback whale has led to greater efficiency models for a variety of industries, including the water industry. His research has revealed that the humpback's tubercles appear to reduce drag by channeling flow over the fin. The analysis showed how the bumps forced the fluid to flow into the valleys in-between the ridges on the back of the fin. Rotating vortex rings occurred along each side of the bump, thus the valleys created pairs of vortices twisting in opposite rotation, which accelerated the fluid down the back of the fin and kept it in contact with the surface. Keeping in contact with the surface and reducing separation is the key component to reducing drag. Furthermore, the accelerated flow on the back of the fin reduces pressure, the same as the Bernoulli effect over an airplane wing. This effect creates a greater pressure difference from the front side, generating more lift on the front or power face (Howle, 2009).

Any product that utilises the movement of fluid (such as water) over a leading edge (for example mixer/ pumps) eventually has limits built in due to the laws of physics. Products for water treatment applications include mixers/ pumps that involve considerations such as drag efficiencies. WhalePower has been issued exclusive rights for devices incorporating tubercle enhanced leading edge technologies for turbines, fans, compressors and pumps. As this technology can be used for a wide range of products, they can license this technology to manufacturing companies and assist with development for optimizing each design as required by manufacturing partners.

5.3.2 Biomimetic Flow technology Research & Development

The dynamics of flow has been studied in a wide variety of fields. It has been found that the meandering flow pattern of river systems enables vortices and spiralling flow forms that are instrumental in ensuring the river systems are cleaned. One of the overarching design principles of flow dynamics is the concept of the golden ratio, spiral design and the resulting vortices that are caused by shapes in a flow environment. This is what Pax Water has emulated in the Pax Lily referred to above. The study and use of these shapes has emerged as a science due to advances in both fluid physics and computer modelling. Apart from the vortex process technology development from Watreco referred to above, research has also been done into how vortices can be used to capture specific size or shape of grains in a fluid environment such as a pine cone capturing pollen. There is the potential that vortices could be used to filter particulates from fluid, or increase the efficiency of flow in fluidic systems and also influence the rate and effectiveness of a water purification process.

An inspiring organism that has been studied extensively regarding flow dynamics, is bull kelp. Bull kelp exists in the extreme environment of a wave swept coastline. It has adapted vortex-like shapes to enable the water to flow past its form without causing excess turbulence. Many near shore algae and kelps have adapted biomechanical strategies for overcoming fluid forces and their study can reveal much about how to create biomimetic flow systems (Denny & Cowen, 1997).

Insects also take advantage of vortices to enable incredible flight characteristics. Understanding of the structures insects use to manipulate flow, at a scale that we might use for filters, could provide us with a relevant source for inspiration and innovation (Lu & Shen, 2008).

In addition, research by Niklas *et al*. (2008) into how conifer pine cones create vortices to capture or filter pollen from the air has revealed the effect of these pine cones for selective filtration of pollen (Niklas & U, 1982). This concept of using a shape rather than a filter to capture particles could be utilised for innovative filtering technologies.

4.4 OTHER BIOMIMICRY WATER TREATMENT TECHNOLOGIES

4.4.1 MARKET SOLUTIONS

Table 5: Biomimicry treatment technologies

What's being mimicked:	Shark skin surface nanotopography	Insoluble (stop) protein = control crystallization (calcium carbonate build up) in oyster shell formation
Product/ Process Resulting:	Sharklet surface technology for prevention of biofilms and anti-fouling (including prevention of algae build-up)	Scale and erosion inhibitor = thermal polyaspartates
Company	Sharklet Technologies	Nanochem/Donlar
Website:	http://www.sharklet.com	http://www.nanochemsolutions.com/
Availability:	On the market. Sharklet Technologies Inc. was established in 2007 and its products have been put on the market in 2009	On the market
Description :	The patented, microscopic pattern manufactured by Sharklet Technologies creates a surface upon which bacteria do not like to grow. The Sharklet pattern is	Thermal Polyaspartic Acid (TPA) is a mimic of a biopolymer originally discovered in oyster shells. In addition to participating in the formation of oyster shells, TPA inhibits the formation of calcium

	manufactured onto adhesive-backed skins that may be applied to surfaces to prevent biofilm build-up. Sharklet emulates how shark skin denticles are arranged in a distinct diamond pattern with tiny riblets that discourage microorganisms from settling. Sharklet also reduces green algae settlement by 85 percent compared to smooth surfaces.	carbonate, calcium sulphate, barium sulphate and mineral scale, as well as limiting the oxidation of metals. TPA is a polymer made of polyaspartate, with an active carboxylate chemical group attached to it that gives TPA its function. But what makes the polyaspartate of TPA unique is that its polymer backbone is made of chains of amino acids (peptides) instead of the hydrocarbon chains that make up the backbone of polyacrylate. TPA's polymer, then, is degradable by bacterial action.
Further info:	http://www.youtube.com/watch?feature=player_embedded&v=nyfsuXGMG4Q	
Contact info:	Sharklet-patterned film products are available through Tactivex®. To learn more and purchase products, visit www.tactivex.com	Tel: + 1 708.563.9200 Email: nanochems@nanochems.com

Case studies on Sharklet and Nanochem are included in Appendix A.

Since the discovery of bacteria, conventional thinking has led people to kill microorganisms to control them. Yet, overuse and abuse of antibiotics, disinfectants and other kill strategies have contributed to the creation of superbugs such as Methicillin-resistant Staphylococcus aureus (MRSA) and others commonly found in hospitals and the general community. As biocidal approaches have made bacteria stronger, new strategies are needed to manage bacterial growth while contributing to an overall healthy environment to protect people. Such a solution may be found in Sharklet which emulates shark skin's antibacterial properties. Research identified that using an engineered topography emulating sharkskin could be a key to new antifouling technologies (Sharklet, 2008).

The surface technology developed and patented as Sharklet in 2006 is a new approach to microorganism control. The engineered surface is a no-kill, non-toxin and long-lasting technology developed to control the growth of undesirable microorganisms and to inhibit biofilms formation that could result in bacterial colonization. The engineered and patented surface is made up of millions of tiny raised, microscopic features arranged in diamond shapes to form a pattern emulating sharkskin, embedded in different plastic materials.

Although not developed for water treatment applications, this biomimetic technology could have several applications in this field. Similarly, how nature manages scaling can be applied in the water treatment. Mechanisms for prohibiting the growth of calcium carbonate can be found in nature in a biopolymer that stops the growth of shells, e.g. oyster shells. This biopolymer – TPA (thermal polyaspartic acid) inhibits the formation of calcium carbonate, calcium sulphate, barium sulphate and mineral scale, as well as limiting the oxidation of metals. The unique properties and functions of TPA may inspire innovation in the plumbing/piping industry (anti-scaling), diaper/feminine-hygiene/incontinence industry (TPA retains water well, could replace polyacrylics currently used), the oil and gas industry, the detergent industry (anti-redeposition agent), the water treatment industry and agriculture.

6 NATURAL WETLANDS LITERATURE SURVEY

This section examines existing literature regarding natural wetlands, with specific focus on their functions and processes. The review has been undertaken with the specific aim of understanding how wetland ecosystems, their functions and processes can inform better design of constructed wetlands, using the biomimicry technique.

6.1 What is a wetland? Legislation and Policy Context.

Wetlands encompass a broad range of ecosystems, from submerged coastal grass beds to salt marshes, pans, and swamp forests. There are various international and national policies and laws that provide definitions of what constitutes a wetland. Those that are relevant to wetlands in the South African context are outlined here.

6.1.1 International Wetland Definitions

South Africa is a signatory to the Ramsar Convention Convention on Wetlands of International Importance especially as Waterfowl Habitat (1971), more commonly known as the Ramsar Convention. Article 1 of the convention defines wetlands as follows:

'For the purpose of this Convention wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.'

The convention was entered into force in South Africa in December 1975. Contracting parties are obliged to designate suitable wetlands within its territory for inclusion in a List of Wetlands of International Importance, on the basis of their international significance in terms of their support of internationally significant waterfowl populations, as well as notable ecology, botany, zoology, limnology or hydrology.

To date, 22 Ramsar Sites have been designated in South Africa, ranging from wetlands associated with river floodplains such as Nylsvley Nature Reserve; coastal wetlands such as the Turtle Beaches/Coral Reefs of Tongalan Marine Reserve; and lacustrine wetlands such as the Lake Sibaya site.

6.1.2 National Wetland Definitions

<u>WETLAND LEGISLATION</u>

The South African National Water Act (Act 36, of 1998) defines a wetland as:

"land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which

land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil".

No specific distinction is made between types or classes of wetlands, and specifically not between natural and artificial (including constructed) wetlands. All wetlands are protected under the Act.

The Integrated Coastal Management Act (Act No. 24 of 2008) further defines estuarine and coastal wetland systems as follows:

- **Estuary**: a body of surface water—(a) that is part of a water course that is permanently or periodically open to the sea; (b) in which a rise and fall of the water level as a result of the tides is measurable at spring tides when the water course is open to the sea; or (c) in respect of which the salinity is measurably higher as a result of the influence of the sea
- **Coastal wetland**: any wetland in the coastal zone: including (i) land adjacent to coastal waters that is regularly or periodically inundated by water, salt marshes, mangrove areas, inter-tidal sand and mud flats, marshes, and minor coastal streams regardless of whether they are of a saline, freshwater or brackish nature; and (ii) the water, the subsoil and substrata beneath, and bed and banks of, any such wetland.

WETLAND POLICY AND BEST PRACTISE GUIDANCE

The most recent South African wetland classification guidance, published by the South African National Biodiversity Institute (SANBI) (Ollis *et al.,* 2013), defines three primary categories of wetland systems in South Africa: marine, estuarine and inland. Inland systems differ from estuary and coastal systems, in that inland wetlands are aquatic ecosystems with no existing connection to the ocean, and are characterised by the complete absence of marine exchange and/or tidal influence. The SANBI guidance provides specific direction on the definition of the various **inland** wetland types that occur in the country. It refers to three broad types of inland wetland systems, namely:

- **Rivers**: 'lotic' aquatic ecosystems with flowing water concentrated within a distinct channel, either permanently or periodically.
- **Open waterbodies**: permanently inundated 'lentic' aquatic ecosystems where standing water is the principal medium within which the dominant biota live.
- **Wetlands**: transitional between aquatic and terrestrial systems, and are generally characterised by (permanently to temporarily) saturated soils and hydrophytic vegetation. These areas are, in some cases, periodically covered by shallow water and/or may lack vegetation.

The Ramsar definition of 'wetland' encompasses all three types of Inland Systems listed above, whereas rivers and open waterbodies are not wetlands according to the narrower definition of the South African National Water Act. The specific inland wetland types are further discussed in Section 0 below.

6.2 Wetland Formation Processes and Biomimicry

The factors contributing to wetland formation and dynamics are many and varied. They are products of a diverse range of processes; the formation, size and persistence of wetlands are controlled ultimately by hydrological factors, whilst the variety of inland wetlands in South Africa is primarily attributable to differences in geology, drainage and climate, and to a lesser extent, human-induced disturbance (Ellery *et al.,* 2008).

The formation and distribution of wetlands in South Africa is comprehensively reviewed in the WET-Origins Water Research Commission Report, which was produced as part of the Wetland Management Series of reports that emanated from a WRC project entitled Wetlands Research Programme: Wetland Rehabilitation (WRC Project No. K5/1408). Key points from this document regarding wetland formation in South Africa are summarised in the following sections, in the context of applying natural wetland formation principals to constructed wetland solutions, i.e. biomimicry.

6.2.1 Water Balance

Wetlands occur in areas where there is a water surplus at or close to the surface of the earth. The periodic saturation of soils by water is the defining feature of wetlands. Not only does the presence of excess water in soil bring about unique physiochemical conditions in a wetland, water also transports nutrients and sediment into a wetland and, in some cases, nutrients and sediments out of a wetland. In addition, these processes also involve the transfer of energy. It is this complex interaction of inflows and outflows of energy, sediment and nutrients which, over time, shapes the physical template of the wetland.

Water availability in wetlands is determined not just by inputs from rainfall and its contribution to runoff and groundwater, but also by atmospheric demand. Thus it is important to consider the water balance, with potential evapotranspiration being a useful indicator of atmospheric demand for water.

The possible sources of water to a wetland are precipitation, surface inflows and groundwater inflows, and losses are as evapotranspiration, surface water outflows and groundwater outflows. Therefore, wetlands occur where the sum of the input components is greater than the sum of the output components for some time during the year.

The water balance of a constructed wetland should thus be the primary guiding principle in wetland biomimicry projects.

6.2.2 Wetland Hydroperiod

The wetland hydroperiod is the hydrological signature describing the seasonal pattern of water level fluctuations (Mitsch & Gosselink, 2000; Elleray *et al.,* 2008). This is the integration of all inflows and outflows and characterises the nature and constancy of fluctuations. The hydroperiod is generally one of the most important factors affecting the functioning, management and rehabilitation of wetlands, and can be easily influenced by human activities in the catchment and wetland.

The wetland hydroperiod ranges from permanently flooded to intermittently flooded, and various zones of a wetland may have different hydroperiods, e.g. a pan may have temporarily flooded zones, seasonally flooded zones as well as permanently flooded zones, whereas a floodplain may only be temporarily flooded. The hydroperiod of specific wetland zones is determined in the field through a combination of the type of vegetation present and the extent to which they are hydrophilic[1], as well as the soil morphology, most notably the colour of the soil matrix and the presence and abundance of mottles which indicate the various wetness zones (DWAF, 2005)

In the context of constructed wetlands, the wetland hydroperiod must be artificially realised through appropriate management of water input and outflow to achieve the desired wetland outcome. The base contribution of ground water to the wetland must be measured, and supplemented through engineered solutions for groundwater and surface water management, and a pumped water supply where necessary.

6.2.3 Wetland Geomorphology: Erosion and Sedimentation

EROSION

The strong linkage of South African inland wetland systems with the drainage network makes it necessary to understand forms and processes of fluvial[2] systems and particularly the fluvial geomorphology involved in wetland formation. In essence, fluvial geomorphology can be defined by the processes of erosion and deposition, which occurs as a result of surface water movement. Wetlands are normally a sediment sink, given their typical landscape setting, and are highly susceptible to damage and even loss through erosion. Although natural erosion can take place, wetland erosion typically occurs as a result of human activity, and is triggered through creation of 'nick' points, such as confinement of flow through culverting river crossings,

---

[1] Having a strong affinity for water.
[2] Processes associated with rivers and streams and the deposits and landforms created by them.

or through excessive use, e.g. overgrazing resulting in decreased vegetation cover and physical destruction of wetland structure by cattle hooves.

From the biomimicry perspective, it is therefore important to assess the range of erosional processes that are occurring in the catchment of the proposed constructed wetland and devise feasible solutions to counteract these.

SEDIMENTATION

Wetlands, particularly unchannelled valley bottom wetlands and floodplains (Kotze, Marneweck, Batchelor, Lindley, & Collins, 2007) are typically sinks for clastic[3], organic and chemical sedimentation. This characteristic feature of unchannelled valley bottoms and floodplains is key to their provision of regulatory and supporting ecosystem services[4] including sediment removal, toxicant trapping, nutrient uptake, carbon storage, water purification, flood attenuation, habitat provision and primary production.

Manipulation of sediment deposition in constructed wetlands is therefore important in biomimicry of natural wetland functions. This can be achieved through use of appropriate substrates in the initial construction process that have the capacity to support new wetland vegetation growth, and provide sites for biochemical and chemical transformations, and storage of removed pollutants (USEPA, 2000). As the wetland matures, vegetation grows and dies back and additional sediment from water flows becomes trapped; contributing to enhanced wetland function.

6.2.4 Soils & vegetation

Soil forms develop over time and indicate the history of the hydrology and geohydrology. Some South African soil forms are specifically associated with wetland conditions, e.g. Champagne, Katspruit, Willowbrook and Rensburg (DWAF, 1999). (Soils that develop or occur under anaerobic conditions exhibit unique morphological and chemical properties that result from the presence of water for extended periods of time, and these unique properties can then be used as indicators of soil wetness. Soil form indicators and soil wetness indicators are used together for the identification of wetland conditions within the landscape, in combination with vegetation indicators.

Certain vegetation types are considered indicative of wetland conditions in the South African landscape. Wetland vegetation types are categorised according to the capacity of their roots

---

[3] Sediment consisting of broken fragments derived from pre-existing rocks and transported elsewhere and re-deposited before forming another rock
[4] As defined in Landsberg *et al.*, 2013

to grow in permanently saturated (no oxygen present) to temporarily saturated conditions. The standard classification of plants according to occurrence in wetlands is shown in Table 6; only the Obligate Wetland and Facultative species are considered as wetland indicator species.

Table 6: Classification of plans according to occurrence in wetlands, based on US Fish and Wildlife Service Indicator Categories (Reed, 1988)

Wetland Plant Type	Growth Requirements
Obligate wetland (ow) species	Almost always grow in wetlands (> 99% of occurrences) (e.g. *Phragmites australis*, *Typha capensis*, *Juncaceae*).
Facultative wetland (fw) species	Usually grow in wetlands (67-99% of occurrences) but occasionally are found in non-wetland areas (e.g. *Cyperus congestus, Phragmites mauritianus*)
Facultative (f) species	Equally likely to grow in wetlands and non-wetland areas (34-66% of occurrences).
Facultative dryland (fd) species	Usually grow in non-wetland areas but sometimes grow in wetlands (1-34% of occurrences).

Vegetation types are not only an important wetland indicator; wetlands can also be formed as a consequence of particular vegetation communities. The most significant functions of plants in a wetland is due to their growth and subsequent decomposition; plant growth provides a vegetative mass that deflects and moderates flows and provides attachment sites for microbial development; while plant dieback and decomposition creates litter and releases organic carbon to fuel microbial metabolism (USEPA, 2000). In addition, plants stabilise substrates and enhance their permeability (USEPA, 2000), e.g. dense stands of common reed (*Phragmites australis*); in the Nuwejaarspruit downstream of Sterkfontein dam, Willow (*Salix* sp.) root systems become so dense that they form barriers across streams causing impoundments and bank flooding as well as weirs.

6.3 Wetland types

An inventory of South African wetlands has been developed by the South African National Biodiversity Institute (SANBI), which is being continually added to and updated. The most recent wetland inventory map is available as part of the National Freshwater Ecosystems Priority Areas (NFEPA) dataset (Nel *et al.,* 2011).

Wetlands are generally classified according to function and hydrogeomorphology. Differing systems of classification occur in various parts of the world. In South Africa, inland wetlands are characterised according to a tiered system progressing from Marine vs Estuarine vs Inland at the broadest spatial scale, to the wetlands regional setting, its landscape setting (e.g. valley bottom or floodplain), and its hydrogeomorphic (HGM) unit at the finest spatial scale (Ollis *et al.,* 2013). The hierarchical system is illustrated in Table 7 below:

Table 7: Conceptual relationship of HGM Units (Ollis, Snaddon, Job, & Mbona, 2013)

Wetland / Aquatic Ecosystem context		**Functional Unit**		**Wetland / Aquatic Ecosystem Characteristics**
Level 2: Regional Setting	**Level 3: Landscape Unit**	**Level 4: HGM Unit**	**Level 5: Hydrological Regime**	**Level 6: Wetland Descriptors**
DWAF Level 1 Ecoregions OR NFEPA WetVeg Groups OR Other spatial framework	Slope Valley floor Plain Bench	River	Perenniality	Natural vs. Artificial Salinity pH Substratum type Vegetation cover type Geology
		Floodplain wetland	Period and depth of inundation Period of saturation	
		Channelled Valley-Bottom wetland		
		Unchannelled Valley-Bottom wetland		
		Depression		
		Seep		
		Wetland Flat		

Despite the classification of various wetland types, it is widely recognised that each wetland is extremely unique with specific functioning, which occurs in each case as a result of multiple, complex interactions and processes. This is allowed for in the classification scheme through the inclusion of wetland descriptors (Level 6).

Areas belonging to the same HGM type with similar geology and climate are likely to exhibit similar processes. These HGM types provide a means of delineating wetland units and are utilised as measurement units for assessing wetland functionality (Kotze *et al.*, 2008), present ecological status (PES) (Macfarlane, et al., 2008) and ecological importance and sensitivity (EIS).

6.4 Wetland functions and ecosystem services

Wetlands are extremely complex ecosystems which support numerous functions and processes. Examples of the relationships between ecosystem functions, role players and interdependencies that together ensure sustainable and robust wetland functioning are provided in Table 3.

Table 8: Examples of key role players within wetlands

Function	Key role player	Microfunction	Description of Interdependencies which maintain ecosystem balance
Flood Attenuation	Hydrological zonation – wetland vegetation	Plants exist within and are adapted to various 'hydrological zones' according to the amount of water they receive. Each type of plant provides specific energy dissipation and flood resistance. Typha lies flood in the channel or waterway, yet absorbs and reduces energy with friction and undulation. Phragmites sp. will pose more resistance with more rigged lignin laden stem that yet still have large are compartments for floatation, while Typha sp. has a mesophilic structure with less woody characteristics. Sedges and Restios might rate between the two, with plasticity yet a conical structure that would offer more resistance to flow than Typha.	Plant *plasticity* enables survival during times of excessive inundation or complete lack of water, inundation allows plants to deposit seed beds up and down bank, ensuring survival.
Streamflow regulation			
Sediment trapping	Root systems of wetland plants.	Hydrophytes such as Phragmites, act as mechanical filters for silt and clay particles in water. Hyacinths, Water Lettuce, Water ferns, etc. also provide good mechanical filtering. Phragmites and other macrophytes like Papyrus for effective sediment filters and will effectively immobilise larger sand particles as well. Good examples of the functioning are	Water inflow containing sediment is trapped by vegetation which in turn takes up nutrients from sediment and creates habitat for macro-invertebrates, fish and birds.

Function	Key role player	Microfunction	Description of Interdependencies which maintain ecosystem balance
		seen in the Okavango Delta systems.	
Phosphate assimilation		P is rapidly recycled and reused by bacteria and small phytoplankton and over longer periods by zooplankton in open water (Moss B. , 2009) . P can also be mobilised from the sediments of some wetlands Microorganisms such as Daphnia feed off algae that thrive on excessive phosphates which result from excessive organic runoff	Birds such as flamingo's (Phoenicopterus sp.) are attracted to and feed on excess organisms which have multiplied for various reasons. Thus parameters are controlled within a narrow range around a certain optimal level. Phosphate is essential for most megafauna and the filter feeders are able to concentrate the resource.
Nitrate assimilation	Atmospheric nitrogen fixation by diazotrophs (input) and further nitrification is offset by losses due to microbial N mineralization to gaseous forms (dinotrogen, nitrous oxide) via denitrification	High productivity of wetland plants allows for uptake and removal of nitrates from the water. Nitrogen compounds are reduced to nitrogen gas which is released into the atmosphere	Plants are grazed/browsed by animals, thereby removing the nutrients and allowing them to be redistributed
Nitrate assimilation	Atmospheric nitrogen fixation by diazotrophs (input) and further nitrification is offset by losses due to microbial N mineralization to gaseous forms (dinotrogen, nitrous oxide) via denitrification	High productivity of wetland plants allows for uptake and removal of nitrates from the water. Nitrogen compounds are reduced to nitrogen gas which is released into the atmosphere	Plants are grazed/browsed by animals, thereby removing the nutrients and allowing them to be redistributed
Toxicant assimilation	Fauna and flora	Bioaccumulation of toxicants by species of flora and fauna within the wetland.	Elements which are toxic to some organisms, are often not toxic for others and are thus hyeraccumulation of the toxins occurs within these species. . Copper, for example is toxic to numerous plants at high concentrations while being an essential trace element (at low densities) to fauna species which eat these plants.

Function	Key role player	Microfunction	Description of Interdependencies which maintain ecosystem balance
Erosion control	Stoloniferous vegetation root networks	Wetland vegetation roots hold substrate and prevent loose substrate from being carried away in water	Sediment and soils are bound by strong root systems that penetrate them and bind them. This retains habitat for other flora, micro-organisms and avifauna.
Carbon storage	Flora and microbes.	Water cover, plants and micro-organisms	Anaerobic conditions created through water cover, as well as high productivity of plants due to environmental conditions result in plant production which usually exceeds decomposition in wetlands and results in the net accumulation of organic matter and carbon
Biodiversity Maintenance	Wetlands are biodiversity hotspots where various ecotones come together and support large varieties of life forms from microbes to macrophytes and fauna species	Balance of species abundance within wetland generally occurs as high concentrations of food sources will be utilised by migratory species that will move on once conditions aren't ideal any more.	Various species perform this role, daphnia will control algae and diatom blooms, flamingos will concentrate in large numbers where a daphnia bloom occurs and will filter out the nutrient resource. In wetland systems like Lake Natron, hyena, baboons and fish eagles will begin preying on flamingo populations.

Wetland functions include physical, chemical, and biological processes and attributes that are vital to the integrity of the wetland system, operating whether or not they are viewed as important to society, (Adamus *et al*., 1991). These functions have been categorised in the WET-Ecoservices (Kotze *et al.*, 2008). The ecosystem services delivered by natural wetlands are often used as goals in wetland rehabilitation and construction. For example, the capacity of a wetland in the supply of nutrient removal, sediment trapping and flood attenuation ecosystem services are used as a measure of wetland function (Kotze *et al*., 2008). Quantitative magnitude of functions may vary from one system to another (Table 9).

Table 9: WET- ecoservices, ecosystem services classification (Kotze, Marneweck, Batchelor, Lindley, & Collins, 2007)

Ecosystem services supplied by wetlands	Indirect benefits	Regulating and supporting benefits		Flood attenuation	The spreading out and slowing down of floodwaters in the wetland, thereby reducing the severity of floods downstream.
				Streamflow regulation	Sustaining streamflow during low flow periods.
			Water quality enhancement benefits	Sediment trapping	The trapping and retention in the wetland of sediment carried by runoff waters.
				Phosphate assimilation	Removal by the wetland of phosphates carried by runoff waters.
				Nitrate assimilation	Removal by the wetland of nitrates carried by runoff waters.
				Toxicant assimilation	Removal by the wetland of toxicants (e.g. metals, biocides and salts) carried by runoff waters.
				Erosion control	Controlling of erosion oat the wetland site, principally through the protection provided by vegetation.
				Carbon Storage	The trapping of carbon by the wetland, principally as soil organic matter.
	Direct benefits	**Biodiversity maintenance**			Through the provision of habitat and maintenance of natural process by the wetland, a contribution is made to maintaining biodiversity.
		Provisioning		Provision of water for human use	The provision of water extracted directly from the wetland for domestic, agriculture or other purposes.
				Provision of harvestable resources	The provision of natural resources from the wetland, including livestock grazing, craft plants, fish, etc.
				Provision of cultivated foods	The provision of areas in the wetland favourable for subsistence farming.
		Cultural benefits		Cultural heritage	Places of special cultural significance in the wetland, e.g. for baptisms or gathering of culturally significant plants.
				Tourism and recreation	Sites of value for tourism and recreation in the wetland, often associated with scenic beauty and abundant birdlife.
				Education and research	Sites of value in the wetland for education or research.

6.4.1 Stream flow regulation

Stream flow regulation refers to the sustaining effects of a wetland on downstream flow during low flow periods. It recognises that wetlands do not generate water; being in fact users of water through evaporation and transpiration. However, wetlands also promote downstream flow in low flow periods, through 'plugging' sub-surface movement of water downslope, increasing the storage capacity of the slope above the wetland and prolonging the contribution of water to the downstream system (Kotze *et al*., 2008)

A number of factors contribute to a wetland's capacity to regulate stream flow, including the extent of linkages of the stream network, hydrological zonation of the HGM, extent of fibrous peat or mineral soils, presence of floating marshes, reduction of evapotranspiration through frosting back of the wetland vegetation, and the geology underlying the wetland's catchment. (Kotze *et al*., 2008). Literature regarding stream flow is well researched and the process drivers and wetland responses are well understood. Hydrology, hydraulics and their effect on habitat and aquatic and semi-aquatic organisms are used for ecological reserve determination in lotic systems (DWAF, 1999), (DWAF, 2004). These drivers are now being studied and applied to wetland systems in order to determine the ecological reserve for these.

The positioning of a wetland in the landscape is an important aspect to consider as it has direct effect on the nature and functioning of the particular wetland system (Carol *et al.,* 1990). Wetlands such as reedbeds in low energy zones of rivers (valley bottoms) will assist with flood attenuation, sediment capture and habitat supply for specific avifauna, whilst other wetlands such as hillslope seeps prolong the contribution of water to the downstream systems during the dry season (Kotze *et al.,* 2008).

Depressions or pans are (generally) low energy systems on or near watersheds where hydrology is ill defined. They are accumulators of sediment and often nutrients, and supply habitat to waders and open water filter feeders. As they are generally not directly connected to a stream channel, their role in stream flow regulation is minimal.

Principal components of stream flow regulation and quality are also associated with the seasonal export of organic matter, organic nitrogen and orthophosphate. (Carol *et al.,* 1990).

Table 10: Table illustrating primary functions of wetlands associated with position in the landscape

Type	*General Primary Function*	*Description*
Flood Plain	Flood attenuation Sediment trapping	Topography allows for spreading out and slowing of water velocity in order that flooding is prevented at lower reaches. Slowing of water allows for greater sediments to be deposited and trapped.
Hillside seepage	Water provision	Subsurface flow from higher altitude and often the groundwater table and vadose zone is channelled to accessible surface source
Depression	Biodiversity Maintenance	Seasonal flooding of depression/pan allows for the accumulation of surface water. Species richness results as water, food and habitat are abundant.

Flood attenuation refers to the spreading and slowing of water which serves to reduce the severity of floods downstream and therefore preventing potential damages downstream. (Kotze *et al.,* 2008). The value that wetlands hold in terms of their function in flood attenuation is well recognised.

A number of characteristics influence the ability of wetlands to attenuate flood waters but size of wetland plays a role in the attenuation of floodwaters. Basic rationale suggests that the larger the wetland relative to its catchment, the greater will be its potential influence on flood flows (Kotze *et al.,* 2008). Additionally, slope, surface roughness, presence of depressions, frequency with which storm flows are spread across the HGM, sinuosity of the stream channel, hydrological zonation, slope of the catchment, determining the inherent runoff potential of soils, land use within catchment and rainfall intensity all are influential in flood attenuation capacity of wetlands (Kotze *et al.,* 2008). The mechanisms of flood attenuation are numerous. These vary from physical energy and flow dissipation like that provided by *Phragmites* reed beds, to the sponge effect of softer sedge dominated systems, to the dispersion and distribution of flow in swamp forests.

The action of attenuating flooding is recognised to not only be an ecosystem service but a requirement of wetlands for maintenance of wetland health and integrity. Species within the system are particularly adapted to flooding events and are therefore dependent on it. Cycles of flooding, followed by soil drainage are essential for regeneration, growth and preservation of biodiversity. Any changes in the timing and/or frequency of flooding of such systems may result in inadequate seed supplies, poor seed, deficiencies of groundwater and mineral nutrition; all of which may affect the extent of vegetation cover and the wetland's capacity to attenuate flooding.

Adverse impacts of prolonged flooding on wetland vegetation are associated with physiological dysfunctions induced by soil anaerobiosis; changes in respiration, photosynthesis, protein synthesis, mineral nutrition, hormone relations, together with increased exposure to phytotoxic compounds may occur within the wetland (Kozlowski, 2002.)

6.4.2 Sediment trapping

Sediment is a major pollutant which threatens water quality (Liu *et al.,* 2000), and wetlands are directly linked to sediment trapping. (Zierholz *et al.,* 2000). Sediment trapping refers to the trapping and retention of sediment carried by runoff waters. Excess sediment diminishes quality of the water by contributing to increases in turbidity (Kotze *et al.,* 2008). The sediment trapping capacity of a wetland is influenced by effectiveness of flood attenuation, evidence of sediment deposition, reductions in sediment inputs from the catchment (Kotze *et al.,* 2008).

Table 11: Sediment trapping mechanisms in wetlands (Liu *et al.,* 2000).

Processes and features of wetland	Aspect	Mechanisms which contribute to greater sediment trapping
Hydrogeomorphology	Slope	Various topographic features result in slowing and spreading of water which results in sediments settling to floor of wetland. Sediment removal rates are best with shallow, uniform flow across the filter area.
Vegetation	Vegetation buffer width	Slowed water velocity allows the sediments to settle and allow plants hold the accumulated sediments in place
Geomorphology	Ratio of Wetland size to drainage area	Higher area ratios result in greater efficacy of sediment trapping
Vegetation structure	Height of vegetation in relation to water depth	Vegetation height must be upright in order to decrease the amount of sediment in the water column

The trapping of sediment which is enriched with nutrients contributes to the general health and productivity of the wetland system. It further assists in the recovery of sediment-impacted systems further downstream. Sediment trapping is also the beginning of the process of bioremediation, as much of the sediment is loaded with toxic chemicals, which then become entrapped in the root systems which provide microbial attachment sites that may assist in toxin breakdown.

The process of sedimentation and the associated feedback mechanisms which occur in wetlands, contribute to the morphology and functioning of that wetland. This process is significantly obvious in the Okavango and has been researched extensively by McCarthy *et al*. (1992). This study, as well as a number of other significant international wetlands studies (reference) of this process make a valuable contribution to this understanding.

Factors influencing a wetland's efficiency for sediment trapping include extent of vegetation cover in the wetland, surface roughness (expressed as vegetation height), slope of the HGM unit, and its effectiveness in attenuating floods: the greater the extent to which a wetland attenuates floods (e.g. through high surface roughness), the more effective it will be in trapping sediment (Ammann and Lindley-Stone, 1991).

A particular comparison of degraded wetland functions to non-degraded, natural flow wetland revealed non-degraded wetlands significantly improved water quality, reducing suspended loads of sediment and nitrate, with specific retention of N, total P and SRP (Knox *et al.,* 2008). However the regulation of inflow rates was highlighted to be an important aspect

Sorptive[5] assimilation of organic compounds in wetlands appears to be dependent on the unique hydrological conditions that promote sediment water exchange and accretion rather than the enhanced ability of wetland soils themselves (Pardue *et al.,* 1999).

6.4.3 Phosphate and Nitrate accumulation

Phosphate (P) and nitrate (N) removal refers to the removal of these nutrients when carried by runoff waters, thereby enhancing the quality of the water downstream. (Kotze *et al.,* 2008)

A number of factors influence phosphate and nitrate accumulation by wetlands; effectiveness of sediment trapping, pattern of low flows, extent of vegetation cover, levels of fertilizers which are directly applied to the water, levels of nitrate and phosphate in the water (Kotze *et al.,* 2008). High levels of nutrients such as phosphorous and nitrogen, can be significantly reduced through uptake by wetland vegetation and retention in wetland sediments (USEPA, 2000a). This may prevent phosphorous and nitrogen compounds from reaching toxic levels in surface

[5] a physical and chemical process by which one substance becomes attached to another

and groundwater. It also helps to reduce the risk of eutrophication in surface-water bodies further downstream, which occurs when high nutrient (phosphate and nitrogen) levels cause a massive boost in algal growth, depleting oxygen and blocking out the light that other aquatic plants and animals need to survive.

Some wetland plants have the capacity to take up and remove toxic substances that have come from pesticides, industrial discharges and mining activities from aquatic ecosystems. This is discussed in detail in Section X.

Plant composition and temperature play important roles in the nutrient removal efficiency of these wetlands, but the interactions between these variables are not well understood (Picard *et al.,* 2005).

Wetlands used for the control of non-point pollution provide a variety of secondary benefits in addition to their primary role of flood attenuation and water quality enhancement (Knight, 1992). Such benefits include adding to the aesthetic value of the wetland, as well as increasing its capacity to support a greater diversity of wetland plants, waterfowl and other fauna (USEPA, 2000a).

In their review of the levels of nutrient removal achieved by fifty-seven wetlands, Fisher and Acreman (2004) state that there is little difference in the number of wetlands that reduce N to those that reduce P. However, some wetlands increase nutrient loadings, by increasing the loading of soluble N and P species thus potentially driving aquatic eutrophication. Wetland N and P uptake is largely dependent on degree of waterlogging, rate of nutrient loading, duration of nutrient loading (Fisher & Acreman, 2004).

The condition of the receiving water body is of particular importance in consideration of nutrient uptake. Increases in nutrient loading are also seasonal; nutrient loading may be increased in autumn as plants die back, in addition increases in flows and erosion may occur during summer months due to increased rainfall volumes. For maximum P removal wetland substrate should not be reducing (Fisher and Acreman, 2004.).

Phosphate assimilation efficiency in wetlands has also been linked to high flow periods by specific studies (references). Downstream wetlands have different characteristics than headland water wetlands, affecting their nutrient retention capacity (Carol *et al.,* 1990).

There is abundant information regarding the uptake of nutrients in riparian conditions, swamp, marsh and floodplains however there is less information regarding uptake in bogs and fens (Fisher & Acreman, 2004) However, swamps and marshes are thought to be more effective at nutrient reduction than riparian zones, largely due to the lentic (vs lotic) flow conditions.

Attributes that make wetlands more effective in the assimilation of N and P therefore need to be considered further when constructing wetlands (Fisher & Acreman, 2004). Brinson *et al.* (1984) stresses the need for consideration of shape and size in this regard. Fleischer *et al.* (1997) similarly states the correlation between nutrient uptake and wetland size. However, Fisher and Acreman (2004) state that there is much variation in the descriptions of hydrology and effectiveness of nutrient uptake.

6.4.4 Toxicant removal

Removal of toxicants which are carried by runoff waters or non-point sources by wetlands enhances water quality further down the stream. Toxicants may include metals, biocides, salts and bacteria. Wetlands are extremely effective in the removal of toxicants and increasing evidence supports this function (Kotze *et al.*, 2008)

<u>SULPHATES</u>

Wetlands have been proven to be capable of removing sulphates. Anaerobic microbial processes play particularly important roles in the biogeochemical functions of wetlands, affecting water quality, nutrient transport, and greenhouse gas fluxes (Whitmire & Hamilton, 2005). A key requirement of a successful passive sulphate reduction technology is the development of a passive sulphide oxidation technology that is capable of removing the sulphides produced from sulphate reduction before they can be reoxidised back to sulphate (Pulles & Heath, 2009). Many pool systems in nature are followed by riffles or rapids, so one has a slow deep low energy system, followed by a high energy aeration system.

There is extensive literature regarding this process as a result of two major South African biological sulphate reduction research initiatives. The first initiative has been ongoing for 15 years by Pulles Howard & de Lange. The second initiative has been ongoing for a period of around 15 years by the Environmental Biotechnology Research Unit at Rhodes University.

The leading position in the field of passive sulphate removal technology is occupied by South African researchers and is the product of a sustained and concerted research effort. (Pulles & Heath, 2009)

<u>PHYTOREMEDIATION</u>

Macrophytes play a prominent role in nutrient and heavy metal recycling in many aquatic ecosystems (Dhote & Dixit, 2009).

There is a growing body of literature confirming the capacity of wetlands as sinks for metals. Studies on the accumulation of metals including lead, zinc, copper and cadmium by various plant species are prolific.

Phytoremediation potential in wetlands is complex due to variable conditions of hydrology, soil and sediment types, plant species diversity, growing season and water chemistry. The success of long-term phytoremediation projects are reliant on the role of wetland plants in reducing contaminant loads in water and sediments, including metals, volatile organic compounds, pesticides and other organohalogens (Williams, 2002).

Investigations of the phytoremediation potential of natural wetlands have mainly involved laboratory microcosm and mesocosm studies. Initially, a few large scale field studies have addressed remediation actions by natural wetland communities (Williams, 2002; other references).

A review of plant species which hold the greatest potential for uptake of nutrients was performed by Dhote and Dixit (2009) in order to establish which macrophytes perform best in the uptake of nutrients. Their findings are very encouraging with regards to phyto-extraction and degradation by rhizosphere and plant tissue enzymes. They state that the next phase in advancing acceptance of phytoremediation as a regulatory alternative must demonstrate sustained contaminant removal by intact wetlands.

According to Weis & Weis (2005) most wetland plants have similar patterns with regards to metal uptake; that is metal concentration occurs primarily in root systems. Thereafter, some species redistribute the metals to above ground tissues, especially the leaves. Storage in roots is beneficial for phytostabalization of metal contaminants; as metals in leaves may be excreted over time through salt glands, returning the metals to the marsh environment, and may accumulate in deposit-feeding invertebrates, thereby entering into estuarine food webs (Weis & Weis, 2005). Wetlands can therefore be understood as both sources and sinks of metals, thus plant selection criteria for high metal load wetlands should be based on metal tolerance and rhizosphere surface area rather than metal bioaccumulation.

Radioactive contamination has been linked to wetland processes in Chernobyl (Burrough *et al.,* 1996). The evidence of radiocaesium from contaminated soils being absorbed by plants and animals was directly linked to flooding which results in the uptake of radiocaesium into the food chain, particularly in unimproved pastures on peaty soils. The detailed interactions between flood deposition, retention in the soil and uptake into the food chain have not been fully investigated but are directly linked to drainage network.

Numerous studies of specific removal rates of wetland plant species examine below and above ground bioaccumulation of metals. Growing conditions for greatest removal and effectiveness are also explored.

Removal of radionuclides such as uranium, and arsenic has similarly a large body of literature. Short and long term outcomes of utilization of specific plants such as *Lemna gibba* provide conclusive evidence for phytoremedial capacity of these metals.

The importance of certain plant families is increasingly evident for the clean-up of the metal contaminated and polluted ecosystems. The families dominating these members are Asteraceae, Brassicaceae, Caryophyllaceae, Cyperaceae, Cunouniaceae, Fabaceae, Flacourtiaceae, Lamiaceae, Poaceae, Violaceae, and Euphobiaceae (Prasad & Freitas, 2003). Some have been largely studied, such as Asteraceae, Brassicaceae and Euphorbiaceae, which are well known for their capacity for accumulation of nickel (Turnau, & Mesjasz-Przybylowicz, 2003). *Berkheya codii* is also well known for its capacity for hyperaccumulation of heavy metals (Keeling, Stewart, Anderson, & Robinson, 2003) . Although this is not a wetland-obligate plant, numerous *Berkheya* species (all part of the Asteraceae family) occur within wetlands.

Indigenous wetland sedges within South Africa have recently been studied by the South African Council for Scientific and Industrial Research (CSIR,) focussing on their phytoremedial capacity (Schachtschneider, Muasya, & Somerset, 2010). The species *Schoenoplectus corymbosus* and *Cyperaceae haspan* were found to be particularly good in their phytoremedial capacity (Schnachtschneider *et al.,* 2010), (Table 12).

International studies have explored a number of wetland plants which have phytoremedial capacity and illustrate themselves to be good hyperaccumulators[6]. These include a number of species found in South African wetlands; *Lemna minor, Lemna gibba, Typha latifolia, Typha capensis, Echornia crassipes, Juncus effuses, Cladium mariscus and Phragmites australis*. (Schnachtschneider *et al.,* 2010)

[6] a plant capable of growing in soils with very high concentrations of metals, absorbing these metals through their roots, and concentrating extremely high levels of metals in their tissues

Table 12: South African hyperaccumulator plant species (Schnachtschneider *et al.*, 2010)

Species	Metals Uptake
Berkheya codii	Ni
Berkheya zeyheri	Ni
Berkheya coronatus	Ni
Lemna minor, Lemna gibba	Ni, Al, Fe, Mn and Mg
Typha latifolia, Typha capensis	Al, Fe, Mn and Mg
Juncus effuses	Zn
Cladium mariscus	Co
Schoenoplectus corymbosus,	Al, Fe, Mn and Mg
Cyperaceae haspan	Al, Fe, Mn and Mg
Phragmites australis.	Al, Fe, Mn and Mg
Eichornia crassipes (Exotic)	Cd, Cu, Hg, Pb, Zn
Pistia stratiotes (Exotic)	Cd, Hg, Cr, Cu
Azolla filiculoides	Ni, Pb, Mn

SODIUM

The capacity of natural wetlands to remove or remediate sodium in water is not well researched or understood. Certain potential toxicants, (e.g. high levels of dissolved sodium and chloride) are thought not to be effectively removed by wetlands (Kotze *et al.*, 2008). There is a body of research which explores salt marshes and salt gradients, however this knowledge has not yet found application in design. The feedback interactions of vegetation, groundwater elevation and chemistry, as well as soil chemistry as they relate to reduction of salinity levels in aquatic systems needs further research.

6.4.5 Erosion control

Erosion control is afforded though a number of onsite factors which reduce loss of soil, reduction in downstream flooding and erosion downstream of the wetland. Similar to sediment trapping; vegetation cover, surface roughness, current level of soil erosion, slope and erodibility and intensity of runoff all contribute to this process (Kotze *et al.*, 2008). Erosion control by natural wetlands is well published. This function is largely a product of the sediment trapping nature of wetlands as well as flood attenuation and stream flow regulation.

6.4.6 Carbon Storage

Carbon storage refers to the wetland's trapping of carbon in the form of living and decomposing organic matter, which effectively serves as a carbon sink. The organic carbon is converted into compounds including carbon dioxide and methane which may be released as gas, or stored in plants, dead matter, micro-organisms, or peat. The lack of oxygen, or anaerobic conditions found in wetlands, is the main factor in determining plant detritus turnover (Kayranli *et al.*, 2010). The various decomposition reactions take place in different horizons, for example respiration and methane oxidation which take place in aerobic zones while methanogenesis occurs in the anaerobic zones (Kayranli *et al.*, 2010).The organic matter content within the wetland system is impacted by processes such as biodegradation, phytochemical oxidation, sedimentation, volatilization, and sorption (Kayranli *et al.*, 2010).

The cumulative effect of this carbon storage has great significance for global climate change; carbon sequestration by wetlands is recognised as a valuable ecosytem service. Storage of carbon additionally has positive effects in terms of water and nutrient retention at a landscape level (Kotze *et al.*, 2008).

Peatlands have been well researched, with conclusive findings which reflect them to be effective carbon stores and instrumental in carbon sequestration.

Dissolved organic matter is an extremely important water quality parameter which is associated with the performance of treatment wetland systems. Some microorganisms including bacteria use dissolved organic matter as an energy source for processes such as denitrification (Kayranli *et al.*, 2010).

Different types of wetland systems such as natural, constructed, treatment, and integrated constructed wetlands have the potential to sequester carbon (Kayranli *et al.*, 2010).

Constructed wetlands have more carbon sequestration capacity than natural wetlands (Kayranli *et al.*, 2010).

The role of many wetland plants and microorganisms in carbon turnover and emitting methane is unclear. More research is required to better understand the impacts of the different plant species under variable nutrient regimes and loading rates (Kayranli *et al.*, 2010).

6.4.7 Biodiversity maintenance

Wetlands provide habitat and maintain natural processes, thereby contributing to the maintenance and support of biodiversity. Integrity of the wetland plays a major role in this ecosystem service provision. Biotic community health is therefore of major importance. The extreme complexity of wetland communities means that understanding and assessing the integrity of specific systems can be challenging (Kotze et *al.*, 2008).

Biodiversity dependence on regular functioning of the wetland, including flooding events has been explored. Linear relations between spatial variation, flood frequency and species richness have been identified (Pollack *et al.*, 1998).

Species richness is directly linked to greater productivity. Biodiverse wetlands have been illustrated to have higher nitrogen retention capacity (Hansson *et al.*, 2005).

6.5 Natural Wetlands and Biomimicry: Summary and Conclusions

In consideration of natural wetlands and biomimicry there is obvious scope for learning from and mimicking the various aspects and processes which occur.

The extensive body of research regarding natural wetlands offers valuable insight into how and why natural processes occur, which could better inform designers and engineers on the application of these processes to constructed wetland design. Much of the research on natural wetlands has been applied to the design of constructed wetlands, however, with the identified knowledge gaps and synthesis of research, there is scope for further application of the natural technologies which exist. The emulation of the wetland formation processes, types and functions described above in constructed wetland design through biomimicry approaches could contribute to enhanced functioning of constructed wetlands, particularly those which are smaller in extent.

7 CONSTRUCTED WETLANDS

Natural wetlands are environments intermediate between terrestrial and aquatic systems, and have been used either deliberately or inadvertently to treat wastewaters for centuries (Haberl, 2003). Constructed wetlands (CWs), also known as treatment wetlands (TWs), are engineered wastewater treatment systems that mimic the bioremediatory processes taking place in natural wetland ecosystems (Vymazal J. , 2005). Typically, the wetland substrate supports the growth of plants and microbial communities that function synergistically to remediate polluted water (Vymazal J. , 2005) (Kiviasi, 2001). By designing CWs with a range of structural characteristics and hydraulic flow regimes, the systems can be tailored for the treatment of different target waste streams.

(a) (b)

Figure 3: Examples of (a) a pilot-scale, experimental constructed wetland (http:www.japanfs.org) and (b) an operational full-scale constructed wetland (http:www.waterlink-international.com)

7.1 Types

Three classification schemes have been applied to CWs. The first system is incumbent on the complexity involved in the design and operation of CWs. In this scheme, CWs are divided into two types, type A and type B. Type A CWs are usually quite natural, with plants often encroaching via spontaneous recruitment (Kadlec, 2009). These CWs are cost effective to construct and operate and are usually gravity fed, with low energy requirements (Kadlec, 2009). Conversely, type B CWs are highly engineered with comparatively high construction and operational expenses. The use of energy-demanding pumping and piping systems for water transfer and recycling is common in type B CWs (Kadlec, 2009). The second and third classification systems are more widely used and are based on the type of macrophytic growth and the hydraulic flow regime, respectively.

Planted systems: classification and impact of plants on CW function

Planted CWs are classified according to the dominant type of macrophytic growth (Vymazal J. , 2005). In natural and constructed wetlands, macrophytes are either free-floating or attached to the substratum. Attached macrophytes may be either emergent, submerged (at various depths within the photic zone) or have leaves which float on the water surface (Figure 4.2) (Wetzel, 2001).

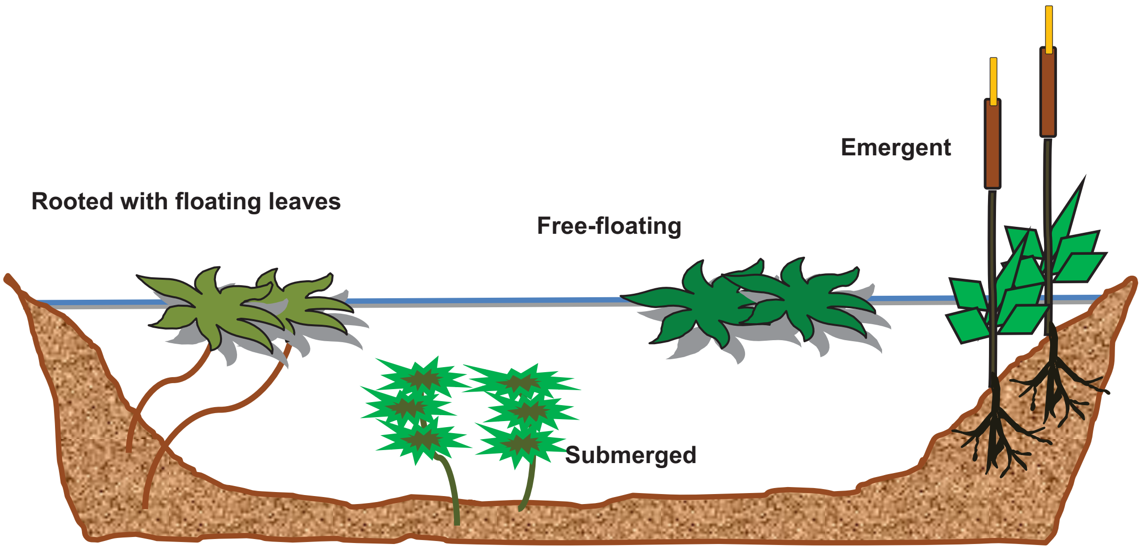


Figure 4: Diagram showing the four broad categories of macrophytic growth that is used to classify constructed wetlands.

CWs containing free-floating macrophytes have proven effective for reducing organic load and pathogens. However, in free-floating systems: (i) large volumes of water may be lost by evapotranspiration, (ii) the rapid growth rate of many species necessitate frequent harvesting and (iii) many species are exotic invaders (e.g. water hyacinth) (Kiviasi, 2001).

Most CWs are designed to support the growth of emergent macrophytes in a range of substrates. In nature, these plants are found in water-saturated or submerged soils, from the point where the water table is about 0.5 m below the surface of the soil to where the sediment is covered with about 1.5 m of water (Wetzel, 2001). The most common macrophytes utilized in CWs are *Typha* spp. *Phragmites* spp. and *Juncus* spp., but for aesthetic reasons, even ornamental species (*Kanna, Heliconia*) have been successfully grown in CWs used to treat domestic wastewater (Brisson, 2009) (Konnerup, 2009).

The roots of plants provide expanded attachment sites for microbial growth and nutrient uptake (Li J. W., 2008). There is abundant evidence that the removal of N and to a lesser extent, P, may be enhanced by the presence of emergent macrophytes; the rate of nutrient removal varying according to the genus and species of the dominant macrophyte/s (Arienzo, 2009) (Brisson, 2009) (Kadlec R. , 2008) (Tietz, 2008). Plants can modify the microbial community structure and increase the species richness of constructed wetlands (Li J. W., 2008) (Calheiros, 2009). Most literature sources identify that emergent macrophytes enhance nutrient removal by delivering oxygen to the CW substratum via root systems, but there is also evidence that nutrient removal rates are related to the development of functional rhizospheric bacterial communities; for example, it has been shown that the presence of *Typha angustifolia* and *Cyperus involucratus* enhances the growth of the ammonium oxidising genus, Nitrosomonas in the rhizosphere (Kantawanichkul, 2009) (Calheiros, 2009) (Li J. W., 2008). Removal of phosphorus (P) in CWs is often poor; any P removal due to the presence of plants is almost exclusively due to bioaccumulation within plant tissues, and unless the macrophytes are regularly harvested, P may be released upon plant senescence (Greenway, 1999).

Some wastewaters may have a negative impact on macrophytic growth. Winery and molasses wastewaters are examples of which have been identified as potentially phytotoxic (Arienzo, 2009) (Sohsalam, 2008). In some cases, macrophytes which have been adversely affected by wastewater may be naturally replaced by more resilient species (Kadlec R. , 2008). Wetland plants are also capable of taking up heavy metals and other environmental contaminants from wastewater, which can then be removed by harvesting plant biomass in a process known as phytoremediation (Kiviasi, 2001). In CWs designed for phytoremediation, the harvesting procedure is least labour intensive in CWs containing free-floating macrophytic species.

7.2 HYDRAULIC FLOW REGIME

The third and most widely used classification system for CWs is based on the hydraulic flow regime. The flow of wastewater may take place predominantly over the surface (surface flow) or within the substratum (subsurface flow). Subsurface flow may be from top to bottom (vertical subsurface flow) or from inlet to outlet (horizontal subsurface flow) (Vymazal J. , 2005). The three basic hydraulic regimes employed in constructed wetlands are termed free water surface flow (FWSF) Figure 5; horizontal sub-surface flow (HSSF) Figure 5 and vertical subsurface flow (VSSF) Figure 7 (Vymazal, 2007). Hybrid CW systems are also becoming popular; these combine the advantages of different hydraulic regimes, either by employing a series of CWs, each with different modes of operation, or by combining more than one hydraulic regime within the same CW (Burton, 2011) (Toscano, 2009). Some of the comparative advantages and disadvantages of the different hydraulic regimes are discussed below.

7.2.1 Free-water surface flow constructed wetlands

FWSF CWs may offer some ecological advantages over SSF systems as they create a habitat for aquatic species and increase biodiversity (Kadlec, 2009). In the case of domestic wastewater, at low loading rates, COD removal efficiency of FWSF CWs may be comparable to that of some HSSF systems (Kadlec, 2009) (Naz, 2009). However, because the most important P removal processes typically take place in the substratum, the removal of P is lower in FWSF systems than in SSF systems (Verhoeven, 1999). In the case of highly contaminated wastewaters, FWSF CWs may expose humans and wildlife to toxins, pathogens and odours and may provide a habitat for nuisance species such as mosquitoes (Kadlec, 2009). The formation of algal blooms, with resultant increased effluent chemical oxygen demand (COD) and possibly toxin formation is also likely to occur in FWSF CWs (Naz, 2009).

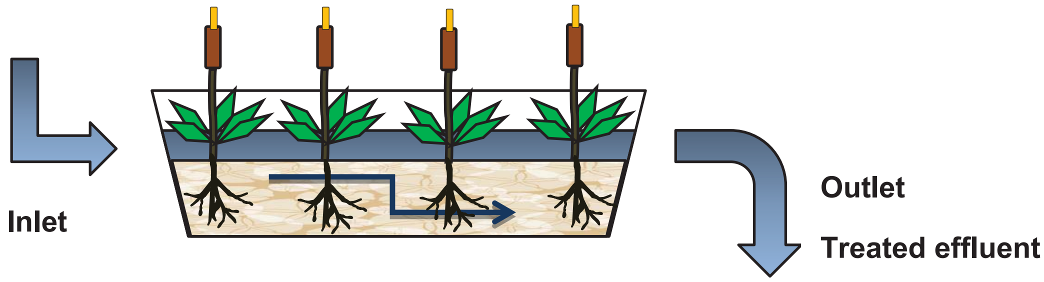


Figure 5: Schematic diagram of a free water surface flow (FWSF) CW. The substrate is permanently inundated and flow takes place horizontally, mostly over the surface, to the outlet which is located at surface level or above the surface.

7.2.2 Horizontal and vertical subsurface flow constructed wetlands:

<u>MODE OF OPERATION</u>

Subsurface flow CWs are either operated in batch mode or continuous mode: batch mode is typically applied to VSSF CWs and continuous mode to HSSF CWs. In continuous mode, the wastewater flows constantly through the substratum, without inundation of the CW surface (Figure 5). The flowpaths and consequent removal efficiencies are affected not only by the substrate medium, but by the relative positions of the inlet/s and outlet/s (Suliman F. F., 2006). The inlet may be located either above or below the surface, while the treated effluent exits below the surface.

In batch mode, which is typically applied to VSSF CWs, the surface of the CW is flooded intermittently, followed by a period of drainage. If the period of drainage is protracted (days), the flow is termed “tidal” with shorter periods being termed “pulsed” (Austin, 2009). The inlet is located above the surface and effluent is generally collected via drainage pipes located at the bottom of the CW, ensuring a vertical hydraulic flow (Figure 7). VSSF CWs are generally more highly engineered (type B), with extensive piping located on the CW floor for collection of effluent.

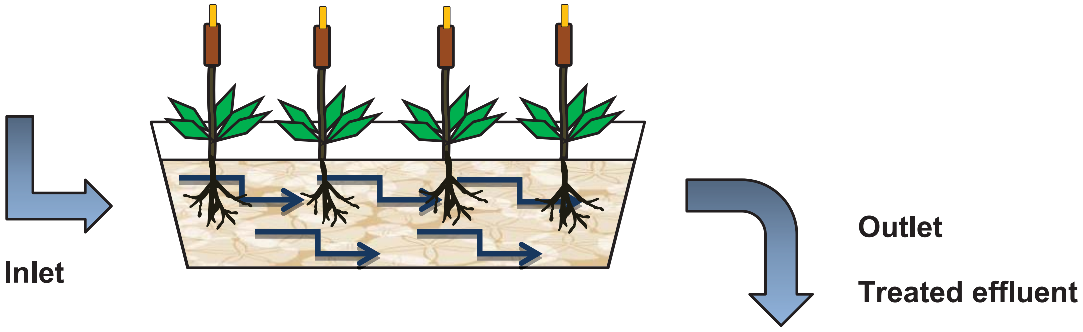


Figure 6: Schematic diagram of a horizontal subsurface flow constructed wetland operated in continuous mode.

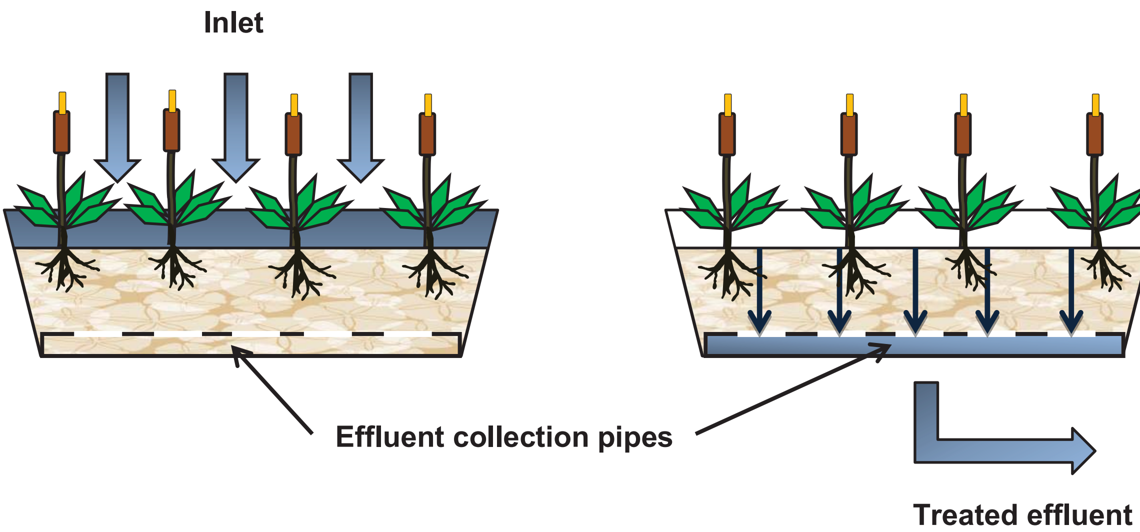


Figure 7: Schematic diagram of a vertical subsurface flow CW operated in batch mode. A "fill" period (left) is followed by a "drain" period (right).

<u>REDOX POTENTIAL</u>

During CW design, it is critical to understand the effect of redox potential on the biodegradative function of CWs. The redox potential is significantly dependent on the hydraulic regime of CWs. Aerobic processes, such as nitrification are favoured in oxidised environments (high redox potential), while under reduced conditions (low redox potential), anaerobic processes, such as sulphate reduction and methanogenesis are more likely to occur (Faulwetter, 2009). Under reducing conditions, the anaerobic mineralization of organic matter results in the production of greenhouse gases (GHGs). The global warming potential of nitrous oxide and methane is 296 and 23 times higher, respectively for these gases when compared to carbon dioxide (IPCC, 2001). This is an important factor to be considered during design of CWs for the treatment of high COD waste. The incorporation of artificial aeration to increase the redox status of CWs has been shown to reduce the formation of GHGs, but the energy requirements of such systems may mitigate any benefits derived (Maltais-Landry, 2009).

Due to continuous inundation of the surface, the matrix of FWSF systems is generally anoxic or anaerobic (low redox potential). Conversely, the highest redox potential (aerobic) environments are encountered in VSSF systems. These are typically operated in a batch mode, resulting in alternating periods of flooding and drainage with attendant draw-down of atmospheric gases into the CW substratum (Herouvim, 2011) (Pedescoll, 2011) (Tietz, 2008) (Torrens, 2009). Nitrification and organic degradation is enhanced under aerobic conditions; accordingly, the efficiency of these processes is characteristically higher in VSSF systems (van de Moortel, 2009). In a comprehensive study, (Tietz, 2008) found that most carbon originating from domestic wastewater was degraded in the upper 10 cm of VSSF CWs and that the presence of plants had little effect on either total organic carbon (TOC) removal, bacterial productivity or microbial biomass (hydraulic retention time 2.5 to 3 days). On the other hand, HSSF systems which are characteristically operated in a continuous mode, exhibit a lower redox potential than VSSF systems. This results in less efficient nitrification and organic degradation, but enhances denitrification (Verhoeven, 1999). Moreover, it has been shown that organic removal rates in HSSF systems can be increased by changing the mode of operation from continuous to batch mode (Calheiros, 2009) (Pedescoll, 2011)

It must be borne in mind that not only biotic, but also abiotic removal processes are influenced by CW redox status; for example P binds preferentially to Fe(III) in clay under aerobic conditions (Verhoeven, 1999).

7.3 Functions

Industrial and domestic wastewater, as well as agricultural run-off may contaminate aquatic environments, rendering water unsuitable for human consumption, land irrigation, fish production or recreation. It is important to treat contaminated water before discharge, either via irrigation or directly into the environment. CWs have been used to treat municipal wastewater, landfill leachate, agricultural wastewater and industrial wastewater (Vymazal J. , 2005) (Poach, 2003). In a comprehensive literature survey, Vymazal and Kröpfelova (2009) reported that from 292 HF CWs from 36 countries, the highest average inflow COD concentrations were found in industrial wastewater and the lowest in municipal wastewater (Table 4.3).

Table 13: Performance characteristics of 292 horizontal flow constructed wetlands

Wastewater type	**No of CWs**	**Ave Influent COD (mg.L^{-1})**	**Ave effluent COD (mg.L^{-1})**	**Ave COD removal (%)**
Industrial[a]	25	1 865	789	63.1
Agricultural[b]	17	871	327	63.0
Landfill leachate	6	933	698	24.9
Municipal secondary	244	287	76	63.2

[a] Farm effluent, chicken manure, shrimp aquaculture effluent, trout farm effluent and dairy parlour effluent

[b] Abattoir and meat processing effluent, food processing effluent, distillery effluent, winery effluent, petrochemical effluent, lignite pyrolysis effluent, mixed industrial effluent

In order to distil the functions of constructed wetlands, the project team investigated the various wastewater streams commonly being treated by constructed wetlands. These wastewater streams are discussed in further detail in this section.

7.3.1 Domestic wastewater

Due to their relatively large land requirements and long retention time, wetlands cannot be used for domestic wastewater treatment in highly urban areas with large waste water volumes, and are mostly limited to usage in rural and underdeveloped areas (Yan, 2006). Constructed wetlands, however, have been proven to be an effective low-cost system for water treatment, and due to their simplicity and scalability, can be used for treatment of waste from single houses and small communities (Mimis & Gaganis, 2007). Constructed wetlands require little to no energy input, depending on the topography, and can be designed to have relatively short retention times.

In a typical free water surface constructed wetland with emerging macrophytes, the shallow water depth, low flow velocity and mass of living plant matter results in a plug flow system designed for maximum contact time between the waste water and reactive biological surfaces (Vymazal J. , 2008). Domestic waste water consists of nitrogen, ammonia and other such nutrients, as well as micro-organisms. Wetlands are capable of removing all of these substances, and it may even be possible to get drinkable water with certain more complex wetlands (Istenič et al., 2009). This can be done if there are enough nutrients removed, through nitrification, denitrification and absorption by algae, so that microorganisms cannot survive. The sand or soil can also filter out pathogens and viruses.

Wetlands are often combined with other technologies when treating domestic waste. There are multiple reasons for this. The high concentration of nutrients found in waste water attracts mosquitoes, which could result in wetlands acting as mosquito breeding areas (Walton, 2004). The low level of COD in this water due to nitrification and denitrification creates unsuitable conditions for mosquito predators such as insects and fish. For this reason, pre-treatment to secondary standards may be necessary to abate mosquito reproduction.

In an investigation conducted by Mulidzi (Mulidzi R. , 2000), it was found that the effectiveness of a wetland depends largely on pre-treatment. Winey waste water was pre-treated in ponds before being released in wetlands, resulting in a much cleaner final outflow.

A common pre-treatment step is filtering out of excessive solids (ARTEC, 2011). This step is used to avoid clogging up the beds of the wetlands, especially in vertical flow wetlands. However there is an exception in the 'French type' of vertical flow filters which are designed to function without pre-treatment.

Wetlands are also commonly used as a polishing step after another secondary system has been used (Sheikh, 2011). Once most of the pollutants have been removed from the water, wetlands polish the water in an aesthetic manner, creating a habitat for land and aquatic creatures. According to (Masudi, 2001), polishing wetlands are usually surface flow wetlands.

As seen by the study of Khan and Shah (2010), nutrient lockup efficiency is directly related to biomass density in wetlands. If the biomass is regularly harvested it is a great help in the reduction of nutrient load and it reduces eutrophication. However, it should be noted that constant and mass harvesting is undesirable in natural wetlands due to fowl and other animals living there. It is thus best to remove excessive nutrients before it enters the wetlands and to selectively harvest weeds (Khan & Shah, 2010).

There are numerous case studies done on domestic waste treatment constructed wetlands. One of them was done by Sirianuntapiboon and his team in Thailand (2007), and it found that planted wetland systems remove much more nutrients and solids content than unplanted systems. It is also generally noted that systems with longer retention times or lower hydraulic loading are always more efficient.

Another case study was conducted by Gelt (1997) on Tres Rios, a treatment plant in America, where a wetland is used as a polishing step after secondary treatment. The wetland increases the quality of the water to a high level, which is necessary for the wildlife in the area. It is speculated that certain endangered species of wild animals may choose to live at the wetland, making the management thereof very important.

7.4 Stormwater

According to Slack (Slack, 2010) wetlands act as giant sponges, absorbing water and releasing it slowly. This reduces the risk of drought and floods downstream. Wetlands also absorb nutrients, maintaining a good water quality, resulting in a more balanced environment and stable ecosystem.

There are a few different types of stormwater wetlands. The simplest type is the shallow marsh wetland, which uses a large surface area (Manual, 2011). Another type is the pond/wetland system which has at least one pond in conjunction with a shallow marsh, and is usually more effective than a shallow marsh wetland. Extended detention wetlands are made to hold large amounts of flood water for extended lengths of time. They include deep areas and thus do not require such a high land footprint. The last type is a pocket wetland, which is used in areas with very little space. A pocket wetland is usually excavated down to the groundwater table to maintain adequate water levels. But even then, if they rely solely on stormwater runoff, the vegetation may not survive.

In some areas, where the fluctuation of rainfall can cause huge changes in stormwater volume, equalisation basins are used to handle excess stormwater until proper treatment plants and wetlands can handle the water (Helping Nature Take the Strain: Wetland Stormwater Control and Retention, 2010). Equalisation basins are cheap and aesthetic and have been made to handle up to 1500 m^3/h volume flows of water. This water can then be pumped in an even flow rate into wetlands.

In many cases, stormwater runoff holds a large concentration of unwanted nutrients or pollution. Wetlands have been constructed for the sole purpose of controlling this pollution. Natural wetlands may be used with properly pre-treated water, but they are very different to the constructed wetlands. Constructed wetlands are designed with specific plants according to what type of waste they can handle the best, and have different configurations, such as stages of marshland and ponds. On the other hand, natural wetlands are not designed to handle high concentrations of pollutants and can be affected negatively if untreated wastewater enters them. Stormwater wetlands are a very effective and aesthetic method of pollution removal which requires minimal maintenance.

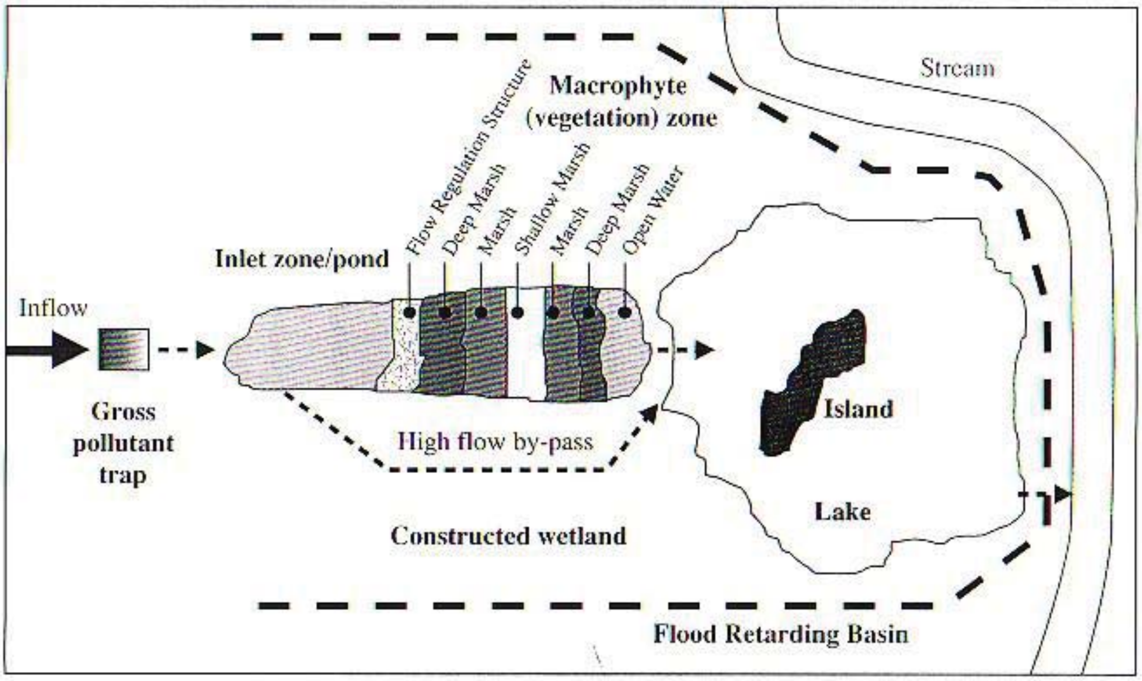
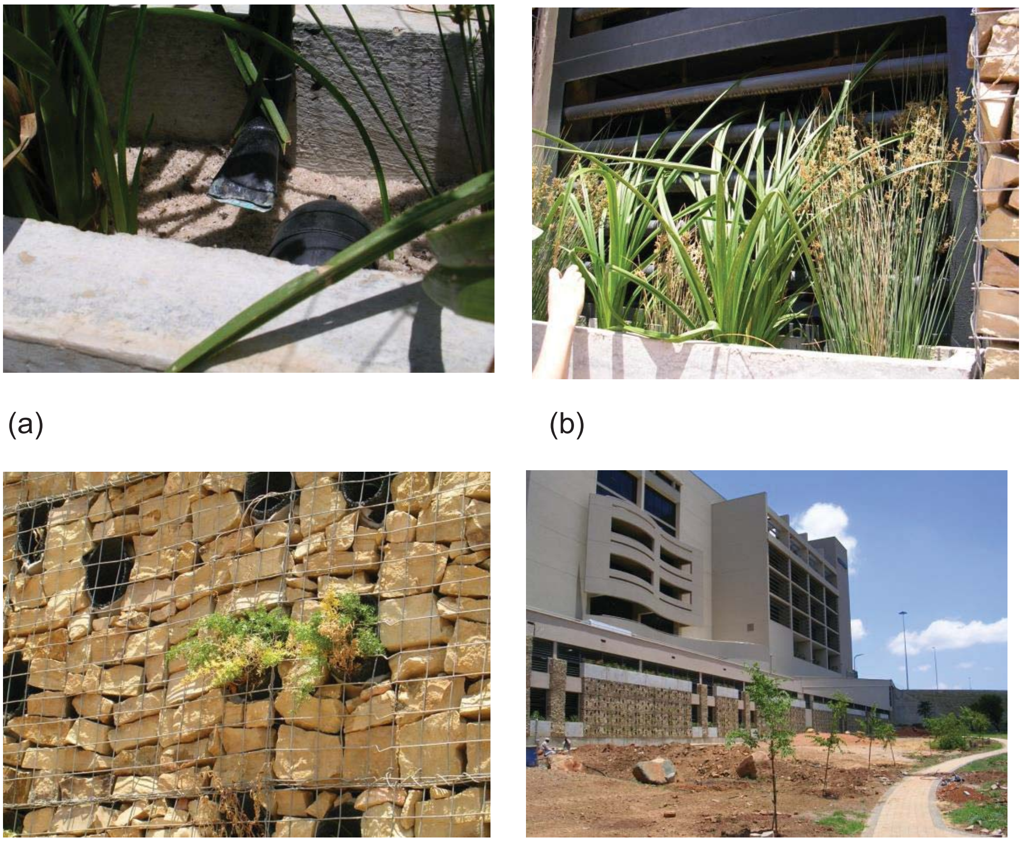


Figure 8: Example of a stormwater wetland.

With the exception of highly built-up areas and arid regions, there are very few places where these wetlands cannot be used. If wetlands are used in arid or semi-arid regions, care must be taken to ensure that there is a permanent pool, so that the wetland plants do not die (SMRC). In highly built-up areas, land is an expensive commodity. However, if there is a relatively large area downstream of the site, wetlands can still come in handy. Aurecon, together with wetland consulting, overcame the hurdle of land shortages by designing and constructing their stormwater treatment wetland on the side of their building.



(a) (b) (c) (d)

Figure 9: Stormwater wetland on Aerocon (Menlyn) building. a) hidden piping for transferring effluent between cells b) wetland vegetation within single cell, c) additional plants within rock cladding for aesthetic appeal, d) Side wall of building with wetland.

In cases of highly-polluted water, such as runoff from gas stations, the wetland needs to be significantly far from any large water bodies or streams. Also, care must be taken that the pollutants do not get carried up the food chain of aquatic animals living nearby. Another large problem posed by these large, shallow wetlands, is the heating of water, which then runs into cold water bodies and has a negative effect on aquatic life.

7.5 Agricultural

As with domestic waste water treatment, pre-treatment is important in treating agricultural wastes (Van Deun). Overloading a wetland can cause a great amount of damage to the plants growing there. Reducing pollutants is thus very important. According to Van Deun, not only is pre-treatment important, but management of the wetlands as well. Maintenance is not high, but wetlands need to be monitored for plant disease or stress.

When it comes to animal waste, the wetland system is very similar to that used to treat domestic waste. However, where pesticides and fertilizers are involved, wetlands need to be modified.

Some surface flow wetlands for the treatment of animal wastes were investigated by Henry *et al*. (2003). These wetlands were used to treat the runoff from small livestock operations. This treatment method replaces other storage, treatment and land application systems.

Fertilizers can cause an overgrowth of plants, even in wetlands, which decrease the oxygen content of the water to such an extent that the aquatic life downstream of the wetland suffocates. As stated previously (Khan & Shah, 2010), one way of minimizing this oxygen reduction is by regularly harvesting excessive plant life, which reduces the creation of dead plant matter and thus the growth of microorganisms.

A case study was done by Borges *et al*. (2009) on ametryn-contaminated water. Ametryn is a pesticide used in farming. Subsurface flow constructed wetlands were used in the study, and it was found that there was a 39% decrease of ametryn in the final outflow from the wetland. It was concluded that wetlands act as suitable buffer filters between emission sources and downstream water bodies.

In Switzerland, wetlands are used to restore lakes and coastal waters by retaining agricultural runoff (Reinhardt, 2005). Retention time is the main factor in phosphorus removal, according to Reinhardt *et al*. After sufficient amounts of phosphorus and nitrogen have been removed from the water, it is safely discharged into the larger water bodies.

7.5.1 Industrial

There is a wide variety of wastes produced in industry. Some of these wastes are highly contaminated and are unacceptable for discharge into free water bodies.

A study on the effect of different types of plants on the removal of COD from winery waste water was done by Zimmels *et al*. (2008). The amount of COD and other contaminants in raw winery wastewater is very high, and has a detrimental effect on the plants in the wetlands, which means that it has to be diluted beforehand. With 1:1 to 3:1 diluted wastewater, a removal of 95.9% to 97% of COD was achieved. This study was conducted under artificial lighting, however, and so does not account for possible environmental and seasonal changes.

In Mexico, a system consisting of a primary sedimentation tank, aerated lagoons and wetlands in series was used to treat abattoir wastewater. It was found that although the nitrogen, pathogen and COD removal rates were high, the final effluent did not meet the environmental standards required (Gutiérrez-Sarabia, 2004). When it came to P, there was no removal. In fact, it was often seen that the effluent P concentration was higher than the influent concentration. It was decided that an additional sand-filter followed by disinfection should help to meet the required standards.

In Thailand, which is the biggest producer of rubber worldwide, there is a wide variety of treatment methods for the highly contaminated rubber waste water. Wetlands are not extensively used, but they have shown a high capability of removing nutrients, suspended solids, organic compounds, pathogens and metallic ions in a very cost-effective, efficient and self-maintaining way (Mohammadi, 2010).

Wetlands have also been used to reduce heavy metals concentration from tannery sludge (Khilji & Firdaus-e-Bareen, 2008). In this case study a certain plant species, *Hydrocotyle Umbellata*, was used with different concentrations of tannery sludge. These plants had a high tolerance, surviving up to 60% concentration of tannery sludge. At the same time, they were also very efficient in removing heavy metals from the sludge, especially chromium.

7.5.2 Landfill leachate

It is known that certain plants such as water hyacinths grow in contaminated water and soil (landfills). These water hyacinths were investigated by Mehmood *et al*. in Pakistan (2009). It was found that not only do the plants take up heavy metals very well, and the microbes on the roots fix nitrogen, but the microbes also play a key role in phytoremediation. Results from this investigation show that these plants can be used to remove As, Cd, Cr, Se, Cu, Pb, Hg, As, Zn and Ni.

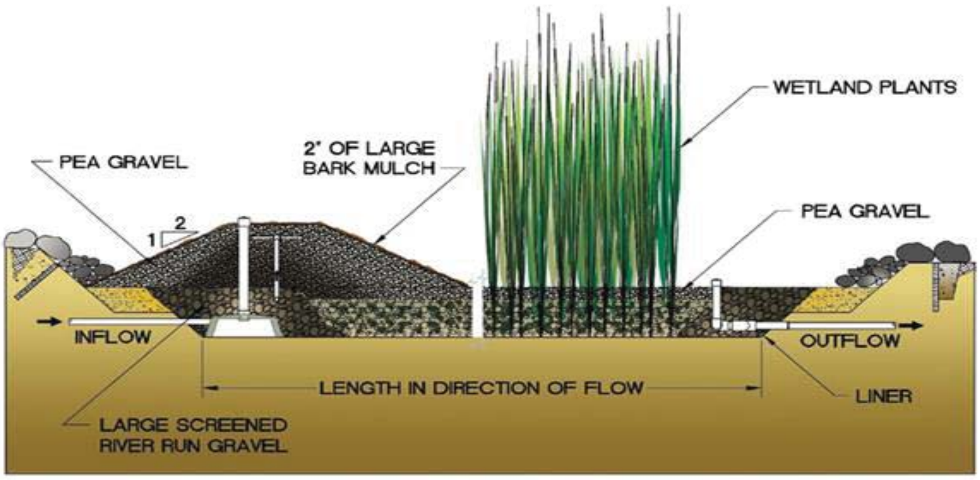


Figure 10: Typical layout of a landfill leachate wetland

Hussain *et al.* (2010) did a similar study on the same plant, but this time only on the removal of Ni^{++} from contaminated water and soil. It was found that the removal of Ni^{++} was more effective from soil than from water. The ash of water hyacinth adsorbed more nickel than normal removal by growing hyacinths in water.

7.5.3 Sludge consolidation

An example of sludge consolidation is where seepage from municipal waste sludge is treated in a wetland. In this case the constructed wetlands consist of gravel/soil filters with emergent plants such as reeds (Montangero & Strauss, 2002). Three pilot constructed wetlands were investigated in Bangkok, each fitted with drainage and ventilation systems, treating sewage from approximately 3000 people, according to Montangero and Strauss. The percolate from the wetland was pumped into an attached-growth waste stabilization pond system. It was found that the longest period for the percolate to stay in the pond system without causing plant wilting was 6 days, which was also the length of time for maximum nitrogen removal. However, if the percolate were then to be dried and used as compost, a higher nitrogen concentration would be desirable, in which case the residence time in the pond system should be reduced to the shortest time that still promotes plant health.

Figure 11: Sludge drying bed with emergent plants.

Another result found by the investigation Montangero and Strauss conducted, was that nitrogen, phosphorus and pathogen removal increased over time, most likely due to the gathering septage creating an additional filtration layer.

7.5.4 Minewater

Acid mine drainage is a large problem in many countries and is recognised as one of the most serious environmental issues regarding mining. Ochieng *et al*. (2010) conducted an investigation on acid mine drainage and treatment thereof in general. According to them, wetlands have a variable efficiency, but are known to increase the activity of sulphate reducing bacteria which in turn decreases the pH of water, allowing precipitation of heavy metals as sulphides. A base layer of limestone is also used to help raise the pH. This system requires a large area of land which is not always available.

Sobolewski (1996) investigated different wetlands associated with contaminated mine water. He notes some natural wetlands which are known to retain metals, namely cupriferous and uraniferous bogs. Uranium associates highly with organic matter, and can be accumulated in sediments up to a few thousand ppm. A Canadian cupriferous bog of 1 hectare in size was estimated to contain 300 tons of copper during an investigation done in 1950. No method of recovery for this copper has yet been found.

According to Sobolewski, plants do not accumulate much metal, but hydrolysis and biological reactions account for most of the metal found in the sediment. Neutralisation of the acidity is accomplished by the biological production of bicarbonate.

As has been noted before, wetlands have variable efficiency. Sobolewski mentions some cases where water was purified to acceptable levels and other cases where the outflows from wetlands were still contaminated to a high degree. However, Kleinmann (2006) found that in general, wetlands reduce chemical treatment costs enough to repay any wetland construction costs within a year.

7.6 Principles

7.6.1 Nitrogen removal

Two microbially mediated reaction pathways have been clearly described for the removal of ammoniacal nitrogen in CWs treating wastewater: nitrification-denitrification and partial nitrification followed by annamox (Figure 12). Both rely on nitritation, which is the oxidation of ammonia to nitrite by ammonium oxidizing bacteria (AOB) (Qiao, 2010) (Capuno, 2007):

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O \qquad \textit{(nitritation)}$$

In classical nitrification, the second step, (oxidation of nitrite to nitrate), is mediated by nitrite oxidizing bacteria (NOBs) (Capuno, 2007):

$$NO_2^- + 0.5O_2 \rightarrow NO_3^- \qquad \textit{(nitrification)}$$

In the annamox reaction (anaerobic ammonium oxidation), the annamox bacteria directly combine nitrite (electron acceptor) and ammonia (electron donor) to produce dinitrogen gas and low amounts of nitrate (Qiao, 2010):

$$NH_4^+ + 1.3NO_2^- + 0.066HCO_3^- + 0.13H^+ \rightarrow 1.02N_2 + 0.26NO_3^- + 0.066CH_2O_{0.5} + 2.03\ H_2O$$

(Qiao, 2010)

Denitrification of oxidized N species occurs by step-wise reduction of nitrate and nitrite to dinitrogen gas. Denitrification relies on the presence of organic electron donors and is mediated by heterotrophic (organotrophic) organisms.

The AOBs, NOBs and annamox bacteria are autotrophic chemolithotrophs, and are more sensitive to environmental parameters (temperature, pH, oxygen, COD:TKN ratio, presence of toxins) than the heterotrophic population (Rittman, 2001). The nitrifiers are obligately aerobic, requiring extended aeration in conventional wastewater treatment systems (Rittman, 2001). In contrast, the annamox bacteria cannot grow in the presence of oxygen (obligately anaerobic) (Austin, 2009). Even under ideal conditions, autotrophic reactions are not as energetically favourable as heterotrophic reactions; consequently AOBs, NOBs and annamox organisms have low specific growth rates requiring extended HRTs in conventional wastewater treatment systems (Rittman, 2001).

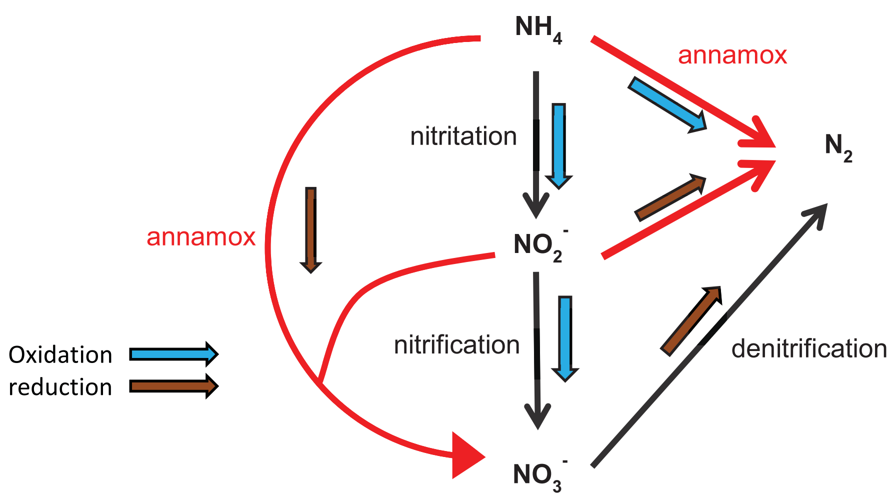


Figure 12: Schematic diagram showing the various forms of nitrogen and the major processes involved in the removal of total nitrogen

Complete and reliable nitrification at practical loading rates has not been demonstrated in passive CW systems (Austin, 2009). To comply with discharge N limits, mechanical power inputs are required to pump water or air to enhance nitrification; these energy requirements depend on site conditions, CW operational design and removal requirements (Austin, 2009). Model operational energy requirements have been calculated to be between 0-56% of conventional (MLE) activated sludge systems and can be minimized by employing pulsed flow regimes (Table 5-1) (Austin, 2009). However, land requirements for pulsed flow systems are extensive, and although tidal flow systems require more energy, land requirements are comparatively minimal (Table 5-1)

Table 14: Model energy requirements for removal of nitrogen from wastewater

Wastewater treatment process	Process energy ($kW.hr/m^3.day^{-1}$)	Area requirements ($m^2.m^3$ flow)
Activated sludge (MLE)	0.88	0.24
Aerated wetland	0.49	10.3
Tidal flow wetland	0.21	5.0
Pulsed flow wetland (flat site)	0.07	21.1
Finishing pond for pulsed flow wetland	-	40.0

Design wastewater parameters: Flow rate 1 000 ML/day; influent COD 300 mg/L; effluent COD 10 mg/L; influent TN 60 mg/L; effluent TN 10 mg/L

In high ammonia wastewater, such as swinery waste, CW processes designed to optimize classical nitrification-denitrification and/or nitritation-annamox can enhance overall nitrogen removal (Poach, 2003) (Tao, 2009). A pre-nitrification step using aeration has been shown to both decrease ammonia volatilization and increase denitrification (Poach, 2003). Benefits are twofold: firstly, by lowering influent ammonia, the effluent is rendered less toxic to CW biota and secondly, because denitrification of high ammonia wastewater is often nitrate limited, pre-nitrification serves to increase the overall N removal efficiency (Poach, 2003) (Tao, 2009).

The annamox process has only been recently described in CWs, where it has been shown to increase the removal of ammonia (Tao, 2009). The conversion of nitrite to nitrate via annamox may be considered preferable to classical nitrification-denitrification for the removal of ammonia in CWs because of (i) reduced aeration requirements (ii) elimination of requirements for organic electron donors and (ii) reduced emission of GHGs. However, annamox bacteria (i) have slower specific growth rates than NOBs and denitrifiers (ii) have stoichiometric nitrite substrate requirements (1 mol ammonia to 2.32 mol nitrite) and (ii) are sensitive to the presence of oxygen and acidity (Tao, 2009). The optimization of annamox in CWs treating high ammonia, low carbon wastewater is a relevant strategy where input and process conditions are stable.

In some cases where classical nitrification-denitrification is the major pathway for nitrogen removal, removal rates may be hampered, not by the nitrification rate, but by the lack of electron donors available for nitrate reduction. In CWs designed for the remediation of low carbon, nitrate contaminated groundwater, the denitrification process is limited at high loading rates, no longer obeying first order removal kinetics (Lin, 2008); Thus, the application of optimal process conditions to enhance the annamox process and/or the use of combination wastewater to ensure correct C:N ratios may be necessary to achieve compliance with effluent standards.

7.6.2 Phosphorus removal

Under anaerobic conditions there is a lack of electrons acceptors for oxidative metabolic processes. Under these conditions, certain heterotrophic bacteria known as polyphosphate accumulating organisms (PAOs) can sequester electrons and carbon into intracellular storage products such as polyhydroxybutyrate (PHB) (Rittman, 2001). The energy for these reactions is derived from the hydrolysis of polyphosphates, and P is released into the wastewater. Under aerobic conditions the PAOs have an ample supply of electron acceptors stored in PHB and are capable of using this energy for the rapid intracellular uptake and storage of extracellular P (Rittman, 2001). In conventional suspended-growth wastewater treatment systems designed for enhanced biological P removal, the metabolic capabilities of PAOs are optimized by alternating anaerobic with aerobic conditions to induce maximal P uptake, with subsequent wasting of the P-rich biomass (Rittman, 2001) In CW systems, although microbial P uptake may theoretically be optimized, the *in-situ* removal of microbial biomass from the CW substratum is not possible. In addition to the incorporation of P into microbial biomass, it may also be adsorbed and/or precipitated in the substratum. However, net P removal can only be achieved by the harvesting of macrophytes or desludging of the substrate.

In CWs, the location of the P fractions is influenced by a combination of physical, chemical and biological processes and interactions (Sindilariu, 2009) Although there is usually a net P removal, in some cases the concentration of dissolved PO_4-P and/or total P in the effluent may exceed that of the influent (Sindilariu, 2009) (Greenway, 1999). P removal capability generally decreases with the age of the CW, and in older CWs, effluent/influent ratios may be > 1 (Greenway, 1999). This net export stems from the solubilization of particulate P trapped in the sediments, and is more likely to occur in older CWs and/or those with higher loading rates (Sindilariu, 2009). Some substrates such as clay aggregates and steel slag improve PO_4-P removal, but the binding capacities of the media is also limited (Naylor, 2003). The chemistry of P is also strongly influenced by redox conditions, being related to the changes in solubility of Fe and Mn complexes (van de Moortel, 2009).

7.6.3 Sulphate removal

A key requirement of a successful passive sulphate reduction technology is the development of a passive sulphide oxidation technology that is capable of removing the sulphides produced from sulphate reduction before they can be reoxidised back to sulphate (Pulles & Heath, 2009). Many pool systems in nature are followed by riffles or rapids, so one has a slow deep low energy system, followed by a high energy aeration system.

There is extensive literature regarding this process as a result of two major South African biological sulphate reduction research initiatives. The first initiative has been ongoing for 15 years by Pulles Howard & de Lange. The second initiative has been ongoing for a period of around 15 years by the Environmental Biotechnology Research Unit at Rhodes University.

The leading position in the field of passive sulphate removal technology is occupied by South African researchers and is the product of a sustained and concerted research effort. (Pulles & Heath, 2009)

7.6.4 Organics

CW substrata can become saturated with inorganic, non-volatile wastes, requiring mechanical removal. One of the major advantages of using CWs for the treatment of organic waste streams is that it is theoretically possible to achieve complete mineralization of many hydrocarbon pollutants (Welz, 2011). High COD removal rates can be achieved in VSSF CWs treating domestic wastewater by applying low loading rates and loading frequencies (Prochaska, 2007). However, with non-domestic wastewaters, there is a risk of toxic metabolites and priority pollutants being formed in CWs (Welz, 2011) (David, 1999). The biodegradability of organic compounds also needs to be considered during CW design. Olive mill wastewater, for example, which contains an inherently high concentration of recalcitrant phenolics, cannot easily be treated to discharge standards using biological systems such as CWs (Herouvim, 2011).

The functional microbial community involved in hydrocarbon degradation, transformation and mineralization has been reported to be influenced by the wastewater composition, microbial acclimation and CW substrate type and plant species (Welz, 2011) (Rodriguez-Caballero, submitted April 2011) (Burton, 2011) (Li J. W., 2008). The quality of microbial attachment sites afforded by different macrophytes and substrates can influence the removal of organics both qualitatively and quantitatively (Li J. W., 2008). This was demonstrated in HSSF CWs used to treat contaminated river water in Shanghai: there was a reduction in the number of carbon molecules of hydrocarbons in the river water after treatment in CWs with different substrates and macrophytes (Li J. W., 2008). The concentrations of various substrates and metabolites between replicates differed, suggesting the presence of different microbial metabolic pathways (and by inference different microbial community structures) between replicates (Table 5-2) (Li J. W., 2008).

Literature results pertaining to the effect of plants on the degradation of organics in CWs are varied. In HSSF CWs filled with volcanic gravel used to treat diluted stillage wastewater (COD 1 181 $mg.L^{-1}$; HRT of 5 days), over 80% COD removal was achieved in CWs planted with *Pontederia sagittata* in comparison to only around 40% in unplanted replicates, demonstrating a decisive advantage of including plants in this case (Olguin, 2008). However, in unplanted, sand-filled VSSF CWs with a bi-weekly loading frequency, a hydraulic loading rate of 1.95 $L.m^2.day^{-1}$ and a high influent COD (ethanol) of 15 800 $mg.L^{-1}$, > 98% COD removal was consistently achieved (Welz, 2011). Although no planted control was included in this study, results strongly suggest that the presence of plants is not a requisite for effective organic removal in CWs. This was supported by the findings of (Tietz, 2008) and (Melian, 2010), who reported that plants had no significant influence on CW productivity, microbial biomass or TOC removal from pre-settled municipal wastewater, but that the type of substrate medium did significantly affect COD and TOC removal. Using sensitive molecular methodology (terminal restriction fragment length polymorphism), (Sleytr, 2009) reported similar microbial diversity but different community composition in the rhizospheres but not in the bulk soil of CWs with different emergent macrophytes. In these studies, organics were not identified in the effluent, so the effects of plants on overall COD removal may have been qualitative rather than quantitative. From the available data, it can be hypothesized that the benefit of plants on organic removal rates is extremely variable and is interdependent on the hydraulic regime and/or the substrate medium. Additional research is needed to clarify which parameters are more important for selected organic wastes.

Table 15: Comparison of organic compounds identified in contaminated river water (influent) and the effluent of pilot-scale HSSF constructed wetlands with different media and plants

Organic compound	Influent[a]	Reeds Gravel (n=3)	Mixed plants[b] Gravel (n=3)	Reeds Mixed medium[c] (n=3)
Aromatic hydrocarbons	11.54	15.02	42.53	36.16
Alcohols	29.87	10.29	3.45	11.59
Phenolics	3.61	11.5	5.75	1.6
Nitrogenous compounds	1.07	3.77	0.79	2.37
Aldehydes	0.22	1.24	-	1.66
Acids	28.87	28.22	8.25	12.37
Ketones	4.31	15.74	2.07	4.88
Alkyl hydrocarbons	2.73	4.26	32.84	28.07
Alkenes	13.63	2.5	0.35	0.79
Esters	4.12	7.47	3.97	0.51

[a]Influent COD: 77-100 mg/L^{-1};

[b]Mixed plants: reed, cattail, bulrush;

[c]Mixed medium: zeolite, slag, gravel

7.6.5 INORGANICS

In conventional CWs, trace elements may be precipitated and/or adsorbed in the CW substratum, but to ensure net removal from the system, the harvesting of plant biomass (phytoremediation) or removal of sediment (rehabilitation) is necessary. There are seasonal differences in the translocation rates of different elements into above ground biomass of emergent macrophytes, so harvesting times of different plants species need to be optimized for the removal or target element/s when employing phytoremediation procedures (Vymazal J. K., 2010). The solubility and substrate binding of metals is related to the substrate composition and redox conditions.

The goals for the treatment of acid mine drainage (AMD) are to neutralize acidity, create excess alkalinity and remove dissolved metals (Riefler, 2008). Conventional, planted CWs have been employed for the remediation of acid mine drainage with limited success (Nyquist, 2009). The success of phytoremediation for the removal of metals from AMD is controversial, with authors reporting both promising and poor results (Nyquist, 2009) (White, 2011). The correlation between DOC and metal availability in planted wetlands is well documented. It has recently been described that in the case of iron, the correlation originates from the phenolic component of humic material which increases the solubility of iron oxides by the formation of iron-phenolic complexes (White, 2011). Thus, the presence of plants may be counterproductive in CWs used to treat iron-rich wastewaters (White, 2011).

A successful approach for treating AMD is via a combination of CWs which are collectively termed successive alkalinity producing systems (SAPS). SAPS consist of a series of limestone-containing anaerobic vertical flow wetlands (AVFWs), also known as reducing and alkalinity producing systems (RAPS) and “aerobic” CWs (Riefler, 2008) (Barton, 1999), In AVFWs, the AMD is permeated through an upper organic layer (usually compost) in which oxygen is removed through microbial respiration and Fe (III) is reduced to Fe (II) (Riefler, 2008). The lower layers of compost contain an abundance of organic electron donors and form an ideal environment for the growth of sulphate reducing bacteria (SRB) which facilitate the reduction of sulphate ions and hydrogen sulphide and bicarbonate is produced:

$$C_6H_{12}O_{6(s)} + 3SO_4{}^{2-}{}_{(aq)} \rightarrow 3H_2S_{(g)} + 6HCO^-{}_{(aq)}$$

The benefits of SRB are two-fold; firstly bicarbonate ions provide alkalinity and secondly, metals are removed by the formation of insoluble metal sulphide precipitates:

$$H_2S_{(g)} + M^{2+}{}_{(aq)} \rightarrow MS_{(s)} + 2H^+{}_{(aq)}$$

At neutral pH, Fe (III) precipitates while Fe (II) is soluble, so reduction of Fe (III) in the compost layer effectively prevents precipitation when the pH is raised in the limestone layer. Further treatment results in the oxidation and precipitation of Fe (II) as oxyhydroxides in aerobic CWs, which must be periodically de-sludged (Riefler, 2008). In SAPS, a number of sequential AFVF-aerobic CW combinations are used, which can result in significant alkalinity generation and metal removal.

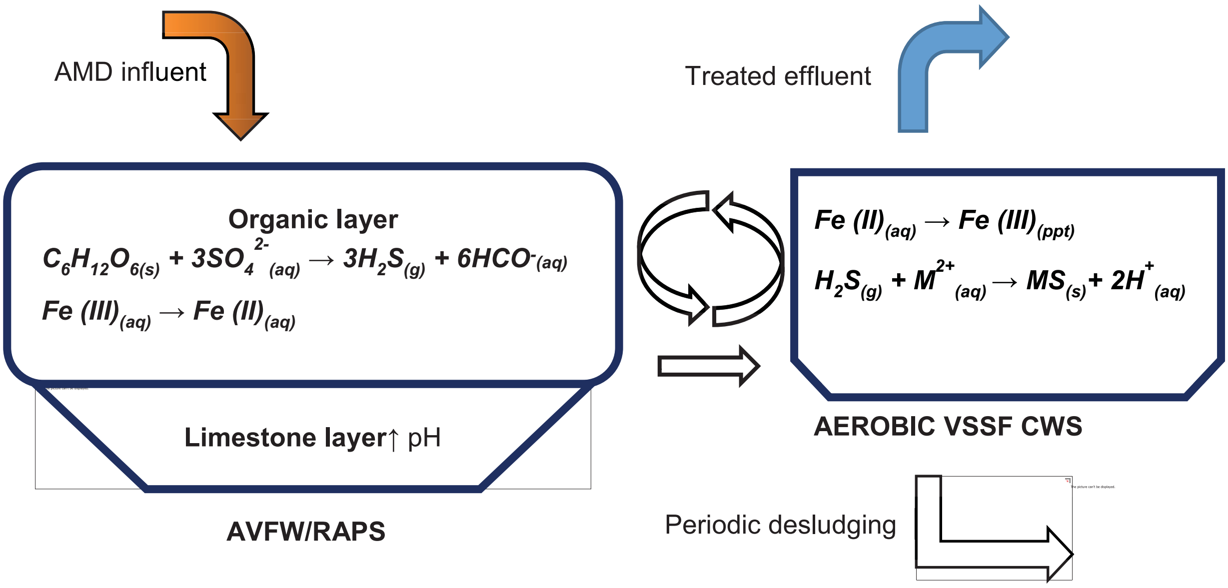


Figure 13: Schematic diagram of a successive alkalinity producing system (SAPS) for the treatment of AMD.

7.7 Constructed wetland design considerations

Wetland performance is very much dependent on the ability of a wetland to manage unpredictable events such as fluctuating loads (flows and concentrations), changing weather patterns, ecosystem factors such as animal activity and the evolving dynamics within a wetland.

POLLUTANT REMOVAL MECHANISMS

The following table summarises the functions and major controlling factors for pollutant removal in wetlands. (Ellis, Shutes, & Revitte, 2003)

Table 16: Major controlling factors for various water treatment mechanisms in constructed wetlands. Table adapted from (Ellis, Shutes, & Revitte, 2003)

Pollutant removal mechanism	Pollutant	Major controlling factors
Sedimentation	Solids, BOD/COD, Bacteria, pathogens, heavy metals, phosphorous, synthetic organics	Low turbulence, residence time, emergent plants
Adsorption	Heavy metals, dissolved nutrients, synthetic organics	Neutral to alkaline pH, iron and manganese oxide particles, high organic carbon
Biofiltration and microbial decomposition	BOD/COD, phosphorous, hydrocarbons, synthetic organics	Filter media, dense herbaceous plants, high plant surface area, organic carbon, dissolved oxygen, microbial populations
Plant uptake and metabolism	Phosphorous, Nitrogen, Heavy metals, hydrocarbons	Large biomass with high plant activity and surface area, extensive root system
Chemical precipitation	Dissolved nutrients, heavy metals	High alkalinity
Ion exchange	Dissolved nutrients	High soil cation exchange capacity, e.g. clays.
Oxidation	COD, Hydrocarbons, synthetic organics	Aerobic conditions
photolysis	COD, Hydrocarbons, synthetic organics	Good light conditions
Volatilisation and aerosol formation	Volatile hydrocarbons, synthetic organics	High temperatures and high wind speeds
Natural die-off	Bacteria, pathogens	Plant excretion of phytotoxins
Nitrification	NH_3-N	DO > 2 mg/ℓ, low toxicants, neutral pH, temperature > 5 -7°C, relevant bacteria
Denitrification	NO_3-N, NO_2-N	Anaerobic conditions, Low toxicants, Temperature > 15°C, relevant bacteria
Reduction	Sulphate(resultant sulphide can precipitate metal sulphides)	Anoxic zone in substrate, relevant bacteria
Infiltration	Dissolved species (nutrients, heavy metals, synthetic organics)	Permeable base and underlying soils.

CONTEXT

The context refers to the conditions under which a system will function. The following aspects need to be considered when designing a constructed wetland:

- Feed water quality
- Feed water flow patterns
- Soil conditions
- Topography
- Climatic conditions
- Land availability
- Budget
- Land zoning within catchment
- Water quality objectives of receiving water body
- Environmental enhancement value, e.g. Is the wetland going to be in recreational area?
- Site ecological assessment

WETLAND SIZING

Two of the key considerations when sizing a wetland are hydraulics and pollutant removal requirements.

Stormwater wetlands in particular must be designed to withstand high fluctuations in flow. One rule of thumb is that the stormwater wetland size should be a specified fraction of the contributing catchment, typically between 1 and 5 % is used. (IWA, 2006).

A detailed water budget, (understanding of inflows and outflows) is required to successfully design a CW. (The Interstate Technology and Regulatory Council - Wetlands team, 2003).

$$P + SWI + GWI = ET + SWO + GWO + S$$

Where:

P	=	Precipitation
SWI	=	Surface water inflow
GWI	=	Ground water inflow
ET	=	Evapotranspiration
SWO	=	Surface water outflow
GWO	=	Ground water outflow
S	=	Change in storage

It is important to understand the influent water quality and the water quality objectives of the area in order to make a decision on whether a constructed wetland can be selected as a water treatment option for the site. Source water qualities in wetlands are often influenced by rainfall and it is therefore recommended to have a representative number of water quality samples from both the wet and dry season, taking into consideration the lag time for groundwater flows.

Apart from site specific contaminants, the following should be included:

- BOD/COD, TOC, TSS, TDS, Coliforms
- Pesticides and herbicides
- Oils and grease or total recoverable petroleum hydrocarbons
- Priority pollutant VOCs
- Semivolatile priority pollutants
- Metals
- Nutrients
- Sulfate, sulfide and sulfite
- pH, oxygen, turbidity, temperature

For a first order reaction (IWA, 2006)

$$\left(\frac{C_e - C^*}{C_i - C^*}\right) = e^{-\frac{k_T}{q}} \Rightarrow C_e = C^* + (C_i - C^*) * e^{-\frac{k_T}{q}}$$

Where:

C_e	=	effluent concentration (mg/L)
C_i	=	influent concentration (mg/L)
C^*	=	background concentration (mg/L)
q	=	hydraulic loading rate (m/year)
k_T	=	1st order temp dependent areal removal rate (m/year)

WETLAND LAYOUT

The required surface area and depth will be determined based on the flow rates and effluent quality. The actual layout of the wetland is often dictated by topography, land availability and geological and soil chemistry conditions. The key principles to consider are minimising intercell conveyance and earth moving in order to achieve the required surface area. (IWA, 2006)

COMPARTMENTALISATION

Compartmentalisation is recommended in surface flow wetlands as this reduces short circuiting to an extent (The Interstate Technology and Regulatory Council - Wetlands team, 2003). Factors to be taken into consideration when determining the number of cells in a wetland are:

- redundancy
- maintainability
- separate compartments for particular functions
- site constraints

It is recommended that CWs have at least two cells that operate in parallel to permit operational flexibility. Parallel flow parts allow for flow manipulation during high flow events. It also allows for cells to be drained and worked on if needs be.

Additional cells do lead to additional costs for the system and a cost benefit analysis is recommended when determining the number of cells in a wetland

LINERS

In many instances, CWs will require liners in order to either:

- prevent contamination to groundwater resources
- reduce groundwater ingress into the wetland
- comply with regulatory requirements.

The type of liner would vary depending on the effluent being treated, the depth of the groundwater table and the soil type and geology of the site.

Liner types include:

- PVC
- Polyethylene
- Polypropylene
- Clay liners

OPERATION AND MAINTENANCE

Whilst wetlands are typically based on natural systems, constructed wetlands are by no means walk away systems and would require some form of maintenance and monitoring. It is essential that operation and maintenance is considered in the design phase in order to ensure that aspects such as access and redundancy are taken into consideration.

Typical maintenance activities include:

- Maintenance of inlet and outlet structures
- Management of vegetation
- Control of weeds
- Control of pests
- Odor control
- Maintenance of berms, dykes, cut-off trenches, etc.

In addition to a maintenance plan, regular monitoring is essential in order to ensure that the wetland is meeting its design objectives. A monitoring plan would be agreed upon with the regulator. Changes in outlet water quality should be flagged and investigated as this serves as an early warning system for potential failure of the wetland.

COMPOSITION OF SUBSTRATUM

Removal rates of C, N and P are closely related to the chemical and physical properties of the substrate medium in CWs (Zhang, 2007). Sand, soil, gravel, zeolite, slag, compost and alum sludge are examples of substrate media which have been employed, with sand and gravel-filled CWs dominating (Aslam, 2007) (Babatunde, 2011) (Li J. W., 2008).

Sand particles provide a large surface area for biofilm attachment and surface chemistry. The shape of the sand particles plays a role in biofilm formation and consequent removal performance. It has been demonstrated that natural sand presents a superior biofilm attachment surface to crushed sand, resulting in enhanced removal of C and NH_3 (Torrens, 2009). The major disadvantage of sand-filled CWs is that the small grain size can result in clogging of the matrix pores by suspended solids and/or biofilm. However, clogging can be prevented by the use of pre-filters or clarifiers to remove suspended solids and the use of batch mode to ensure complete biofilm substrate degradation between batches. In addition, the application of low loading rates can compensate for reduced conductivity (Knowles, 2010). An article detailing the use of earthworms to restore clogged sand-filled CWs has recently been published; this method forms and environmentally friendly and cost effective method of preventing CW redundancy (Li H. W., 2011).

In media of similar chemical origin, the removal of N and C may be similar, but removal of P is affected by particle size, presumably because of the larger surface area provided for P adsorption and precipitation (Akratos, 2011).

In gravel-based CWs, the high porosity afforded by the particles can lead to inherently low HRTs and low removal efficiencies (Ghosh D. G., 2010) The hydraulic retention time (HRT) in

CWs is dictated by the flow paths and the interaction of the wastewater with the CW matrix and plants (Grismer, 2003). Poor degradation rates may be improved by increasing the HRT (Mulidzi A. , 2010). In both sand and gravel-filled CWs, the variable nature of the HRT (which is affected by the accumulation of suspended solids and the presence of varying quantities of biofilm), complicates the design process and poses an engineering dilemma (Langergraber, 2008). To achieve ideal HRTs and removal performance, different media with a range of attributes, including conductivity can be incorporated in individual CWs (Herouvim, 2011).

Experiments comparing media types suggest that the major P removal mechanisms in CWs are abiotic. Akratos (2011) demonstrated that removal of TP was 29% lower in carbonaceous rock gravel (D_{50} = 15 mm, rich in Ca and Mg, but poor in Fe and Al content) than in igneous media (gravel, D_{50} = 6 mm and cobbles, D_{50} = 90 mm, rich in Al, Fe, Ca and Mg). The authors determined that differences in media chemistry were responsible for the differences in P adsorption rates (Akratos, 2011). Zhang (2007) found that CWs filled with steel slag removed ≥30% more P than CWs filled with any of seven other media types (gravel, zeolite, anthracite, shale vermiculite, ceramic filter media and round ceramsite). Korkusuz (2005) also found the P removal efficiency in slag-filled CWs (45%) to be substantially superior to that in gravel-filled CWs (4%). The authors related this to the relative abundance of P-complexing Fe, Al_2O and CaO in the slag.

MICROBIAL COLONIZATION AND ACCLIMATION IN CONSTRUCTED WETLANDS

Microbial transformation, degradation and mineralization are the most important biotic processes involved in the treatment of wastewater in CWs. CWs become colonized over time with microbes adapted to a particular CW-wastewater environment. The colonization of CWs by microorganisms and attending biomass leads to a reduction in hydraulic conductivity of CWs, which is a useful indicator of biomass growth (Burton, 2011) (Knowles, 2010). However, the surface of biofilm may become smoother with age with a resultant reduction in surface area, so the relationship between biomass biofilm and hydraulic parameters is not always linear (Suliman F. F., 2006).

Acclimation is a process by which bacterial species adapt over time to new environmental factors. Microbial acclimation to toxic chemicals (e.g. acrylonitrile and *p*-nitrophenol), substrates (e.g. cellulose) and physical parameters (e.g. cold) has been has been described (Cheng, 2010) (Koda, 2002) (Hu, 1997) (Zaida, 1996). The toxicity and concentration of chemicals as well as the acclimation period influence the success of acclimation, with longer acclimation times leading to higher substrate degradation rates and the period of acclimation being shortened at lower concentrations (Zaida, 1996) (Chou, 1978). It has been determined that the use of a procedure, termed “incremental priming” during the start-up phase of sand-filled VSSF CWs enhances acclimation of the resident microbial communities and results in significantly superior degradative rates and capacities when compared to unprimed CWs containing non-acclimated microbial populations (Burton, 2011) (Welz, 2011).

Using synthetic wastewater, it was also established that there is a maximum concentration of ethanol and plant phenolics to which the microbial population in sand-filled VSSF CWs can adapt, after which metabolites with a range of toxicities begin to accumulate in the substratum and hamper CW performance. It is thus recommended that COD maxima are established for CWs treating industrial wastewater and the CWs are designed incorporating features that allow for dilution of effluent in periods of high concentration and/or low precipitation (Burton, 2011) (Welz, 2011).

8 GAP ANALYSIS

The review on Biomimicry under the context of water treatment revealed that while lots of information is available on "water treatment champions" historical research focussed mainly on the species and functions being performed. Insufficient information was available in terms of the mechanisms which enable the champion to perform this function. It was further noted that whilst extensive biological research is being carried out, this information is not in a format that can be easily interpreted by design engineers.

Feedback obtained from information dissemination sessions on biomimicry indicate that while the concept is good, and the methodology has been proven through success stories, insufficient information is available on the process to be followed in using the biology to design solutions to everyday challenges.

Several studies have been carried out in terms of natural wetlands and restoring wetlands. A large portion of natural wetlands have been impacted by changes within its catchment. A large portion of restoration projects fail due to the minimal control one has over other developments within the catchment. A biomimicry approach of studying how nature adapts to changes in its environment and design these measures into the wetland.

In South Africa, readily available sand/soil or gravel is typically incorporated as substrate material in constructed wetlands. The latter is generally used if clogging is perceived to be problematic. There is a gap in local knowledge about the cost and availability of suitable substrates to be incorporated in constructed wetlands. To encourage the development and construction of CWs in South Africa, it would be helpful for engineers to have access to a region-specific database containing useful facts pertaining to substrates, including which substrates are most suited to each particular application. For example, slag is helpful for the removal of P, natural sand may provide a better biofilm attachment site than crushed sand. Research into the use of readily-available industrial waste materials as substrates is a topic that also merits further attention.

In South Africa, most CWs incorporate *Typha* spp and to a lesser extent, *Phragmites* spp., principally because these have been used world-wide and are tolerant of the conditions present in most CWs, especially those treating domestic wastewater. There is a need for research to find either (i) secondary uses for these plants, or (ii) to find local plants that have known secondary uses and test their efficacy in constructed wetlands.

The substrate of CWs used to remove P and/or metals becomes saturated with time and requires rehabilitation, usually by removal and "dumping". Methods that can be used to regenerate substrates from different wastewater treatment processes *in-situ,* merit attention.

An example is the extraction of valuable metals from constructed wetlands used to treat industrial effluent.

The use of plants for the remediation of organic-laden wastewater in constructed wetlands is controversial with mixed results reported in literature. Available data includes one, or at most two variables, e.g. the effect of plants and substrates on organic removal efficiency. There is a need for a multi-dimensional study that includes a range of variables including (i) mode of operation (HSSF, VSSF) (ii) a range of plant species (iii) a range of substrate types, and (iv) a range of wastewaters.

9 BIOMIMICRY WATER TOOL

One of the key findings of the study was that whilst a wealth of biological information is available, it is not available in a format that can be easily sourced by design engineers. Using the Biomimicry methodology, the project team has thus prepared a compilation of natural processes and organisms performing water treatment functions and sorted this information under the functions performed.

Refer to the attached CD for a copy of the Water Tool.

9.1 Objectives

The main objective of the tool to provide budding biomimics in the water sector with a starting point when using the Biomimicry methodology to solve their water treatment and water management challenges.

An addition objective of this deliverable is to identify processes and organisms in nature that can be successfully mimicked in the treatment of water.

9.2 Tool Layout

Biological information is generally sorted in terms of species. This tool was however developed for designers. The information in the tool was therefore sorted in terms of function.

9.2.1 Categories

The following functions were identified for water treatment:

- Particle removal
- Dissolved solids removal
- Pathogen removal
- Surface protection
- Flow management

9.2.2 Presentation

Information on natural processes, organisms and mechanisms was sourced from various literature sources and presented under the following subheadings.

- Biomimicry Innovation
- Design Principles
- Possible Applications
- Biological foundation
- Context
- Case studies

- References

9.3 Using the tool

The Tool has been developed in an Acrobat Portable Document Format (PDF) with hyperlinks.

Clicking one's mouse on the title will lead to the contents page as show in Figure 14.The various functions included in the tool are listed on the contents page.

Figure 14: Contents page for the tool

The user can click on the image relating to the function they wish to explore to go to the landing page for the function. The landing page will provide a description of the function and all the examples included in the tool under that function. Clicking on the examples will lead to the title page for the example and clicking on the back button will take the user back to the contents page.

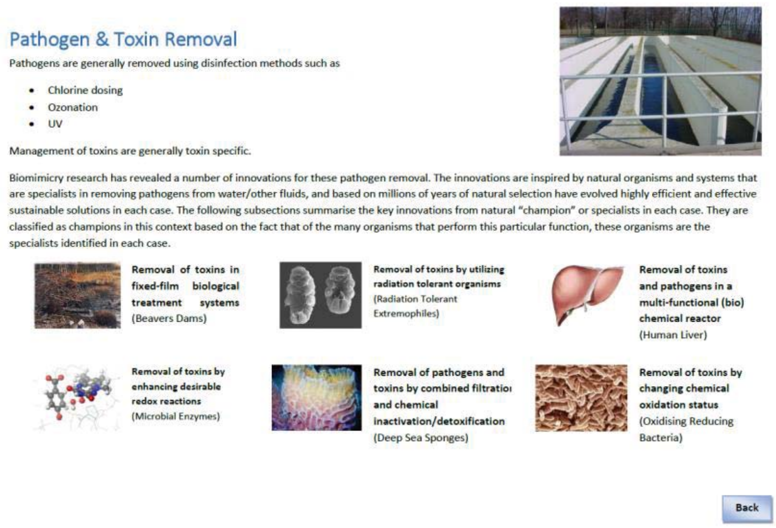


Figure 15: Example of the landing page included in the tool

The user can navigate through the example using the buttons displayed at the bottom of the title page as presented in Table 17. The back button on the title page will take the user back to the landing page. Back buttons within the example will take the user back to the title page for the example.

Table 17: Navigation buttons used in the tool

Symbol	Description
	**Design Principles** – The principles or design strategies which enable the champion to perform the function being studies.
	**Graphical Illustration** – The design principles presented in a graphical format. This facilitates communication between different disciplines.

Symbol	Description
	**Possible Applications** – Examples or applications in which this champion can be mimicked.
	**Biological Foundation** – A description of the biological principles inherent in the champion which make the function it is performing possible.
	**Context** – The external conditions under which the function can be mimicked.
	**Case Studies** – Examples in which the champion has been mimicked.
	**References** – List of references cited in the tool.

The various examples included in the tool have been indexed to allow the user to print specific examples easily.

10 CONCLUSIONS

One of the key factors highlighted in the literature review carried out is that whilst similarities exist between natural and constructed wetlands, one of the biggest challenges facing designers is contaminant loads produced by man far exceed those occurring naturally in nature.

We do however note that nature has adapted to aspects such as high flows and contaminant loads and the aim of this research project is to understand the processes and principles applied in adapting to these conditions and apply these principles in our designs.

Several examples refer to in this report refer to invader species. Biomimicry involves the mimicking of mechanisms observed, rather than using the species. Users of this study and the Water Tool provided need to be cautious of utilizing invader species. Biomimicry is a design methodology, a way of studying nature and mimicking processes, forms and systems to solve challenges that nature has solved through adaptation and evolution.

11 LIST OF REFERENCES

Agre, P., Bonhivers, M. & Borgonia, M.J. (1998). The aquaporins, blueprints for cellular plumbing systems. *Journal of Biological Chemistry. 273*, 14659-14662.

Agre, P. & Kozono, D. (2003). *Aquoporin water channels: Molecular mechanisms for human disease*. Retrieved from FEBS Letters: http://ns.iephb.ru/conference/pdf/marples/agre.pdf

Akratos, C.T. (2011). Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. *Ecological Engineering*, 29: 173-191.

Arienzo, M.C. (2009). Phytotoxicity testing of winery wastewater for constructed wetland treatment. *Journal of Hazardous Materials*, 169: 94-99.

ARTEC. (2011). *Constructed Wetlands for Wastewater Treatment.* Retrieved from Constructed Wetlands for Wastewater Treatment

Ask Nature. (2011). *Siphon filters sea water:Sea Squirt*. Retrieved from Ask Nature: http://www.asknature.org/strategy/553c151091cd4b2355b7bb64a332db0b

Aslam, M.M. (2007). Treatment performances of compost-based and gravel-based vertical flow wetland operated identically for refinery wastewater treatment in Pakistan. *Ecological Engineering*, 20: 34-42.

Austin, D.N. (2009). Energy requirements for nitrification and biological nitrogen removal in engineered wetlands. *Ecological Engineering*, 35: 184-192.

Avant, P. (2002). *Plymouth: Marine Biological Association of the the United Kingdom.* Retrieved 2011, from Sabella pavonia. Peacock worm. Marine Life information network:Biology and Sensitivity key information subprogram. : http://www.marlin.ac.uk/species/Sabellapavonina.htm

Babatunde, A.Z. (2011). Performance evaluation and prediction for a pilot two-stage on-site constructed wetland system employing dewatered alum sludge as main substrate. *Bioresource Technology*, doi:10.1016/jbiortech.2011.02.065.

Baghour, M. (2001). *Phytoextraction of Cd and Pb and physiological effects in potato plants (solanum tuberosom var. spunta): Importance of root temperature.* Retrieved from Journal of Agriculture and food chemistry: http://hera.ugr.es/doi/15025342.pdf

Barton, C.K. (1999). Renovation of a failed constructed wetland treating acid mine drainage. *Environmental Geology*, 39: 39-50.

Biomimicry 3.8. (2011, October). *Biomimicry Guild*. Retrieved 2011, from Biomimicry 3.8: http://www.biomimicry.net/

Biomimicry institute. (2010). *Lamella filter food of different sizes: Flamingo*. Retrieved 2011, from Ask Nature: http://www.asknature.org/strategy/b4f4d235d40e5d6bbc387df164c2ef1d

Biomimicry Institute. (2011). *Specialised Gills Filter Plankton:Basking Shark*. Retrieved June 2011, from Ask Nature: http://www.asknature.org/strategy/98b5b412f2c7129587e3152f486a3122

Brisson, J.C. (2009). Maximizing pollutant removal in constructed wetlands: Should we pay more attention to macrophytes species selection. *Science of the Total Environment*, 407: 3923-3930.

Brodie, P. & Vikingsson, G. (2009). *On the feeding mechanisms of sei whale (Balaenaptera borealis)*. Retrieved June 2011, from Journal Atl. Fish. Sci: http://journal.nafo.int/42/brodie/5-brodie.html

Burton, S.W. (2011). Health for purpose in constructed wetlands. *WRC report*.

Calheiros, C.D. (2009). Substrate effect on bacterial communities from constructed wetlands with Typha latifolia treating industrial wastewater. *Ecological Engineering*, 35: 744-753.

Cantona, C.S. (2010). *Wastewater treatment – A closer look at Eco Machines – Biomimicry solutions.*

Capuno, R. (2007). Mathematical modeling for nitrogen removal via a nitritation: anaerobic ammonium oxidation-coupled biofilm in a hollow fiber membrane bioreactor and a rotating biological contactor. *Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering*.

Chakrabarti, N., Tajkhorshid, E., Roux, B. & Pommes, R. (2004). Molecular basis of proton blockage in aquaporins. *Structure 12*, 65-74.

Cheng, S.K. (2010). Pre-acclimation of a wastewater inoculum to cellulose in an aqeous-cathode MEC improves power generation in air-cathods MFCs. *Bioresource Technology*, 102: 367-371.

Chou, L.S. (1978). Acclimation and degradation of petrochemical wastewater components by methane fermentation. *Biotechnology Bioengineering Symposium*, 8: 391-414.

Croll, D.A. (2008). *Filter Feeding*. Retrieved June 2011, from University of Santa Cruz, Bio. Research: http://bio.research.ucsc.edu/people/croll/pdf/Croll 2008 2.pdf

David, M.G. (1999). Phenolic compounds in surface water. *Water Research*, 33: 3213-3219.

Denny, M. & Cowen, B. (1997). Flow and flexibility. II. The roles of size and shape in determining wave forces on bull kelp nereocystis luetkeana. *Exp Biology, 200*, 3165-3183.

dos Dantos, G.C. (2010). *Vegetable Species fo pytoextraction of Boron, Copper, Lead, Manganese and Zinc from contaminated soil*. Retrieved from Sci Agri: http://pss.uvm.edu/pss269/pdfs/3-Review_phytoremediation_metals-II.pdf

DWAF. (1999). *Guidelines for delineating the boundaries of a wetland and the zones within a wetland in terms of the South African Water Act. Resource Directed Measures for Protection of Water Resources: Wetland Ecosystems. Version 1.0.* Pretoria: DWAF.

DWAF. (2005). *A practical field procedure of wetlands and riperian areas.* Pretoria: DWAF.

Ellis, J.B., Shutes, R.B. & Revitte, D.M. (2003). *Guidance manual for constructed wetlands.* Swindon: Environment Agency.

Equilibrium Capital Group. (2010, November). Innovative Sustainable water treatment, Sustainable Investment report. *Water and Wastewater, Profitting from the next big wave*.

Fankboner, P.V. (n.d.). *Journal of Marine Biological Association of the United Kingdom.* Retrieved from A re-examination of mucu feeding by the sea cucumber Leptopentacta (Cucumaria) elongata: http://journals.cambridge.org/action/displayAbstract?fromPage=online&aid=4390584

Faulwetter, J.G. (2009). Microbial processes influencing performance of treatment wetlands: A review. *Ecological Engineering*, 35: 987-1004.

Gaylord, B. & Denny, M. (1997). Flow and Flexibility. I. Effects of size, shape and stiffness in determining wave fources on the stipulate kelps eisenia arborea and pterygophora claifornica. *Exp Biology, 200*, 3141-3164.

Ghosh, D.G. (2010). Effect of hydraulic retention time on the treatment of secondary effluent in a subsurface flow constructed wetland. *Ecological Engineering*, 36: 1044-1051.

Ghosh, M. & Singh, S.P. (2005). *A review on phytoremediation of heavy metals and utilization of it's by products*. Retrieved from Asian Journal on Energy and Environment: http://www.asian-energy-journal.info/Abstract/A%20review%20on%20phytoremediation%20of%20heavy%20metals%20and%20utilisation%20of%20it%20s%20by%20products.pdf

Graham, E.R. & Thompson, J.T. (2009). *JOurnal of experimental marine Biology and Ecology.* Retrieved 2011, from Deposite and Suspension Feeding Sea Cucumbers: – https://edisk.fandm.edu/joseph.thompson/Site/Publications_files/Graham%20%26%20Thompson_2009_JEMBE.pdf

Greenway, M.W. (1999). Constructed wetlands in Queensland: Performance efficiency and nutrient bioaccumulation. *Ecological Engineering*, 12: 39-55.

Grismer, M.T. (2003). Hydraulic characteristics of a subsurface flow constructed wetland for winery effluent treatment. *Water Environment Research*, 73: 466-477.

Groot, B.L. & Grubmuller, H. (2001). Water permeation across biological membranes: mechanism and dynamics of aquaporin 1 and GlpF. *Science 294*, 2353-2357.

Gutiérrez-Sarabia, A.E. (2004). Slaughterhouse Wastewater Treatment in a Full-scale System with Constructed Wetlands. *ProQuest Agriculture Journals*, 334-339.

Haberl, R.G. (2003). Constructed wetland for the treatment of organic pollutants. *Journal of Soils and Sediments*, 3: 109-124.

Helping Nature Take the Strain: Wetland Stormwater Control and Retention. (2010). Retrieved June 27, 2011, from ITT Water and Wastewater: http://www.ittwww.ca/Site/Fr/Parlonspompes/Etudesdecas/Wetlandstormwatercontrol.asp

Herouvim, E.A. (2011). Treatment of olive mill wastewater in pilot-scale vertical flow constructed wetlands. *Ecological Engineering*, doi:10.1016/jecoleng.2011.018.

Howle, L.E. (2009). *The efficiency of a WhalePower Corp. 5 meter prototype, wind turbine blande.*

Hu, H.N. (1997). Analysis of microbial acclimation to refractory chemicals in wastewater using respiratory quinone profiles. *Water Science and Technology*, 37: 349-362.

IPCC. (2001). *Climate change 2001: The scientific basis. Contribution of working group 1 to the third assessment report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

IWA. (2006). *Constructed Wetlands for Pollution Control.* London, UK: IWA publishing.

Jenkin, P.M. (1957). *The filter feeding and food of flamingoes (Pheonicopteri)*. Retrieved 2011, from Philosophical transactions of the royal society of london: . http://www.oucom.ohio.edu/dbms-witmer/Downloads/1957_Jenkin_flamingo_filter-feeding.pdf)

Kadlec, R. (2008). The effects of wetland vegetation and morphology on nitrogen processing. *Ecological Engineering*, 33: 126-141.

Kadlec, R. (2009). Comparison of free water and horizontal subsurface treatment wetlands. *Ecological Engineering*, 35: 159-174.

Kantawanichkul, S.K. (2009). Treatment of high-strength wastewater in tropical vertical flow construced wetlands planted with Typha angustifolica and Cyperus involucratus. *Ecological Engineering*, 35: 238-247.

Keeling, S., Stewart, R., Anderson, C. & Robinson, B. (2003). Nickel and cobalt phytoextraction by the hyperaccumulator Berkheya coddii: implications for polymetallic phytomining and phytoremediation. *International Journal of Phytoremediation*, 235 244.

Khan, M.A. & Shah, M. (2010). Studies on Biomass Changes and Nutrient Lock-up Efficiency in a Kashmir Himalayan Wetland Ecosystem, India. *Journal of Ecology and the Natural Environment*, 147-152.

Khilji, S. & Firdaus-e-Bareen. (2008). Rhizofiltration of Heavy Metals from the Tannery Sludge by the Anchored Hydrophyte, Hydrocotyle Umbellata L. *African Journal of Biotechnology*, 3711-3712.

Kiviasi, A. (2001). The potential for constructed wetlands for wasatewater treatment and reuse in developing countries: a review. *Ecological Engineering*, 16: 545-560.

Knowles, P.D. (2010). Clogging in subsurface flow treatment wetlands: occurrence and contributing factors. *Ecological Engineering*, 37: 99-112.

Koda, N.I. (2002). Response of the ice-nucleating bacterium Pantoea ananas KUIN-3 during cold acclimation. *Bioscience, Biotechnology and Biochemistry*, 66: 866-523.

Konnerup, D.K. (2009). Treatment of domestic wastewater in tropical, subsurface flow constructed wetlands planted with Canna and Helicona. *Ecological Engineering*, 248-257.

Korkusuz, E.B. (2005). Comparison of the treatment performances of blast furnace slag-based and gravel-based vertical flow wetlands operated identically for domestic wastewater in Turkey. *Ecological Engineering*, 24: 187-200.

Kotze, D., Marneweck, G., Batchelor, A., Lindley, D. & Collins, N. (2007). *WET-EcoServices: A technique for rapidly assessing ecosystem services supplied by wetlands.* Pretoria: WRC.

Laakkonen, L., Jobson, R.W. & Albert, V.A. (2006). A new model for the evolution of carnivory in the Bladderwort plant (Utricularia): Adaptive Changes in cytochrome C Oxidiase (COX) provide Respiratory Power. *Plant Biology, 8*, 758-764. Retrieved from http://deepblue.lib.umich.edu/bitstream/2027.42/74764/1/s-2006-924459.pdf)

Langergraber, G.G. (2008). Recent development in numerical modelling of subsurface flow constructed wetlands. *Science of the Total Environment*, 407: 3931-3943.

Li, H.W. (2011). A practical method for the restoration of clogged rural vertical flow subsurface flow constucted wetlands for domestic wastewater treatment. *Water Science and Technology*, 63: 283-290.

Li, J. W. (2008). Influence of vegetation and substrate on the removal and tranformation of dissolved organic matter in horizontal subsurface flow constructed wetlands. *Bioresource Technology*, 99: 4990-4996.

Lin, Y.J. (2008). Nitrate removalfgrom goundwater using constructed welands under various hydraulic loading rates. *Bioresource Technology*, 99: 7504-7513.

Lu, Y. & Shen, G.X. (2006). Dual leading-edge vortices on flapping wings. *Exp Biol*, 5005-5016.

Lu, Y. & Shen, G.X. (2008). Three-dimentional flow structures and evolution of the leading-edge vortices on a flapping wing. *Exp Biol*, 1221-1230.

Macfarlane, D., Kotze, D., Ellery, W., Walters, W., Koopman, W., Goodman, P. & Goge, C. (2008). *Macfarlane, D.M., Kotze, D.C., Ellery, W. N., Walters, W., Koopman, V., Goodman, P. & Goge, C. (2008). WET-Health – A technique for rapidly assessing wetland health. WRC Report TT 340/08. .* Pretoria: Water Research Commission.

Maltais-Landry, G.M. (2009). Greenhouse gas production and efficiency of planted and artificially aerated contructed wetlands. *Environmental Pollution*, 157: 748-754.

Manual, M.U. (2011). *Stormwater Wetlands.* Minnesota: Metropolitan Council/Barr Engineering Co.

Masudi, A.M. (2001). *Constructed Wetlands for Wastewater Treatment in Tanzania*. Retrieved June 27, 2011, from Science in Africa: http://www.scienceinafrica.co.za/2001/september/wsp.htm

Melian, J.R. (2010). Hybrid constructed wetlands for wastewater treatment and resuse in the Canary Islands. *Ecological Engineering*, 36: 891-899.

Mimis, S. & Gaganis, P. (2007). Vertical Flow Constructed Wetlands for Wastewater Treatment: a Pilot Scale Study. *10th Internation Conference on Environmental Science and Technology* (pp. 501-502). Kos Island, Greece: University of the Aegean.

Mohammadi, M.M. (2010). Treatment of Wastewater from Rubber Industry in Malaysia. *African Journal of Biotechnology*, 6233-6243.

Montangero, A. & Strauss, M. (2002). *Faecal Sludge Treatment.* IHE Delft.

Moss, B. (2009). *Ecology of fresh waters, Man and medium, Past to future, 3rd ed. B. Malden, U.S.A.: Blsckwell Pulishing*

Mulidzi, A. (2010). Winery and distillery wastewater treatment by constructed wetland with shorter retention time. *Water Science and Technology*, doi:10.2166/wst2010.206.

Mulidzi, R. (2000). *Monitoring Performance of Constructed Wetlands in California*. Retrieved June 27, 2011, from Wynboer: http://www.wynboer.co.za/recentarticles/200505wetlands.php3

Nature, A. (2010). *Dissolved gold is precipitated: Bacteria.* Retrieved from Ask Nature: http://www.asknature.org/strategy/c7372dfb952636b3557a79e175387755

Nature, A. (2011). *Specialised gills Filter Plankton: Basking Shark*. Retrieved from Ask Nature: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1690094/pdf/UUJHLXT1J6KP8E54_266_1437.pdf

Naylor, S.B. (2003). Treatment of fresh water fish farm effluent using constructed wetlands: the role of plants and substrate. *Water Science and Technology*, 48: 215-222.

Naz, M.U. (2009). Side-by-side comparison of horizontal subsurface flow and free water surface flow constructed wetlands and artificial neural networkd (ANN) modelling approach. *Ecological Engineering*, 35: 1255-1263.

Nel, J., Maherry, K., Petersen, C., Roux, D., Driver, A., Hill, L., . . . Nienaber, S. (2011). *Technical Report for the National Freshwater Ecosystem Priority Areas project. WRC Report No. K5/1801.* Pretoria: WRC.

Niklas, K. & U. (1982). Pollination and Airflow Patterns Around Conifer Ovulate Cones. *Science*, 442-444.

NKUIC. (n.d.). *National kidney and urologic information clearing house*. Retrieved from niddk: http://kidney.niddk.nih.gov/Kudiseases/pubs/yourkidneys/

Nyquist, J.G. (2009). A field study on constructed wetlands for preventing and treating acid mine drainage. *Ecological Engineering*, 35: 630-642.

Olguin, E.S. (2008). Constructed wetland mesocosms for the treatment of diluted sugarcan molasses stillage from ethanol production using Pontederia sagittata. *Water Research*, 42: 3659-3666.

Ollis, D., Snaddon, C., Job, N. & Mbona, N. (2013). *Classification system for Wetlands and other Aquatic ecosystems in South Africa. User Manual: Inland systems SANBI Biodiversity series 22.* Pretoria: SANBI.

Padmavathiamma, P. & Li, L.Y. (2007). *Phytoremediation technology:Hyper-accumulation metals in plants*. Retrieved from Water Air Soil Pollution: http://pss.uvm.edu/pss269/pdfs/3-Review_phytoremediation_metals-II.pdf

Pedescoll, A.C. (2011). Contaminant removal effieciency depending on primary treatment and operational strategy in horizontal subsurface flow treatment wetlands. *Ecological Engineering*, 37: 372-380.

Peoples Power Africa. (2008, August 28). *Peoples Power Africa*. Retrieved January 23, 2012, from Peoples Power Africa: http://www.peoplespowerafrica.co.za

Poach, M.H. (2003). Improved nitrogen treatment by constructed wetlands receiving partically nitrified liquid swine manure. *Ecological Engineering*, 20: 183-197.

Prochaska, C.Z. (2007). Performance of pilot-scale vertical-floe constructed wetlands, as affected by season, substrate, hydraulic load and frequency of application of simulated urban sewage. *Ecological Engineering*, 31: 57-66.

Qiao, S.Y. (2010). High-rate nitrogen removal from livestock manure digester liquor by combined partial nitritation-annamox process. *Biodegradation*, 21: 11-20.

Reed, P. (1988). *National list of plant species that occur in wetlands: national summary.* U.S. Fish and Wildlife Service, Washington, DC. Report No. 88.

Reinhardt, M.G. (2005). Phosphorus Retention in Small Constructed Wetlands Treating Agricultural Drainage Water. *Journal of Environmental Quality*, 1251.

Riefler, R.K. (2008). Role of sulfur-reducing bacteria in a wetland system treating acid mine drainage. *Science of the Total Environment*, 394: 222-229.

Rios, G.M., Belleville, M.P. & Paolucci-Jeanjean, D. (2007). Membrane engineering in biotechnology: quo vamus. *Trends Biotechnology*, 25 (6) p 242-246.

Risgard, H.U. & Carsen, P.S. (2001). *Limnology and Oceanography.* Retrieved June 2011, from Minireview:Cillary Filter Feeding and Bio-Fluid Mechanics present understanding and unsolved problems: http://www.jstor.org/pss/2671055

Rittman, B.M. (2001). *Environmental Biotechnology: Principles and applications.* Chicago: McGraw-Hill.

Rodriguez-Caballero, A.R. (submitted April 2011). Treatment of high ethanol concentration wastewater by constructed wetlands: enhanced COD removal and bacterial community dynamics. *Journal of Environmental Managment*.

Schachtschneider, K., Muasya, M. & Somerset, V. (2010). Are indigenous sedges useful for phytoremediation and wetland rehabilitation?. *CSIR 3rd Biennial Conference 2010. Science Real and Relevant.* Pretoria, South Africa. Retrieved from http://hdl.handle.net/10204/4313

Sharklet. (2008, 11 28). Chief Executive Officer. (DiscoveryNews, Interviewer)

Sheikh, B. (2011). *Use of Constructed Wetlands for Wastewater Treatment and Water Recycling-Application to Saudi Arabian Conditions.* San Fransisco, California: WateReuse Research Foundation.

Sims, D.W. (1999). *Threshold Foraging Behaviour of basking sharks zooplankton:Life on a energetic knife edge*. Retrieved June 2011, from The Royal Society: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1690094/pdf/UUJHLXT1J6KP8E54_266_1437.pdf

Sindilariu, P.B. (2009). Factors indluencing the efficiency of constucted wetlands used for the treatment of intensive trout farm effluent. *Ecological Engineering*, 35: 711-722.

Slack, J. (2010, Febuary 1). *Wetland Restoration Strategy Released*. Retrieved June 28, 2011, from Mississauga: http://www.mississauga.com/news/news/article/603124

Sleytr, K.T. (2009). Diversity of abundant bacterial in subsurface vertical flow constructed wetlands. *Ecological Engineering*, 35: 1021-1025.

SMRC. (n.d.). *Stormwater Management Fact Sheet: Stormwater Wetland*. Retrieved June 28, 2011, from SMRC: http://www.stormwatercenter.net/Assorted%20Fact%20Sheets/Tool6_Stormwater_Practices/Wetland/Wetland.htm

Sohsalam, P.S. (2008). Feasibility of using constructed weland treatment for molasses wastewater treatment. *Bioresource Technology*, 99: 5610-5616.

Suliman, F.F. (2006). Change in flow and transport patterns in horizontal subsurface flow constructed wetlands as a result of biological growth. *Ecological Engineering*, 27: 124-133.

Suliman, F.F. (2006). Effect of the inlet-outlet positions on the hydraulic performance of horizontal subsurface-flow constructed wetlands with heterogenous porous media. *Journal of Contaminant Hydrology*, 87: 22-36.

Tao, W.W. (2009). Effects of vegetation, limestone and aeration on nitritation, anammox and denitrification in wetland treatment systems. *Ecological Engineering*, doi:10.1016/j.ecoleng2008.12.003.

The Biomimicry Group. (January 2011). *The Biomimicry Handbook:A seedbank of Knowledge and Best Practice.*

The Interstate Technology and Regulatory Council – Wetlands team. (2003). *Technical and Regulatory Guidance Document for Constructed Treatment Wetlands.* The Interstate Technology and Regulatory Council .

Tietz, A.L. (2008). Bacterial carbon utilization in vertical subsurface flow constructed wetlands. *Water Research*, 42: 1622-1634.

Todd, J. (2008, April). *A new shared economy for appalachia: An economy built upon environmental restoration, carbon sequestration, renewable energy and ecological design.* Lewis Foundation.

Todd, J. & Josephson, B. (1996). The design of Living Technologies for waste treatment. *Ecological Engineering 6* , 109-136.

Todd, J. & Todd, N. (1993). *From eco-machines to living machines – principles of ecological design.*

Todd, N.J. (2005). *A safe and sustainable world: the promise of ecological design.* Washington DC: Island Press.

Torrens, A.M. (2009). Impact of design and operation variables on the performance of vertical-flow constructed wetlands and intermittent sand filters treating pond effluent. *Water Research*, 43: 1851-1858.

Toscano, A.L. (2009). Modelling pollutant removal in pilot-scale two-stage subsurface flow constructed wetlands. *Ecological Engineering*, 35: 281-289.

USEPA. (2000). *A handbook of constructed wetlands. Volume 1 General Considerations. .* USEPA.

Van de Moortel, A.R. (2009). A comparative study of surface and subsurface flow constructed wetland for treatment of combined sewer overflows: A greenhouse experiment. *Ecological Engineering*, 35: 175-183.

Van Deun, R. (n.d.). *Treatment of Dairy Farm Wastewater with Constructed Wetlands*. Retrieved June 28, 2011, from Constructed Wetlands: http://www.constructedwetlands.net/tisza4/HMV_RVD_tisza4.htm

Verhoeven, J.M. (1999). Wetlands for wastewater treatment: Opportunities and limitations. *Ecological Engineering*, 12: 5-12.

Vincent, J., Bogatyreva, O., Pahl, A., Bogatyrev, N. & Bowyer, A. (2005, Mar). Putting Biology into a TRIZ: A database of biological Effects. *Creativity and Innovation management, 14*(1).

Vymazal, J. (2005). Constructed wetlands for wastewater treatment: editorial. *Ecological Engineering*, 25: 475-477.

Vymazal, J. (2007). Removal of nutrients in various types of constructed wetlands. *Science of the Total Environment*, 380: 48-65.

Vymazal, J. (2008). Constructed Wetlands for Wastewater Treatment: A Review. *The 12th World Lake Conference* (pp. 965-971). Trebon, Czech Republic: Czech Academy of Sciences.

Vymazal, J.K. (2010). Can multiple harvest of aboveground biomass enhance removal of trace elements in constructed wetlands receiving municipal sewage. *Ecological Engineering*, 36: 939-945.

Walton, W. (2004). *Managing Mosquitoes in Surface-Flow Constructed Treatment Wetlands*. Retrieved June 28, 2011, from UC IMP Online: http://www.ipm.ucdavis.edu/PMG/PESTNOTES/mosquitowetlands2.html

Welz, P.R. (2011). Ethanol degradation and the benefits of incremental priming in pilot-scale constructed wetlands. *Ecological Engineering*, doi:10.1016/j.ecoleng2011.03.009.

Wetzel, R. (2001). *Limnology: Lake and River Ecosystems* (3rd ed.). London NW1 7BY: Academic Press.

White, R.F. (2011). Plant-derived phenolic compounds impair the remediation of acid mine drainage using treatment wetlands. *Ecological Engineering*, 37: 172-175.

Yan, C.S. (2006). *Novel Vegetated Sequencing Batch Biofilm Reactorfor Treating Suburban Domestic Wastewater.* Hong Kong: Pao Yue-kong Library.

Zaida, B.I. (1996). Accelerated biodegradation of high and low concentrations of p-nitrophenol (PNP) by bacterial inoculation in industrial wastewater: the role of inoculum size on acclimation period. *Current Microbiology*, 33: 292-296.

Zhang, X.Z. (2007). Differentiate performance of eight filer media in vertical flow constructed wetlands: Removal of organic matter nitrogen and phosphorus. *Fresenius Environmental Bulletin*, 16: 1468-1483.

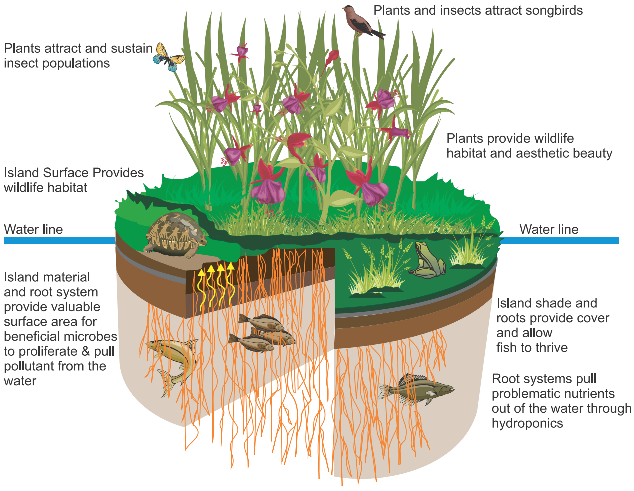
APPENDIX A – Case Studies

Case STUDY: Floating Islands

Product Background:

Floating Islands International (Montana, USA) has created an inert, floating matrix known as a BioHaven. BioHaven floating islands (also knowns as floating treatment wetlands or FTWs) are a new and powerful tool in water stewardship. They biomimic natural floating islands to create a "concentrated" wetland effect. Constructed of durable, non-toxic, post-consumer plastics, injected with foam for initial buoyancy and vegetated with native plants, BioHaven islands float on top of water, providing a beautiful habitat for birds and animals. Underneath the surface, a dynamic process takes place.

The Product:



In wetland ecosystems, 80 percent of the biological action is performed by aggregates of microorganisms attached to all submerged surfaces, called biofilm, but to be effective, they need a surface to stick to. The floating island matrix, with its dense fibers and porous texture, is the perfect surface area for growing large amounts of microbes in a short time.

In six weeks to three months the bacterial biofilm starts sequestering nutrients, trace metals, pharmaceuticals and more. Recent independent laboratory tests showed removal rates far in excess of previously published data; 20 times more nitrate, 10 times more phosphate and 11 times more ammonia, using unplanted islands. They are also extremely effective at reducing total suspended solids and dissolved organic carbon in waterways.

Nutrients circulating in the water come into contact with these biofilms and are consumed by them, while a smaller fraction is taken up by plant roots. At the right scale, the technology can reduce the outflow of phosphates by about 30%. Suspended solids slough off into the benthic zone below the island and organic solids stick to the biofilms and become the base of the freshwater food web. These pathways represent a concentrated wetland effect; nature's way to clean water.

Scalability:

Because Biohaven floating islands are able to withstand fluctuations in water levels, without becoming stranded or inundated, they are very suitable for the treatment of runoff and drainage, such as urban storm water, agricultural runoff and other non point-source applications. They can be launched over deep or shallow water, including streams and detention basins, and they represent an inexpensive option to 'retro-fit' to existing systems, such as wastewater lagoons.

Competition:

While many have tried to create 'floating wetlands', to-date only Floating Islands International has been successful in combining all of the abiotic and biotic components necessary to create a semi-natural biological engine. Other types of floating devices have focused on plant support and nutrient uptake via plant growth, and this is where they fail in comparison to BioHavens; in that they lack the biofilm support component.

To date over 4000 BioHavens have been launched. It is estimated that half a million square meters have been launched in the U.S., Canada, Mexico, England, Germany, New Zealand, Singapore, People's Republic of China and Korea. They have also been installed locally at The Stables development in Cape Town.

Sources:

- www.floatingislandinternational.com

IRIN News, 2011. South Africa – De-stressing the water. Humanitarian News and Analysis.

Harding, 2010. Floating Islands; Natures Marvel. DH Environmental Consulting.

Buczynski, 2010. Recycled Bio-Islands Restore Fresh Water Habitats. Crisp Green.

Case STUDY: Sharklet Technologies

The problem:

Biofouling can be divided into **microfouling**; biofilm formation and bacterial adhesion on surfaces, and **macrofouling**; attachment of larger organisms, e.g. barnacles, mussels, worms and seaweed. Both micro and macrofouling cost governments and companies $billions and result in thousands of deaths every year.

In the healthcare sector, hospital-acquired infections (caused by biofilm development) account for $30.5 billion in excess healthcare cost every year (between $8,000 and $15,000 per patient!) and MRSA infections in emergency rooms have increased 211 percent between 2000 and 2008. Until now, antibiotics, disinfectants and chemicals have been the primary weapons to control bacterial growth. These strategies share a common trait; they kill bacteria to control it. These kill strategies and their overuse has led to increased bacterial resistance to antimicrobial and so-called superbugs.

While in the marine industries, governments and corporate spend more than $5.7 billion annually to prevent and control marine biofouling. The practical problem for ships is simply that biofilm can add up to 20 percent drag and barnacles over 60 percent. As a result nearly 70 percent of the world's industrial shipping and recreational boating fleet use copper-based paints as an antifouling strategy. These bottom paints are designed to slowly release copper into surface waters to kill and slow the growth of microorganisms such as algae and barnacles; compounding to often toxic levels in our oceans, lakes and waterways.

A Solution:

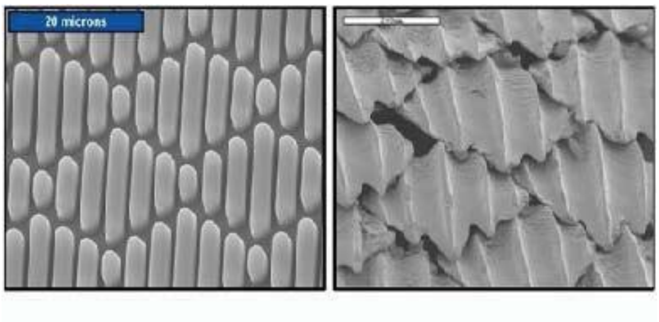
New strategies are needed to inhibit biofouling without further contribution to the problem of antimicrobial resistance or use of toxic paints. Sharklet presents such a solution. Sharklet is the world's first technology to reduce bacteria growth through pattern alone. Sharklet doesn't kill biofouls to control them. The patented microscopic features of Sharklet simply create an unstable surface on which organisms don't like to grow.

Sharklet Technologies puts Sharklet pattern into adhesive-backed films and manufactures the pattern into medical devices and consumer goods to prevent organism growth. Sharklet is the first no-kill, environmentally friendly solution created to inhibit the growth of biofouling.

Product Background:

In 2002, Dr. Anthony Brennan, a materials science and engineering professor at the University of Florida, was visiting the U.S. naval base at Pearl Harbor to find new antifouling strategies to reduce use of toxic antifouling paints and trim costs associated with dry rock and drag. Dr. Brennan was convinced that using an engineered topography could be the key to new antifouling technologies. When he and several colleagues watched an algae-coated nuclear submarine return to port, Dr. Brennan remarked that the submarine looked like a whale lumbering into the harbor. In turn, he asked which slow moving marine animals don't foul. He got the answer; the shark.

Dr. Brennan was inspired to take an actual impression of shark skin, or more specifically, its dermal denticles. Examining the impression with scanning electron microscopy, Dr. Brennan confirmed his theory. Shark skin denticles are arranged in a distinct diamond pattern with tiny riblets. When width-to-height ratios of these 'riblets' were measured, Dr. Brennan found it produced a surface that would discourage microorganisms from settling. The first test of Sharklet yielded impressive results; Sharklet reduced green algae settlement by 85 percent compared to smooth surfaces.



Sharklet™ Surface Technology *Galapagos Shark Skin*

While the U.S. Office of Naval Research continued to fund Dr. Brennan's work for antifouling strategies, new applications for the pattern emerged. Brennan evaluated Sharklet's ability to inhibit the growth of other microorganisms. Sharklet proved to be a mighty defence against bacteria.

The Product:

Sharklet is a simple solution to a complex problem. The patented, microscopic pattern manufactured by Sharklet Technologies creates a surface upon which bacteria do not like to grow. The Sharklet pattern is manufactured onto adhesive-backed skins that may be applied to high-touch areas to reduce the transfer of bacteria among people. Sharklet Technologies is also developing Sharklet-patterned medical devices including a Sharklet Urinary Catheter.

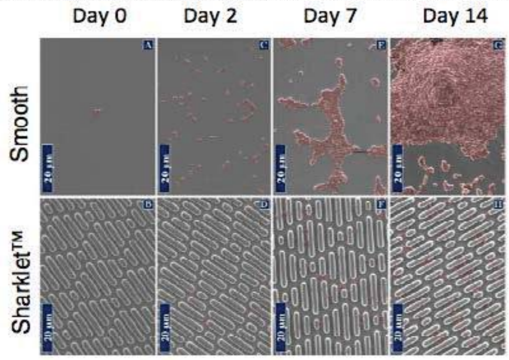
Sharklet Technologies manufactures a variety of Sharklet-patterned products that may be converted into surface skins, patterned medical devices, OEM (original equipment manufacturer) products and marine based anti-fouling surfaces. All use the Sharklet Technology to reduce the build-up of biofouling using no-kill, environmentally friendly, effective outcomes.

The strong Sharklet surface protection films are idealy suited for surfaces in healthcare, public restrooms, points of sale tops or other frequently touch bacteria-prone surfaces where bacterial inhibition is desired. This may include a variety of other public environments, food preparation surfaces and surfaces involved in water storage/transportation. Sharklet patterned films are a flexible, cost-effective and innovative bacterial solutions.

Where Sharklet protection films are inappropriate for application, Sharklet provides OEMs a new alternative through the manufacturing of Sharklet diretly into the surfaces fo durabel goods. Embedded materials to date include: polypropylene, ABS, polycarbonates, PMMA and other materials.

Site cultured	# Cultures	#/% Positive Cultures	Site cultured	# Cultures	#/% Positive Cultures
Infusion Pumps	73	19 (26%)	Monitors	40	5 (13%)
EKG Leads	68	18 (26%)	Suction Canister	142	17 (12%)
Bed Rails	175	33 (19%)	Chairs	101	11 (11%)
Shelves	48	9 (19%)	Doors	202	22 (11%)
Overbed Tables	179	32 (18%)	IV Poles	190	19 (10%)
Bedside Tables	187	31 (17%)	Oxygen Meters	202	16 (8%)
Pulse Oximeters	176	24 (14%)	Faucets	206	13 (6%)
Stethoscopes	142	18 (13%)	Miscellaneous	90	13 (14%)
			Totals	2,221	300 (13.5%)

Falk PS et al., :Outbreak of Vancomycin-Resistant Eneterococcin a Burn Unit, *Infection Control and*



Sharklet marine is perfectly adapted (as it is for the inspirational organism; the shark) for macrofouling reduction on boat haulls; inhibiting the attachment of certain types of barnacle cyprid and algal zoospores, both precursors to the development of mature barnacles and algae that foul vessels. It is estimated that through the streamlining of the boat hulls handling will be inproved, drag reduced and cleaining using toxic chemicals eliminated. It is estimated that Sharklet could save $1.6 million of fuel per year per large vessel.

Sharklet reseach and testing has shown excellent results on a variety of surfaces, particularly when comparing biofilm development of a smooth surface to that on Sharklet.

Day 0 – bacteria presence at 1% on smooth surface versus 0% on Sharklet.
Day 2 – bacteria presence at 7% on smooth surface versus 4% on Sharklet.
Day 7 – bacteria presence 22% on smooth surface versus 4% on Sharklet. Biofilm has developed on smooth surface.
Day 14 – bacteria biofilm on smooth surface versus 7% on Sharklet. No biofilm on Sharklet surface.

Scalability:

Due to the fractal nature of the technology, Sharklet is well adapted to scalable applications from micro (20 micrometres; or the size of one 'diamond') to macro (oil tanker hulls) geometries. The effectiveness of Sharklet Surface Technology is operationally restricted only to the emulation of the specific topography of sharkskin and the nano technology needed to generate such a surface. The variety of materials the micro topography can be directly manufactured into is also growing.

Competition:

Sharklet Technology is currently the only physical surface technology developed by reduction of biofouling. It is not, however, the only alternative for toxic copper paint used to reduce marine biofouling. Ultrasonic Antifouling is a product that uses very high frequency sound to reduce biofoul on boat hulls. This mechanical approach could be used in the variety of other biofouling situations, such as water storage and piping, however it would not be able to be used in the medical industry due to obvious potential to interfere with medical apparatus. The process does not impact on hull portions that come into contact with air. However, Shaoyi Jiang's work on preventing fouling using coatings that incorporate zwitterionic-mixed-charged-compounds is a strongly competing product. Although chemically stable, the balanced mix of positive and negative charges that such coatings naturally exhibit acts to prohibit the attachment of bio-molecules and microorganisms, effectively protecting surfaces from becoming colonized, in both laboratory tests and field trails.

Sources:

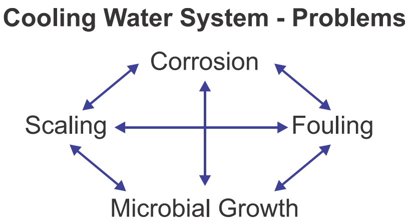
- www.sharklet.com
Ultrasonic Antifouling, - www.ultrasonic-antifouling.com
Office of Naval Research, New hull coatings for Navy ships cut fuel use, protect environment, 2009, - www.eurekalert.org/pub release/2009-06/oonr-nhc060409.php

Case STUDY: Vortex Generator

The problem:

Water naturally contains impurities, gasses and undissolved minerals. Conventional water use or manipulation often results in a variety of unwanted effects:

Precipitate fouling such as Calcium carbonate build up (also known as scaling), inside domestic and industrial appliances, as well as plumbing, results in millions of dollars of maintenance annually. In 2006 it was estimated the economical loss due to boiler and turbine fouling in China utilities at 4.68 billion dollars, which is about 0.169% of the county's GDP. Biological fouling in the form of biofilms can develop where water movement is slow and inefficient in piping, resulting in water contamination and restricted water movement. Chemicals and detergents are often used as a quick but unstable method of reducing biofilm and calcium build up. This has far reachi9ng consequences for water quality as water is leached or evacuated into the greater environment.



While creating artificial ice in use in ice rinks (as well as other applications), gas bubbles trapped in ice results in weaknesses and poor retention time; the gas bubbles accelerate heat conduction rates and so cause ice to melt more rapidly.

Water filtration and purification is conventionally a slow, energy and labour intensive process requiring a variety of expensive specialist equipment. Access to clean, cheap water is a widespread and growing problem.

A Solution:

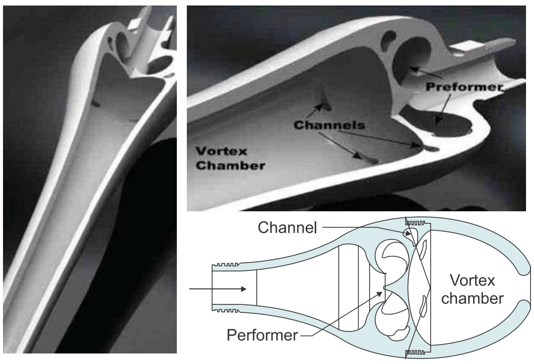
Watreco's water treatment products use the patented Vortex Generator and the technology platform VPT (Vortex Process Technology) to create energy-efficient, low-cost solutions for several water treatment problems.

Vortex Process Technology (VPT) has borrowed its working principle from the natural flow in water. Inside the Vortex generator, the water is put into a powerful and coherent rotation balancing pressure and sub pressure. The continuous process alters the inner properties of the treated water. This process has been developed by Watreco to, amongst other things, purify water, reduce scaling, alter freezing properties of ice and accelerate infiltration of irrigated water into soil.

Product Background:

The Vortex Generator was first inspired by a rainbow trout's ability to hold its position in a river or stream in the presence of a current. Water rushing into a trout's mouth is forced into ever-tightening vortices as it passes through its gills, back into the current. This allows the trout to remain steady even in inconsistent or violent flows, facilitating passive propulsion upstream and low energy feeding.

This vortex flow gives rise to as strong pressure gradient and shear (tearing) forces. Shear forces in a flowing medium occur when the flow velocity changes rapidly over a short distance. The cross-sectional pressure gradient in the vortex chamber results in sub pressure along the vortex axis.



The Product:

Watreco's generator shapes the fluid flow in three stages:

Performer. The inlet of the vortex generator provides a smooth outward direction of the flow through toroidal motion toward a set of well-defined channels.

Channels. After the performer, the fluid is directed through a set of channels, each with vortex-forming geometry. Each channel delivers a jet stream of vortex flow at a precise angle, into a vortex chamber.

Vortex chamber. In the cortex chamber, the vortices from the channels are wound together, similarly to how a rope is spun together from a set of threads. A strong and stable vortex flow is formed inside the vortex chamber, causing a strongly reduced pressure along the vortex axis (centre).

The sub pressure in the Vortex Generator forces gas bubbles to ove inward towards the vortex axis; viscosity decreases between 3% and 17% (depending on the water quality and temperature) and the electrical conductivity increases by 3% and, in addition, the water’s heat capacity is increased; 5% higher for ice and 3% higher for liquid water.

The strong pressure gradient shifts chemical balances, giving rise to reactions that would not happen under normal flow conditions; calcium carbonate (limestone) crystals are changed from Calcite to Aragonite; they are no longer angular but round in shape and thus do not attach themselves to other limestone crystals or other surfaces, reducing scaling.

Watreco has developed two product lines for practical applications of the Vortex Process Technology:

RealICE: It consists of two parts: the hand unit, with two nozzles, and one of the three base units, adapted to different water pressures and flows. The nozzles are used for building the ice foundation and for ice maintenance. The base unit treats the water before filling an ice rink resurfacer.

Watreco IVG: The Watreco vortex generator in the IVC-series affect the water in liquid form. The Watreco IVG is mounted directly on the water pipe or as part of an industrial process. The unit contains no mioving parts and does not need to be connected to the power grid or any other energy source.

As a result, cooling towers achieve higher efficiency and alonger lifespan as limescale deposits no longer build up around the coolong elements. Irrigation gets more out of every drop of water and gieves higher yields (+5%). IVG also makes it possible to produce harder concrete, and many other areas industrial processes, where water is involved can benefit from the technology. To date, by changing water properties so that it freezes faster, stays frozen 1-2 degrees warmer and produces purer/harder ice, Watreco customers using RealICE for ice rinks, have saved a total of 1,304,979 Euros in energy costs

Scalability:

Watreco also offer custom-made devices and components that are directly adapted to the processes pf products they will support in terms of pressure flow, colour and shape. In the process, Watreco collaborates with researchers and universities around the world to ensure results. The development of the Vortex generator is conducted with the latest CAD (Computer Aided Design) technology, which also allows for the production of small series.

Competition:

Watreco has the global patent rights for the Vortex generator and VPT water process technology. The Vortex generator is utilized within many different application areas to create a range of desired effects and results. Watreco has no competitors that produce the same results using vortex technologies; in the absence of any moving parts and chemical applications. Aqua Z’s use of aquaporin technology uses nanotechnology to produce similar results, as does reverse osmosis. However the Vortex generator’s real advantage over its competitor’s use of nanotechnology is in the products robust nature. Manufactured using its single material (PA12 (Polyamide)) with standard CAD technology, the RealICE and IVG products require extremely low levels of maintenance; reducing waste and further production costs.

Sources:

- www.waterco.com
- www.wextech.co.in

Beald N *et al.*, 2006. Passive propulsion in vortex wakes. Journal of Fluid Mechanics, vol. 549, pp. 385-402.

Xu, Zhang & Yang, 2007. Costs due to utility fouling in China, Heat Exchanger Fouling and Cleaning VII, Vol. RP5, pp. 113-118

Case STUDY: Constructed Wetlands

Product Background:

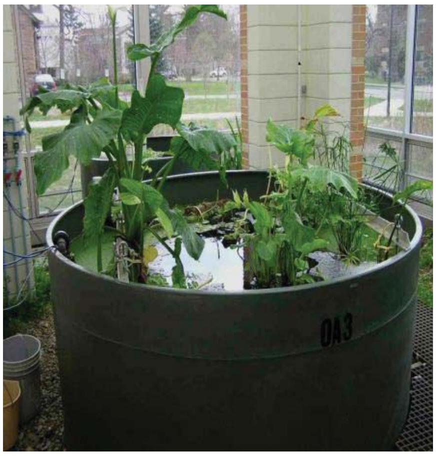
In 1989 Dr John Todd, an internationally respected ecological wastewater treatment inventor and pioneer, began developing a cost-effective, renewable solution to the growing global wastewater crisis. His concept: water reuse rather than disposal and decentralization allowing for in-site, local water recycling. This cost-effective water reuse solution was to be part of green design and water saving for institutions and communities.

Many adaptions to Todd's artificial wetland design have been developed over the past 20 years. In particular, in 1999, Tom Worrell, an inventor and partner of Dr. Todd's, acquired the Living Machine concept, the company and all of its intellectual property from Todd and put his engineers to work in an attempt to make the technology more practical, reliable and cost-effective (the Living Machine will be the example used here).

However, all constructed wetlands use similar technology, functioning similarly to a facultative pond, incorporating both aerobic and anoxic treatment zones. But instead of a body of water, the process occurs within individual tanks, creating independent treatment zones that work in unison to biomimic natural, effective and sustainable wastewater treatments.

The Product:

The Living Machine (as well as all other constructed wetlands) use carefully selected flora and fauna in collaboration with sophisticated control systems. A robust ecosystem is created between the plants, microbial species and distinct treatment zones. All major groups of life are represented, including microscopic algae, fungi, bacteria, protozoa and zooplankton, as well as snail, clam and fish species. Higher plants are grown on adjustable industrial strength fiberglass racks suspended within the system. The result is an efficient and refined wastewater treatment system that is capable of achieving high quality water without the need for hazardous chemicals.



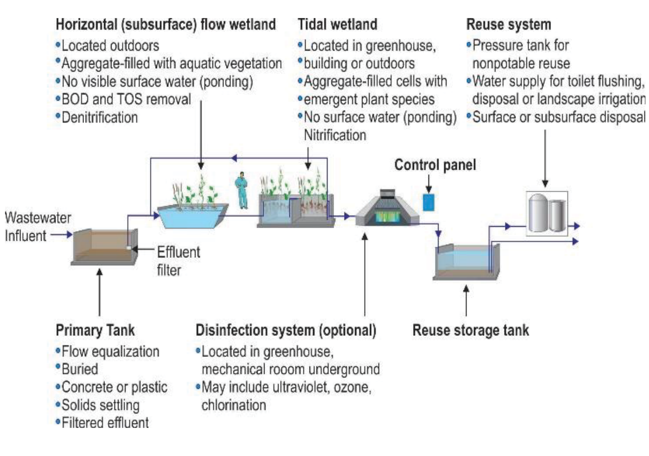
Each Living Machine is constructed to the specifications of the area and the type of wastewater being treated. However there are a number of common features:

Settling Tank: flow is equalized and solids allowed to settle. Larger installations will use a filter for the same purpose.

Control System: a central control system to track water levels and control flow rates through the system. At the same time it monitors water quality and can send alerts to remote locations if it senses a problem with the system.

Wetland Installations: at the heart of the cleaning process wetland beds contain; gravel aggregate, specially engineered films of beneficial microorganisms and plants working together in a living, highly complex ecosystem.

Tidal Flow Wetland: provides superior removal of nitrogen. The system consists of a series of tidal cells which drain and flood many times per day. The tidal cycles bring oxygen to the beneficial microorganisms that do most of the work.



Vertical Flow Wetland: provides the final or "polishing" stage of water treatment. Water enters near the surface of the wetland and passes through two zones containing beneficial microorganisms as it trickles down through the system. If the wastewater has been previously treated by another wetland type, the Vertical Flow Wetland is extremely efficient at final removal of nitrogen and solids.

Disinfection System: uses ozone, ultraviolet or chlorine (alone or in combination). Depending on the types of wastewater being treated, disinfection systems may be required.

Reuse System: Clean, treated water is gathered in a storage tank and distributed for reuse.

Living Machine systems not only speed up natural process of a tidal wetland, but also have aesthetic and biological advantages over other on-site treatment systems while providing the performance, control and monitoring benefits of state-of-the-art engineered systems.

The Living Machine system offers distinct benefits when compared to both traditional on-site technologies such as membrane bioreactors or activated sludge package plants:

Lower operating costs, quality fresh water suitable for reuse, small footprint and readily scalable for high volume, low energy consumption and aesthetic quality, integrating the beauty and complexity of nature into the structure of buildings – providing residents and visitors with an educational experience and direct tangible connection to natural systems.

Scalability:

Most artificial wetlands can be designed to handle almost any level of flow; the ability to handle large flows, above 100,000 gal/day is often dependent on the amount of land area available. Artificial wetlands are strong proponents of the decentralized treatment concept, which can involve a number of smaller systems dispersed throughout the service area, enhancing its ability to service large areas. Because the wetland is modular and each component operation unrestricted by size, artificial wetlands can be built to almost any specification.

Competition:

Even though Living Machines share a common goal to all artificial wetland designs such as Eco Machines, the Living Machine system has significantly evolved over the last two decades, improving upon an original design by Dr. John Todd, to produce a system that is recognized and respected. For more than 10 years, Worrel Water Technologies has invested in extensive research and development to create a viable product that performs reliably and economically.

Sources:

- www.toddecological.com
- www.livingmachines.com

Guterstam, 1996. Ecological engineering for wastewater and its application in New England and Sweden. Ecological Engineering6, pp. 96-108.

Todd and Josephson, 1996. “The Design of Living Technologies for Waste Treatment.” Ecological Engineering6, pp. 109-136.

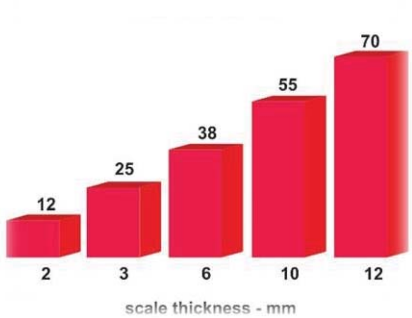
Case STUDY: Nano Chem's Protein Bases Polymers

The problem:

Water, whether saline or fresh, has the ability to corrode and damage materials dramatically over very short time scales. Contact with moisture in the air or direct contact with liquid water often costs millions of dollars in damages to industries worldwide.

The corrosion of metal equipment is a widespread and expensive problem in many industrial applications such as re-circulating cooling systems and in agriculture where liquid fertilizers are used. The U.S. Federal Highway Administration (FHWA) released a breakthrough study in 2002 on the direct costs associated with metallic corrosion in nearly every U.S. industry sector; from infrastructure and transportation to production and manufacturing. Results of the study show that a total annual estimated direct cost of corrosion in the U.S. is a staggering $276 billion; approximately 3.1% of the nation's GDP.

Common scaling



Precipitate fouling, also known as scaling inside waste water treatment, plumbing, domestic and industrial appliances results in millions of dollars maintenance annually as well. The growth of mineral crystals on heat transfer surfaces leads to costly replacements and failures. In 2006 it was estimated the economical loss due to boiler and turbine fouling in China utilities was $4.68 billion! The effects of scaling that we see very time we look inside a kettle is staggering for example 1.5 mm of scale reduces heat transfer in pipes by about 15%

Furthermore, in agriculture, the storage and application of fertilizer solutions can be problematic due to the corrosive nature of the fertilizers themselves leading to further expense and potential contamination of product. Chemicals and detergents build up. This has far reaching consequences for water quality as water is leached or evacuated into the greater environment.

A Solution:

There are existing chemicals that are known to reduce scale, however they are not known to inhibit corrosion and they have a negative effect on the environment. NanChem's new technology provides a more environmentally acceptable solution to both scale and corrosion control. NanoChem develops, produces and markets biodegradable water-soluble polymers for industrial and consumer applications. NanoChem's BioPolymers have a patented unique property of being both a scale and corrosion inhibitor. This enables the user to replace two products in a treatment system, yielding cost and environmental benefits.

NanoChem's technology also provides effective corrosion inhibition of metals in contact with known fertilizer solutions, such as urea ammonium nitrate. An additional benefit of this technology is the potential to enhance the performance of fertilizers.

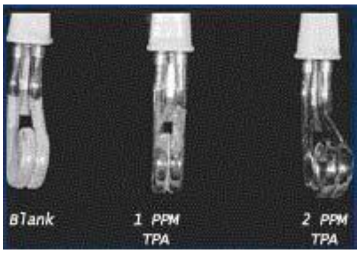
Product Background:

For many years Dr. Alfred Wheeler has been involved in understanding the make-up of naturally calcified structures; in particular the shells of oysters. He has attempted to identify and then investigate several questions that are common to all of these groups. In doing so, he and his co-workers have established that the calcium based structures actually regulates its own growth. Molluscs protects their soft fleshy bodies through the development of calcium based shells. The formation of the shells comes from readily available calcium carbonate and is controlled through the organisms naturally produced protein signals. The development of the shells occurs only when needed and to required proportions. When the molluscs no longer require shell growth the calcification or 'scaling' stops through the production of a simple 'stop' protein.

This magic protein, known as TPA or thermal polyaspartic acid, was developed by Dr. Wheeler and his collaborators to produce synthetic biodegradable polypeptides (proteins). These synthetic versions have found far reaching applications such as in mineral regulators, such as need for scale prevention in cooling water and off-shore oil wells, as dispersants, detergents additives and superabsorbents. In addition, some of these synthetic polymers have been demonstrated as effective in enhancing crop growth. Dr. Wheeler along with Donlar Corporation (now NaniChem) was the 1996 recipient of the EPA Presidential Green Chemistry Award for development of thermal polyaspartate commercial polymers.

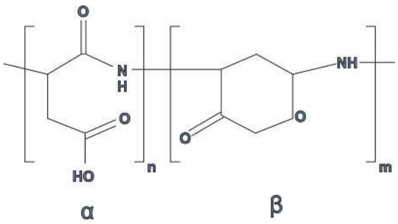
The Product:

NanoChem's BioPolymers (TPA) is a mimic of the biopolymer originally discovered in oyster shells. In addition to participating in the formation of oyster shells, TPA inhibits the formation of calcium carbonate, calcium sulfate, barium sulfate and mineral scale, as well as limiting the oxidation of metals. In practice it has shown a market cost improvement in process and product performance. These products have demonstrated value-added performance in a variety of applications including: oil and gas production, industrial water treatment, dispersants, detergents and superabsorbents for baby diapers and adult incontinence products. In a head to head Round Robin test program performed by BP Exploration, corrosion tests showed that greater than 90% inhibition in a carbon dioxide environment can be achieved.



Scale inhibition with Polyaspartate

NanoChem's BioPolymers allow industry processes and products to become more efficient while significantly reducing the accumulated environmental load. NanoChem's products have gained global regulatory acceptance. In mining applications where seepage water needs to be pumped up to the surface and discharged, NanoChem's BioPolymers were the first approved by the German government for discharge directly into lakes and rivers used as water sources. These biopolymers have also been granted the highest environmental rating for discharge into the North Sea oil fields.



Poly - α, β -D-L-aspartate

NanoChem's BioPolymers have a wide range of molecular weights. The choice among the products depend on the application, formulation and required performance characteristics in specific processes.

Low Molecular Weight BioPolymers have application as general-purpose-anti-scalants in hard water environments, corrosion inhibitor, function as dispersants for mineral slurries and control redeposition of soil in laundry and hard surface cleaners.

High Molecular Weight BioPolymers are used as general-purpose dispersants, clay-soil removal, inorganic scale removal, anti-scalant in hard water environments, mineral slurry dispersant and anti-redeposition of soil in laundry and hard surface cleaners.

Low Color BioPolymers are low color BioPolymers. Because of its low colour, these polymers are specifically designed for applications where colour affects the end use.

Scalability:

With the product being a nano-structure made from synthesized proteins, the coverage the proteins can influence are far reaching. In addition, products that can benefit from TPA are not limited by their form shape as TPA can be introduced directly into the water source and does not need to be impregnated onto a surface.

Competition:

Water-Tec has developed a method of reducing only scaling through electromagnetic fixtures. In a simple explanation coiling the aerials round the pipe work creates an electrical field. The Water-Tec system with its Digital Filter enables both fundamental and useful harmonics frequencies up to a predetermined level to pass and when the calcium crystals are passed through this electric field, the particles become charged and aggregate. Their crystalline form is modified such that hard scale is no longer formed on surface.

However, the scalability of Water-Tec is not clear, and the multi-functional impact is not comparable to that of PTA. It also requires an external power source where as TPA does not once administered and its effects on corrosion are also not attributed.

Bio-Polymers in the form of TPA are at the forefront of synthesized biological solutions. At present no other product is available on the market that has the same influence on corrosion and scaling while avoiding any negative cumulative effects on the environment as a whole.

Sources:
- www.nanochemsolutions.com/index.shtml
- www.water-tec.co.uk/water-conditioning.php
- www.database.portal.modwest.com/item.php?table=strategy&id=1089
- www.clemson.edu/cafls/departments/biosci/facultystaff/wheelera.html

9780639200378