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An Ecological Design Approach to Wastewater Management

Sacha Lozano

University of Vermont

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AN ECOLOGICAL DESIGN APPROACH TO WASTEWATER MANAGEMENT
IN RURAL COMMUNITIES OF COLOMBIA

A Thesis Presented
by
Sacha Lozano
to
The Faculty of the Graduate College
of
The University of Vermont

In Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Natural Resources
Specializing in Ecological Design

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Accepted by the Faculty of the Graduate College, The University of Vermont, in partial fulfillment of the requirements for the degree of Master of Science in Natural Resources, specializing in Ecological Design.

Thesis Examination Committee:

Advisor
John Todd, Ph.D.

Roel Boumans, Ph.D.

Chairperson
Nancy Hayden, Ph.D.

Vice President for Research and Dean of Graduate Studies
Frances E. Carr, Ph.D.

September 7, 2007
ABSTRACT

Global water depletion and unsustainable food production systems represent two iconic crises of our time. These two crises have important themes in common, referring to basic human needs and the way we interact with landscapes in order to satisfy them. But they are also closely related to the way we produce and dispose wastes in our current societal organization. Insufficient, or inadequate, sanitation and waste management practices continue to undermine not only human well-being, but the entire planet’s ecological integrity, on which humans depend. An ecological design approach to manage human waste invites to learn how to participate more harmoniously within the planet’s recycling of matter, using renewable energy sources and mimicking nature’s low entropic states to maintain the life-support systems that we and our economies are part of. This thesis is an in-depth exploration of such an approach, and an attempt to integrate several elements from ecology, engineering, economics, and community development, around issues of water quality, sanitation and waste management in Latin America. As a whole, the thesis explores how can this transdisciplinary approach translate into coherent, feasible, and concrete action, providing appropriate solutions for sanitation, in ways that are effective and viable on a long term, for Latin American rural communities.

Three different papers address different dimensions of the problem, focusing on domestic wastewater and human excreta, as a type of waste of major importance to ecological integrity, public health and economic development. Two of the papers are case studies, carried out at two different rural communities in South West Colombia; one of them focuses on technological and ecological aspects, and the other focuses on social and economic considerations, for a multifunctional-ecological waste management. In the first paper I present an overview of the sanitation problem in Latin America, and the opportunities and challenges of managing waste with an ecological and multifunctional perspective. More specifically, this papers attempts to provide a sound conceptual framework for managing wastewater (sewage) as a valuable resource, in a way that: 1) is affordable –or even profitable– by small communities in developing countries; 2) is safe to the environment and to public health; and 3) provides opportunities for recycling nutrients and organic matter (available in wastewaters), to restore and protect water and soil resources, while enhancing rural livelihoods in tropical agroecosystems. The second paper evaluates the performance and feasibility of an experimental, solar-energy-based, wetland mesocosm, as a complementary aerobic unit to enhance anaerobic wastewater treatment, in a rural locality of the Cauca Valley in Colombia. In the third paper I explore the integration between ecological design and community-based solutions to sanitation, and discuss opportunities and challenges of implementing ecological waste management in the particular bioregional and socioeconomic context of a proposed ecological-low-income co-housing project, in another rural community of Colombia. In doing this, several arguments are presented to support the idea that assuming the responsibility of managing its own waste can be a powerful and transformative experience for a community to fundamentally change its perspective and understanding of its place within the planet. Furthermore, managing waste can be an integrative force linking economic, social and environmental considerations, and favoring human-scale development, genuine progress, and self-reliance in a community. In its broadest level my research aims at reviewing and questioning the very notion of “waste” and the articulation between humans, nature, and technology within that context.
DEDICATION

To John and Nancy Todd,
whose inspiration and hopeful visions
have opened new territories to my imagination…
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Working on this research was a process full of excitement and discoveries, but it also had difficult times. I would not have been able to complete it without the permanent support and encouragement of my family and all my friends. Thank you for always being there! Pili, thank you for joining me in yet another crazy journey! Thank you for being patient, for all the great ideas, and for showing me new ways to look at the problems I encountered. Thank you for believing in me and keeping me confident throughout the entire process!

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CHAPTER 1

Comprehensive Literature Review

Introduction and Overview

Global water consumption increased six-fold during the 20th century, twice the rate of population growth. One-fifth of the planet’s population still lacks access to safe drinking water and 40 per cent lack access to basic sanitation. According to the United Nations if current trend persists, by 2025 the demand is expected to be 56% above the amount that is currently available. On top of that, it is estimated that the world will need 55 percent more food by 2030. This translates into an increasing demand for irrigation, which already claims nearly 70 percent of all freshwater consumed for human use (WWAP 2006).

As the demand keeps increasing, the world’s water supply is being depleted either by pollution, deforestation, soil erosion, desertification or irresponsible over-extraction (Shiva 2002, Brown 2003). At the same time an already uneven distribution of water is being aggravated by mismanagement, corruption, lack of appropriate institutions, bureaucratic inertia and a shortage of new investments in building human capacity as well as physical infrastructure (Biswa 2001, Duda and El-Ashry 2000, WWAP 2006). In this global context, it appears clear that improving the capacity to clean up polluted waters, reuse water and improve self-reliance at a local community level is, and will be, not only an intelligent and effective strategy for sustainable living but a matter of survival for a lot of people. Clearly, we need to protect water sources, but at the same time we
need to re-evaluate the way we use water, the way we think about “waste” and how we deal with it, and the way we grow food. This project is an attempt to integrate ecology, engineering, economy and community development around issues of water use, sanitation and waste management in Latin America.

Sanitation, Ecological Integrity and Public Health

The World Health Organization defines improved sanitation as connection to a public sewer, connection to a septic system, a pour-flush latrine, a simple pit latrine or a ventilated improved pit latrine (WHO-Unicef, 2004). Today, at least 2.4 billion individuals in the world live without improved sanitation (WWAP 2006). But technically, even access to “improved” sanitation does not solve the problem. Another 2.8 billion individuals have access to some type of sanitation, mostly pit latrines of different types, of which many are unhygienic, foul smelling and contaminate the human and natural environments. About 1 billion have flush toilets, of which only about 30% are connected to secondary stage or better sewage treatment facilities (WHO-Unicef, 2004). The rest are sources of contamination downstream. So in actuality, far more than 2.4 billion people need to gain access to effective and sustainable sanitation (EcoSanRes, 2004). The WSSD articulated several targets for the coming decade. Among them, “halve, by the year 2015, the proportion of people who do not have access to basic sanitation”. To reach the WSSD target, we must also account for estimated population growth – about 20% – adding to the present 1.2 billion targeted for coverage by 2015. The persistent delay in reaching international sanitation goals should not be overlooked. More than 4 billion
people will need to gain access to basic sanitation to meet the 2025 target for universal coverage (WHO-Unicef 2004).

Human health risks associated with poor sanitation have long been recognized (Strauss 1990, 1991, 2001; Restrepo 2002, WWAP 2006). The Framework for Action on Water and Sanitation, produced in conjunction with the UN World Summit on Sustainable Development (WSSD), held in Johannesburg in 2002, indicates that close to 6,000 children die each day from diseases related to inadequate sanitation and hygiene, and a lack of access to safe drinking water. Globally, diarrhoeral diseases and malaria killed about 3.1 million people in 2002. Ninety percent of these deaths were children under the age of five (WWAP 2006). On the other hand, lack of adequate sanitation is causing environmental degradation and a decline in water quality in many regions. Evidence indicates that the diversity of freshwater species and ecosystems is deteriorating rapidly, often faster than terrestrial and marine ecosystems (WWAP 2006).

In the Third World, sewage is nearly always discharged into the environment-at-large without treatment. Urban and peri-urban areas in developing countries are among the worst polluted and disease ridden habitats of the world. Much of this pollution is caused by inadequate sanitation services. As cities expand and populations increase, the situation will grow worse and the need for safe, sustainable and affordable sanitation systems will be even more critical (Winblad et al, 1999).
Sanitation in Latin America

Most streams and coastal areas in Latin America receive direct discharges of domestic and/or industrial untreated wastewater and solid wastes, causing serious environmental and public health problems. In 2002, 25% of the population in Latin America (136,283,000 people) was not served with improved sanitation infrastructure, and only 10% (on average) of the wastewater collected in sewers received any type of treatment (Reynolds 2002). Most of the efforts to serve people with adequate sanitation have been made in urban areas with some 87 million more people connected between 1990 and 2002, and the portion of rural population served with some type of sanitation infrastructure increasing from 35% in 1990 to 44% in 2000 (WHO-Unicef 2004).

Some of the difficulties to provide a broader coverage of adequate sanitation in the region include: 1) financial limitations (Reynolds 2002); 2) technical difficulties associated to an atomization of the population in small and scattered urban and rural centers (Bastidas and Garcia 2002); 3) weak or corrupt governance structures and capacities (WWAP 2006); and 4) inadequate technological solutions (Restrepo 2002, Galvis and Vargas 2002). Many of the existing approaches to sanitation are neither viable nor affordable to the vast majority of people, and many cities in the third world cannot access the necessary resources - water, energy, money and institutional capacity – to provide the population with improved sanitation systems (Winblad et al 1999). In addition to that, in Latin America, much of the infrastructure built for wastewater treatment has usually operated for some time, but then deteriorated due to a lack of active
participation and involvement of the communities for which the systems have been built (Bastidas and García 2002, Restrepo 2002).

**A need for alternative solutions**

Although the chemical and physical techniques to clean virtually every contaminant from human wastewaters are available to bring those waters to the status of safe drinking water, the cost of adequate detection and purification can be very high (Adey and Loveland 1998, Peavey et al. 1985). Existing approaches to sanitation are neither viable nor affordable to the vast majority of people. Many cities in the third world cannot access the necessary resources - water, money and institutional capacity – to provide the population with improved sanitation systems. Many of these localities will face serious water scarcity by year 2010. Currently, there are already some 80 countries (40% of the planet’s population) facing water scarcity during certain periods (Winblad et al, 1999).

In 1995, the World Bank estimated that an annual investment of 12,000 million USD during ten years would be required to elevate the levels of sanitation and water supply to acceptable levels in Latin America and the Caribbean (Reynolds 2002). Unfortunately, according to the UN WWD report the funding available for water and sanitation programmes (from international organizations and the private sector) is declining (WWAP 2006). On the other hand, the role of private investment in improving sanitation and water supply conditions remains highly controversial (for arguments in favor see Lee and Floris 2003; for arguments against see Hall and Lobina 2006; Shiva
and it is being strongly opposed in several Latin American countries (Hall and Lobina 2002).

The UN WWD report recognizes that privatization of water and sanitation services, has often failed to satisfy the expectations of national governments and donor countries. However, it also stresses that “financially strained governments with weak regulations are a poor alternative for addressing the issue of poor water resources management and inadequate supplies of water services” (WWAP 2006). In fact, the report highlights the importance of governance in managing the world’s water resources and tackling poverty. Governance systems, it says, “determine who gets what water, when and how, and decide who has the right to water and related services”. Such systems are not limited to ‘government’, but include local authorities, the private sector and civil society (WWAP 2006).

An alternative way to look at this financing and governance puzzle is to shift the focus from large-scale mega-projects, which are centralized and require a lot of infrastructure and money (not to mention the institutional bureaucracy) to more innovative and decentralized systems that work at small scales and are affordable to most communities. In other words, to enhance the self-reliance of smaller communities in relation to a range of issues intimately connected to water, from health and food security, to economic development, land use and the preservation of the natural ecosystems on which water resources depend.
A much more holistic approach is required to find sustainable and affordable alternatives to the problem of sanitation in both developed and developing countries. But the search for alternative solutions should not be a search for panaceas. Instead, solutions should remain as diverse as the particular bioregional contexts where problems occur. This is an antithesis to the universalizing tendency of the development and economic models that currently dominate human society. Ultimately it is a much deeper question of how can we redefine the structures of power that organize our human society and how do we want to relate to the rest of nature.

**Theoretical Framework**

1. Wastewater Treatment

   Domestic wastewater (sewage) is a mixture of water, organic matter, nutrients, pathogens, and depending on the source, it may also contain various inorganic substances, organic pollutants, and metals (Metcalf and Eddy 1991). Sewage treatment is the process of breaking down this mixture by degrading, removing, or taking up its different components, so that water is cleaned up and made safe to discharge back into the environment. There are physical, chemical and biological processes involved in all forms of treatment. However there are different approaches to take advantage of these three types of processes in order to treat wastewaters. This translates in a wide variety of treatment systems, ranging from mechanical, highly engineered and energy demanding (usually more costly) to ‘natural’, low-energy, and usually more affordable systems (Metcalf and Eddy 1991, Reed et al 1995, Peavy et al 1985).
2. Treatment Approaches and Technologies

2.1. Highly engineered mechanical systems

So called ‘conventional’ wastewater treatment separates solids from liquids by physical processes and then purifies the liquid using biological and chemical processes. The process is divided in three phases (mechanical, biological and chemical), which are referred to as primary, secondary and tertiary treatment. The purpose of primary treatment is to separate solids from liquids as much as possible, producing a homogeneous liquid that can be treated biologically, and a sludge that can be disposed or treated separately. Primary treatment removes large objects and reduces oils, grease, sand, grit and coarse solids. This is usually done using large sedimentation tanks and rotating screens to remove floating and larger materials (Metcalf and Eddy 1991, Peavy 1985). Secondary treatment is intended to degrade organic compounds that consume oxygen when degraded and therefore increase the BOD and COD of the water. To do this, most treatment plants in developed countries use a process known as activated sludge, in which the liquid is heavily oxygenated and substrate is provided so that naturally occurring bacteria and protozoans consume the biodegradable soluble organic compounds. These microorganisms also bind less soluble fractions into floc particles that tend to settle to the bottom of the tanks. Eventually the microorganisms also flocculate and settle so that the supernatant liquid can be discharged (Metcalf and Eddy 1991, Peavy 1985). Tertiary treatment is the final stage to raise the effluent quality to the standard required before discharged. This phase usually includes different types of filtration, nutrient removal and chemical disinfection treatments (Metcalf and Eddy 1991, Peavy 1985). The large amounts of sludge that are generated in this process can be a problem.
Although in theory the sludge can be composted, spread in fields as fertilizer or digested to produce methane, the scale of these operations often make them cost-prohibitive. Additionally, the sludge can have highly concentrated contents of heavy metals or other hazardous substances that were removed from the wastewater (Reynolds 2002)

Standard primary and secondary wastewater treatments are engineered to develop optimal conditions for microbial degradation of organic wastes to inorganic nutrients by providing extensive mixing and oxygen input. Thus the oxygen demand by bacteria and organic materials in sewage that would drive receiving waters to the anaerobic state, thereby killing off a major part of the flora and fauna, is largely avoided. However these traditional processes have little capacity to remove nutrients. Nutrients can be removed by physical and chemical “tertiary” processes, but these have limited efficiency, depending on the nutrients to be removed. Since tertiary treatment requires extended residence times in expensive reactors, and in some cases uses of additive chemicals, it is frequently too costly to be implemented, especially by the more numerous smaller communities. Residues that can lead to secondary pollution may also be left in the effluent. Bacterial tertiary treatment is extensively employed to remove dissolved nitrogen by denitrification. However, denitrification, as now practiced, is a lengthy process, requires neutral dilution water, and has variable performance due to daily fluctuations in wastewater loading. Most sewage treatment is brought to the secondary level and promotes heterotrophic respiration without significant reduction of the nutrient levels or elevation of oxygen concentration or pH values required to prevent deterioration of receiving water ecosystems (Adey and Loveland 1998).
Guterstam (1996) has criticized contemporary conventional wastewater treatment, in (1) they generate large amounts of sludge which is often toxic and is thus environmentally stressful if disposed of by ocean dumping, land filling, spreading or incinerating, (2) they employ environmentally damaging chemicals to precipitate out solids, phosphorus and chlorine, (3) they fail to remove metals and synthetic organic compounds, (4) they are costly in terms of financial capital, energy and labor, (5) engineering difficulties are still incurred with the elimination of fine suspended solids, colloidal matter and dissolved substances.

2.1.1. Aerobic vs. Anaerobic Treatment

Sewage treatment is largely dependent on bacterial metabolism, which can occur both with and without oxygen supply. Aerobic bacterial metabolism consumes oxygen during digestion of organic matter, whereas anaerobic metabolism digests the organic matter in the absence of oxygen. Both processes can effectively remove organic matter and suspended solids from sewage, but each of them offer different advantages and disadvantages that need to be considered based on the particular situation. Anaerobic systems can usually be more appropriate than aerobic systems in many situations in the tropics, but they can also be complemented with aerobic treatment units in order to have an overall better performance that takes the most benefit out of both types of bacterial metabolism. Some advantages of anaerobic treatment include: lower sludge accumulation; low nutrient consumption; low energy demand; methane gas production; tolerance to high organic loads and large sewage volumes; long-life of bacterial biofilms; low operation and maintenance cost; applicability at large and small scales. Some of its
disadvantages include: anaerobic bacteria are susceptible to inhibition by a large number of chemical compounds; starting the process can take considerable time; some form of post-treatment is usually required; complex biochemistry and microbiological process need to be better understood; odor generation is an issue; nutrient removal is low (Rivera 1998).

2.2. Natural Systems

Natural systems for wastewater treatment can be divided in three broad categories: 1) Soil-based systems, which include subsurface infiltration, rapid infiltration/soil aquifer treatment, overland flow, and slow rate systems; 2) Wetland systems, which include free water surface and subsurface flow systems; and 3) Aquatic systems, which include waste stabilization ponds and floating aquatic plant systems (Reed et al 1995). Most of the existing wastewater treatment facilities in Latin America use natural systems, with some form of anaerobic pretreatment (e.g. septic tanks).

2.2.1. Soil Application Systems

Soil-based systems include: 1) subsurface infiltration, 2) rapid infiltration and soil aquifer treatment, 3) overland flow, and 4) Slow-rate systems (Reed et al 1995). These types of treatment rely on the structural complexity and enormous biodiversity naturally occurring in healthy soil ecosystems, in order to degrade organic matter and recover nutrients from wastewaters. Slow rate systems purify the applied wastewater through physical, chemical, and biological mechanisms that occur concurrently in the soil-water-atmosphere environment. These mechanisms include filtration, transformation,
degradation, predation, natural die-off, soil adsorption, chemical precipitation, denitrification, volatilization, and plant uptake. Land treatment systems constitute a viable alternative solution for wastewater management in cases where the construction of a mechanical treatment plant is not affordable, or other disposal options are not available. Some of the advantages of these systems include: low energy demands and low operation and maintenance costs (Paranychianakis et al 2006).

2.2.2. Constructed Wetlands

Constructed wetlands probably represent the most consolidated and well-studied ecologically engineered technology for wastewater treatment (Kangas 2004). There are two kinds of constructed wetlands: Surface Free Flow and Subsurface Flow wetlands (Reed et al 1995). The idea in both cases is to take advantage of biological diversity, plant capacity for nutrient uptake, and structural complexity in root systems to support large communities of thriving bacteria, which also receive oxygen that gets sucked in and released at the root zone by various wetland plants. Treatment wetland systems use basically the same physical, chemical and biological processes that are performed in highly-mechanized wastewater treatment plants to treat domestic waste. The difference occurs mainly in dimensions of space and time: wetlands need significantly more space and time, but they can provide effective treatment at a lower cost and utilizing a higher ratio of natural dynamics vs. engineered processes (Kangas 2004).
2.2.3. Aquatic Systems

Waste Stabilization Ponds (WSP)

Waste stabilization ponds are one of the most important natural methods for wastewater treatment. WSP are mainly shallow man-made basins comprising a single or several series of anaerobic, facultative or maturation ponds. The primary treatment takes place in the anaerobic pond, which is mainly designed for removing suspended solids, and some of the soluble element of organic matter (BOD5). During the secondary stage in the facultative pond most of the remaining BOD5 is removed through the coordinated activity of algae and heterotrophic bacteria. The main function of the tertiary treatment in the maturation pond is the removal of pathogens and nutrients (especially nitrogen).

Waste stabilization pond technology is the most cost-effective wastewater treatment technology for the removal of pathogenic micro-organisms. The treatment is achieved through natural disinfection mechanisms. It is particularly well suited for tropical and subtropical countries because the intensity of the sunlight and temperature are key factors for the efficiency of the removal processes (Mara et al 1992).

The WSP becomes an ecosystem governed by the nature of the communities that it supports and the prevailing environmental conditions in which it is maintained. The relationships that bond microscopic fauna and flora with the chemistry of their circumstances can be manipulated to ensure breakdown of organic refuse and to eliminate parasites and other hazards. They ensure effective treatment of organic wastes generated by humankind and their normal functions. At the same time there are opportunities to capitalize on the byproducts of the process (Hosetti and Frost 1998).
Waste stabilization ponds are a very feasible, low-cost and the most commonly used wastewater treatment system in rural areas of Latin America (Biswa 1998, Pena et al 2002, Reynolds 2002), and their performance can be enhanced using aquatic plants (Awuah et al 2002). WSP have demonstrated to effectively remove BOD, TSS and nitrogen (Zimmo et al 2005) as well as fecal coliforms and E. Coli from wastewaters (Brissaud et al 2005). Research done on waste stabilization ponds in Peru (Yanez 1983, Bartone 1985), Colombia (Madera et al 2002), Brazil (Oragui et al 1987) and Thailand (Polprasert et al 1982) has shown that an almost total reduction of pathogenic bacteria and viruses (from $10^8$ to $10^3$ per 100 mL) can be achieved within 2-4 weeks retention time in these type of treatment systems. Appreciable evidence indicates that sunlight is the single most important factor in WSP disinfection (Davies-Colley et al 2000). Therefore increasing sunlight exposure either by using shallower ponds or by extending residence time is an important component of these systems. Advanced pond systems (APS), incorporating high-rate ponds, algal settling ponds, and maturation ponds, typically achieve better and more consistent disinfection as indicated by Escherichia coli than conventional waste stabilization ponds (Davies-Colley et al 2005).

While WSP are generally considered the technology of choice for municipal wastewater treatment within Central America, there are, nevertheless, problem areas that need to be addressed if waste stabilization pond use is to have continued acceptance and long-term sustainability (Oakley et al 2000). In Colombia, where WSP are a common technology used to treat sugar mill wastewaters there are also problems related to biological process design and construction of these units. The situation with regards to
operation and maintenance is far from satisfactory and also contributes to pond malfunctioning (Calero et al 2000).

b. Algal Turf Scrubbers

Algal Turf Scrubbers (ATS) are a unique wastewater treatment system, which utilizes algae to strip pollutants out of water (Adey and Loveland 1998). Although there is a long history of trials employing algae for wastewater treatment in the sanitary engineering field (see review in Kangas 2004), Walter Adey came upon his version of technology from his studies on basic coral reef ecology. Algae are the most important primary producers on coral reefs and they occupy many microhabitats. The algal turf scrubber technology is based on Adey’s adaptation of algal turfs from coral reefs. Algal turfs are short, moss-like mats of algal filaments covering hard surfaces found at the reef crest where wave energy is highest. Adey created artificial algal turfs by growing the algae on a screen in a shallow trough over which water was passed, with artificial lights and wave energy generated by a surge bucket. The algae grow very quickly and strip nutrients out of the flowing water through uptake. By scraping the algae off the screens periodically, nutrients are permanently removed from the system and water quality is improved (Kangas 2004).

A simple, aquarium-type algal turf scrubber was first applied to the scrubbing of domestic wastewater at the Smithsonian Institution in 1986. Raw Washington, D.C., sewage was added to the freshwater unit that had a eutrophic pond-derived algal turf already developed. A typical run showed a spike of the dominant form or nitrogen in the
sewage (ammonia), followed by rapid removal and nitrification to nitrite and nitrate. This was followed, several hours later, by removal of all dissolved nitrogen to low levels. With the addition of the sewage, phosphorus as PO$_4^{3-}$ also spiked to well over 1mg/L, although in about 2 days, concentrations of this nutrient returned to about 1ppb. Oxygen concentrations in this experiment remained close to or above saturation during the entire process. With input levels of biochemical oxygen demand of (BOD) between 50 and 60 mg/L the BOD removal rate was approximately 2000 mg/m$^2$/day. (Adey and Loveland 1998). This technology was patented in 1982 and further developed to be applied to the treatment of a variety of domestic, agricultural, aquacultural and industrial wastewaters (Adey and Loveland 1998).

c. Living Machines (Advanced Ecologically Engineered Systems) and Mesocosms

Living machines are designed systems for water purification that combine mechanical engineered structures and processes with assemblages of different life forms contained in a series of tanks or ponds as mesocosms. In this setting, biological communities undergo a process of self-organization, which allow them to establish in the artificial structure provided. Such self-organization becomes an integral part of the design, in developing a type of partnership between the engineer and the intrinsic capacity of biological communities to self-organize (Todd and Josephson 1996, Todd et al 2003). David Orr (1994) defines living machines as “carefully orchestrated ensembles of plants, aquatic animals, technology, solar energy, and high-tech materials to purify wastewater, but without the expense, energy use, and chemical hazards of conventional
sewage treatment technology”. Living machines represent a fundamental shift in thinking about the relationship of humans with other forms of life in a technological setting.

Twelve key factors have been described as principles required for the design of task-oriented mesocosms, such as living machines, and particularly for their application in wastewater treatment. These factors include: (1) mineral diversity, (2) nutrient reservoirs, (3) steep gradients, (4) high exchange rates, (5) periodic and random pulses, (6) cellular design and mesocosm structure, (7) subecosystems, (8) microbial communities, (9) photosynthetic bases, (10) animal diversity, (11) biological exchanges beyond the mesocosm, and (12) mesocosm/macrocosm relationships (Todd and Josephson 1996).

In 1995 a tank-based living machine or AEES was constructed in the city of South Burlington, Vermont to determine if the technology was capable of treating sewage to high standards in a northern New England climate, particularly during the cold and short day-length seasons (Todd et al 2003). The system was designed to treat 80,000 gallons per day of raw domestic wastewater to advanced tertiary treatment standards. It incorporated over 200 species of vascular and woody plants, microbial communities attached to plant roots, flocculating bacteria in open water areas, higher invertebrates, snails and fish into a modified activated-sludge, extended-aeration treatment process. The design concept was to use both the microbial community attached to plant roots, and suspended, flocculating bacteria to effect nutrient removal in aerated, complete-mix reactors prior to the clarifier. At the clarifier and in post-clarifier filters, higher
invertebrates, such as snails, micro-crustacea, and fish were incorporated into the design to consume residual biosolids. The performance of this system not only met the advanced tertiary treatment standards but it exceeded its design parameters (Austin 2000).

2.3. Ecological Sanitation (EcoSan)

A fundamentally different approach to the problem of sanitation is presented in the concept of Ecological Sanitation. ‘EcoSan’ is a sanitation alternative that limits the use of water as means of waste disposal. It looks at the problem of sanitation from a different angle, with a broader perspective that integrates waste management, water conservation and recycling, health and environmental integrity at a household level. The idea is that human excreta along with household organics are sanitized and the resulting plant nutrients are reused in agricultural production in the proximity of human settlements. Water from the households’ showers/baths and kitchen (grey water) undergoes treatment and can subsequently be safely re-cycled (Winblad et al 1999).

Ecological sanitation includes source-separation of human excreta into urine and faeces fractions, recovering the nutrients for reuse in local cultivation. Human urine contains about 75% of the nutrients excreted by the body and represents about 80% of the total excreta volume. Faeces are sanitized either by dehydration or biodegradation. Sanitized faecal matter, composted with household organics, is an excellent soil conditioner. The use of these approach enables environment-friendly recovery in contrast to many conventional waste-based sanitation systems that mix human excreta with storm water runoff and industrial effluents creating a mega-sized water treatment problem,
which is difficult for most cities around the world to cope with. Most of the world’s sewage treatment plants produce effluents containing human pathogens, nutrients and toxic compounds. Pit latrines, septic tanks and cess pits often contaminate the ground water, the largest source of freshwater on the planet. Ecological sanitation represents a new approach to sanitation, whereby human excreta is recovered to soil systems and kept away from surface and ground water systems (Winblad et al 1999).

The development of ecological sanitation in the industrial world has had two different approaches. One focuses on water and its use and reuse while the other has a more systemic approach, focusing on use and reuse of all associated resources (water, energy, nutrients, etc.). These systems encompass a broad range from low-tech to high tech solutions appropriate to different contexts and situations. There is much experience built up in both the North and South and even if technical solutions may vary, knowledge transfer is invaluable for spreading the concept of ecological sanitation as an appropriate and trustworthy alternative to conventional sanitary systems. Wastes discharged have negative impacts on the environment and people’s health. Recycling may prove more beneficial (Winblad et al 1999).

3. An interdisciplinary approach to Sanitation

It is clear that the crisis of sanitation is not only a technological problem but also a socio-economic, and cultural one. It is a problem that can be addressed much more effectively by the interaction and cooperation of different disciplines, some of which may have traditionally been thought to work in opposing directions, like ecology and
engineering. And it certainly requires the input of social science perspectives. This section introduces the perspective and input that different fields of knowledge, and forms of knowing, can contribute to approaching water and waste issues.

*Ecological Design and Engineering*

The fields of ecological design, environmental, and ecological engineering are examples of the kind of interdisciplinary integration that is required. These fields were first introduced by H.T. Odum in his (1971) book entitled ‘Environment, Power and Society’ and they have been developing ever since. The principles and theories of ecology are fundamental for understanding natural ecosystems and, therefore, also for the design, construction and operation of new ecosystems for human purposes (Kangas 2004). On the other hand, the critical work of engineering is to design, build, and operate useful things. Design is a creative process for making a plan to solve a problem or to build something. It involves rational, usually quantitatively based, decision making that utilizes knowledge derived from science and from past experience.

The approach of ecological engineering is to interface ecosystems with technology to create new, hybrid systems, capable of solving human problems, without causing harm to the environment. Considered by many as the fundamental unit in ecology, the ecosystem is the network of biotic (species populations) and abiotic (nutrients, soil, water, etc.) components found at a particular location that function together as a whole through primary production, community respiration, and biogeochemical cycling (Odum 1982). Functions within ecosystems include (1) energy
capture and transformation, (2) mineral retention and cycling, and (3) rate regulation and control. Ecosystems can be extremely complex with many interactions between species, and it is this complexity what the ecological engineer relies on to design resilient self-organizing systems (Kangas 2004).

There is a constant feedback between design, construction and operation. A protocol is often used to test a design against a previously established set of criteria before full implementation. This protocol is composed of a set of tests of increasing scale (from the lab, to the pilot project, to full scale commercial operation), which builds confidence in the choice of design alternatives. According to Horenstein (1999) a good design is one that (1) works all the time, (2) meets all technical requirements, (3) meets costs requirements, (4) requires little or no maintenance, (5) is safe, and (6) creates no ethical dilemma.

Ian McHarg’s (1969) classic book entitled “Design with Nature” has inspired a generation of landscape architects to utilize environmental sciences as a basis for design. Design with Nature is now a philosophical stance that describes how to interface man and nature into sustainable systems with applications, which range from no-till agriculture to urban planning. Another important precursor for ecological design (and engineering) is Buckminster Fuller’s “comprehensive Anticipatory Design Science”, which prescribes a holistic approach to meeting the needs of humanity by ‘doing more with less’. By using a “design with nature” philosophy and by taking the best of both worlds, ecological engineering seeks to develop a new paradigm for environmental problem solving. The
goal of ecological engineering is to generate cost-effective alternatives to conventional solutions for a broad range of environmental issues (Kangas 2004). Ecological design has been applied to an increasingly diverse range of technologies and innovative solutions for the food sector, waste management, industrial ecology, architecture and landscape design, waste water treatment, erosion control, ecological restoration, among other applications (Todd and Josephson 1996, Todd et al 2003, Orr 1994).

*Ecological Restoration*

Ecological restoration is the process of assisting the recovery and management of ecological integrity. Ecological integrity includes a critical range of variability in biodiversity, ecological processes and structures, regional and historical context, and sustainable cultural practices. Although the terms ecological restoration and restoration ecology are frequently interchanged, there is a difference between them. Restoration ecology is the suite of scientific practices that constitute an emergent sub-discipline of ecology. Ecological restoration is the ensemble of practices that constitute the entire field of restoration, including restoration ecology as well as the participating human and natural sciences, politics, technologies, economic factors, and cultural dimensions (Higgs 2005).

*Ecological Economics*

The forms of socio-economic and political organization currently in force in the world are essentially antagonistic to the achievement of a tripartite harmony between nature, humans, and technology (Max Neef 1992). Contrary to what is stated in
economics textbooks, the last link of the economic process is not consumption but the
geneneration of waste. This means a transformation of low into high entropy, a process that,
although inevitable, is at least susceptible to being slowed down. This is a point many
economists still refuse to recognize: the fact that ‘since the product of economic
processes is waste, waste is an inevitable result of that process and ceteris paribus
increases in greater proportion than the (creative) intensity of economic activity’. Hyper-
urbanization and the increasing pollution that is concomitant with those centers
considered to be the most highly developed is a proof that came as an unexpected and
disconcerting surprise for all economic theories (Max Neef 1992).

Because economics never assigned the natural environment—a system affected by
entropy- its real weight, it was possible for the discipline to remain enclosed within its
mechanistic ivory tower. Economics has thus become a discipline as unhistoric as any
mechanical process (Max Neef 1992). On the other hand, it has long been believed that
economic growth was good for mankind, which is of course true. The problem emerged
when ‘good’ became synonym for ‘more and more’. In the end this obsession generated a
new concept of social justice, especially under capitalism. Social justice became confused
with growth itself. It is no longer a question of better distributing a cake that is already
big enough, so that those who have less will receive a larger proportion. On the contrary,
it is now a question of making a yet larger cake so that all will receive a greater
proportion than before, but keep the same proportion assigned to them by the system. Of
course, in reality what tends to happen is that, even with growth, the poor’s share of the
cake diminishes. Growing evidence of this does not seem to have affected the behavior of
these economic systems or of the theories behind them. There is still insistence to the effect that processes such as the so-called ‘trickle-down effect’ work, despite some overwhelming evidence to the contrary, especially in many third world countries (Max Neef 1992).

Another wrong assumption is to believe that many of the problems affecting the invisible sectors of society (the ‘poor’) are either special cases or isolated phenomena. The truth is that poverty, both rural and urban, is an intrinsic part of the economic system that dominates most of most the world now days. Since it is often not recognized as a structural component of the system, current development strategies tend not only to circumvent such [poor] sectors, but also often to worsen their living conditions. In most third world countries the development styles imposed tend to increase the marginalization of the peasants without generating alternatives for employment. Furthermore the growing ‘industrialization of agriculture’ tends to destroy existing traditional skills (Max Neef 1992, Escobar 2000). To the extent that economists are unwilling to accept the crisis affecting the foundations of economic theories in order to undertake their reconstruction, any hope that they will contribute positively to the adequate interpretation and eventual solution of biospheric problems is extremely thin.

Ecological Economics has emerged as a new field out of a systemic understanding of current environmental challenges, increasingly framed as problems of sustainable development. This field recognizes the need for economic, social and natural science analyses to be brought together in new perspectives, responding to the concerns
expressed worldwide for ecological, social, economic and political dimensions of sustainability. It represents a new practice of economics responding to a specific problem domain, which may legitimately be addressed in a variety of ways (Constanza et al 1997). Ecological Economics envisages the use of analytical tools and concepts coming from many different disciplines and fields of experience, including neoclassical economics if it is placed in a wider framework of interpretation. It recognizes that economic activities are embedded in and depend upon the ecosphere. Therefore it also recognizes that it is necessary to move beyond the simple recognition of biophysical limits to economic growth, in order to explore how, in what ways, and to what degrees the socioeconomic objectives traditionally associated with growth can be reconciled with concerns for environmental quality and preoccupations with social justice and a variety of cultural forms (Constanza et al 1997).

4. Community Development and Self-Reliance

The UN WWD report states that the global crisis of sanitation is a crisis of governance. And this is not limited to ‘government’, but includes local authorities, the private sector and civil society (WWAP 2006). Only about 10% of the different types of official development assistance is directed to support development of water policy, planning and programmes (WWAP 2006), and although there are no accurate figures, it is estimated that political corruption costs the water sector millions of dollars every year and undermines water services, especially to the poor (WWAP 2006).
The inefficiency of government structures may be an inherent failure related to the scale at which they attempt to operate. National development styles wrongly assume that a country is a homogeneous unity and, as a consequence, generate serious and harmful regional imbalances. Furthermore, they represent the interests of the dominant class. The result of such situation is that, while the dominant class designs its own development strategy, the ‘invisible sectors’ are left alone to design their own ‘survival strategies’ (Max Neef 1992).

The process for genuine participation and self-reliance in small communities is well described by Chilean economist Manfred Max Neef in his book ‘From the outside looking in: Experiments of barefoot economics’:

“[…] I know that waiting for grandiose solutions to come from the top is not only self-defeating, but turns me into a passive accomplice of a situation I dislike. Therefore I also know that one must do what one can do. No matter how little it is, it is nonetheless a human testimony, and human testimonies, as long as they are not based on greed or personal ambition for power can have unexpected positive effects. [...] I have already made it clear that, since my concern is with the people of the invisible sectors that account for more than half of the world’s population, I no longer believe in ‘national solutions’ or ‘national styles’. I don’t even believe in ‘national identities’. I do not believe –put it in a nutshell- in any form of gigantism. Hence, as a barefoot economist, I believe in local action and in small dimensions. It is only in such environments, that human creativity and meaningful identities can truly surface and flourish. If national systems have learned to circumvent the poor, it is the turn of the poor to learn how to circumvent the national systems. This is what can be done and, in my opinion, must be done at local levels. Whatever cannot be achieved with national systems must necessarily assume the many forms of local self-reliance. Everything that can be done at local levels is what should be done at local levels. The path, it seems to me, must go from the village to a global order. Think small and act small, but in as many places as possible.”

Unfortunately, Third World countries, with a few exceptions, are fascinated by the temptation of following the road traced by the large industrial powers, forgetting that the
only way to achieve and secure their identity and decrease their dependence lies in promoting a creative and imaginative spirit capable of generating alternative development processes that may secure higher degrees of regional and local self-reliance (Max Neef 1992). Diversified regional development processes can only come about as a consequence of power redistribution and decentralization. There is no truly effective or valid way of promoting human welfare and social justice if not through real participation (Max Neef 1992). Max Neef’s conception of the human social systems and his idealist philosophy coincide to a large extent with the social and political organization structures proposed by Mahatma Gandhi. And as well as Gandhi, Max Neef proposes a fundamentally different conception of the process of ‘development’:

“The kind of development in which I believe and which I seek, implies an integral ecological humanism. None of the present systems provide for this, nor has the capacity to correct itself (in order to provide it) without losing the essence of its identity as a result. And since I don’t believe that any of the existing systems will work itself out of business, I have ceased to believe in the value of corrective measures. It is no longer a question of correcting what already exists. That opportunity was lost long ago. It is no longer a question of adding new variables to old mechanistic models. It is a question of remaking many things from scratch and of conceiving radically new possibilities. It is a question of understanding that, if it is the role of humans to establish values, then it is the role of nature to establish many of the rules. It is a matter of passing from the pure exploitation of nature and the poorer people of the world, to a creative and organic integration and interdependence. It is a matter of bringing the ‘invisible sectors’ into the forefront of life and of letting them finally have their say and ‘do their thing’. It is a matter of a drastic redistribution of power through the organization of horizontal communal integration. It is a matter of passing from destructive gigantism to creative smallness”.

At the Cinara Institute in Colombia, an interdisciplinary group of engineers, economists, biologists, anthropologists and sociologists practices a novel way to look at the problem of sanitation in Latin America. Following a vision similar to Max Neef’s, researchers at Cinara are emphasizing smallness and self-reliance while putting quality of
life at the center of their work with communities. Traditionally in water supply and sanitation the technology has been the central node for solutions. In other words, the treatment plants have been the center of attention, then the distribution networks and unfortunately the household is usually not even considered as part of the systems (Restrepo 2002). Cinara proposes to consider the household as the focal point of water and sanitation systems so that it becomes the linking point to integrate programs of water supply, waste management and health (Cinara 1997). Waste is considered a resource, which should be diluted as minimally as possible. Starting at the household, the analysis expands into the neighborhood, the community and the natural environment.

Such an approach looks at the problem of sanitation as a multidimensional issue, and hence the solutions are thought to enhance different forms of capital (social, natural, built and human), and ultimately the self-reliance and quality of life within a community. This type of approach might prove far more effective in improving the percentage of population in both rural and urban areas served with adequate sanitation, with solutions that can be afforded, operated and maintained by a household (family), a neighborhood, or a small community. After all, prevention of pollution and small-scale localized treatment is much less expensive than trying to clean contaminated water supplies in large and concentrated amounts, or respond to large-scale water-borne disease epidemics.
CHAPTER 2

Ecological Wastewater Management: A Multifunctional Approach

Sacha Lozano
Gund Institute of Ecological Economics, University of Vermont.

1. Introduction

Global water depletion and unsustainable food production systems represent two iconic crises of our time. These two crises have important themes in common, referring to basic human needs and the way we interact with landscapes in order to satisfy them. But they are also closely related to the way we produce and dispose wastes in our current societal organization (Biswas 2001). Global water consumption increased six-fold during the 20th century (twice the rate of population growth). One-fifth of the planet’s population still lacks access to safe drinking water and 40 per cent lacks access to basic sanitation (WWAP 2006). According to the United Nations if current trend persists, by 2025 water demand is expected to be 56% above the amount that is currently available. On top of that, it is estimated that the world will need 55 percent more food by 2030. This translates into an increasing demand for irrigation, which already claims nearly 70 percent of all freshwater consumed for human use (WWAP 2006). Meanwhile, soil quality is declining globally in extensive areas, due to erosion, salinization, and loss of fertility, among various other reasons (Scherr 1999). With increasing food demands, soil degradation is becoming a primary concern of public policy, as it affects food security, agricultural markets and prices, agricultural income and livelihoods, and in some cases national wealth (Scherr 1999). Finally, mismanagement of plant nutrients, and nutrient...
scarcity in certain areas, add on to the declining soil fertility and food production crisis (Driver et al 1999, Gruhn et al 2000), and call for an integrated nutrient management approach, in order to ensure that soil-based agriculture continues to be productive and capable of satisfying human food demands (Gruhn et al 2000).

Water: A crisis of quality and access

While the imminence of a water crisis in terms of quantity is still a matter of controversy (Duda and El-Ashry 2000; Rosegrant and Cai 2001a and b; Shiva 2002; and Brown 2003; Rockström et al 2007), quality, fair distribution and local availability of water are more widely accepted as urgent and major challenges, currently undermining not only food security but also basic needs, such as health, safe drinking water, and a healthy environment, to a large proportion of the global human population (e.g. Biswas 2001, Meinzen-Dick and Rosegrant 2001, van der Hoek 2001, Shiva 2002, Brown 2003). Among various other factors, lack of adequate sanitation and solid waste management, is causing extensive environmental degradation, which compromises water quality and availability in many regions around the globe, especially in third world countries (Biswas 2001, WWAP 2006).

Some of the difficulties to provide a broader coverage of adequate sanitation in these regions include: 1) financial limitations (Reynolds 2002); 2) technical difficulties associated to an atomization of the population in small and scattered urban and rural centers (Bastidas and Garcia 2002); 3) weak or corrupt governance structures and capacities (WWAP 2006); and 4) inadequate technological solutions (Restrepo 2002,
Galvis and Vargas 2002). In order to overcome these difficulties sanitation and waste management need to be understood and addressed with a transdisciplinary approach, capable of producing multifunctional solutions that link waste management and environmental protection to human and economic development, under specific bioregional conditions.

This paper reviews and integrates different pieces of research with the goal of providing a sound framework for managing wastewater (sewage) as a valuable resource, in a way that: 1) is affordable –or even profitable– by small communities in developing countries; 2) is safe to the environment and to public health; and 3) provides opportunities for recycling nutrients and organic matter (available in wastewaters), to restore and protect water and soil resources, while enhancing rural livelihoods in tropical agroecosystems.

2. Wastewater treatment

Domestic wastewater (sewage) is a mixture of water, organic matter, nutrients, pathogens, and depending on the source, it may also contain various inorganic substances, organic pollutants, and metals (Metcalf and Eddy 1991). Sewage treatment is the process of breaking down this mixture by degrading, removing, or taking up its different components, so that water is cleaned up and made safe to discharge back into the environment. There are physical, chemical and biological processes involved in all forms of treatment. However there are different approaches to take advantage of these three types of processes in order to treat wastewaters. This translates into a wide variety
of treatment systems, ranging from mechanical, highly engineered and energy demanding (usually more costly) to ‘natural’, low-energy, and usually more affordable systems (Metcalf and Eddy 1991, Reed et al 1995, Peavy et al 1985).

Natural systems for wastewater treatment can be divided in three broad categories: 1) Soil-based systems, which include subsurface infiltration, rapid infiltration/soil aquifer treatment, overland flow, and slow rate systems; 2) Wetland systems, which include free water surface and subsurface flow systems; and 3) Aquatic systems, which include waste stabilization ponds and floating aquatic plant systems (Reed et al 1995). Most of the existing wastewater treatment facilities in Latin America use natural systems, with some form of anaerobic pretreatment (e.g. septic tanks).

Engineers have extensively studied and monitored all of these systems in order to optimize their design and performance (Metcalf and Eddy 1991, Reed et al 1995). However, a strong emphasis on optimization has tended to favor reductionism over a more holistic systemic approach to understand and enhance these systems. Consequently, the role of biological and ecological processes involved in the treatment has been generally regarded as one more component of the designed system, which can be simplified and optimized by focusing on specific organisms primarily responsible for removing specific kinds of substances from the sewage. This reductionist approach takes organisms out of their ecological contexts, making imperative to artificially supply all the conditions that would otherwise be provided in a natural ecosystem; and doing this, usually means increasing costs and energy demand to treat the waste.
Natural aquatic ecosystems, including wetlands, lakes and ponds, have processes inherent in their dynamics that make them capable of degrading or capturing and storing wastewater contaminants (Adey and Loveland 1998). A relatively novel approach taken by the integrative discipline of ecological engineering is to take the mechanisms, pathways, nutrient flows and assemblages of organisms found in all of these natural ecosystems and design them into small-scale and relatively controlled ‘replicas’ of natural ecosystems, called mesocosms (Kangas and Adey 1996, Odum 1996). These mesocosms use the natural abilities and self-regulation qualities of entire biological communities to break down macromolecules and metabolize organic nutrients typically found in wastewater and polluted water bodies, while providing an economic means for large-scale clean up (Todd et al 2003).

One step further in this direction is a fundamentally different approach to the problem of sanitation that includes humans and their wastes as part of a larger ecological system, and focuses on recycling materials (such as nutrients and organic matter) within the system. This approach is known as Ecological Sanitation, and its main premise is that human excreta can be much more efficiently, economically, and safely treated and recycled, by not using water to flush it away. Instead, dry composting toilets, if properly designed and used, can deal much more effectively with pathogens (i.e. preventing public health problems), provide good quality soil amendments, and protect natural water bodies from organic pollution, all at once (Winblad et al 1999, Sawyer 2003).
Human excreta separation and use

If urine and feaces are stored separately after excretion, both of these fractions can be easily treated and utilized. The urine fraction can be safely used as a fertilizer as long as it is totally free of feaces. The feaces fraction must be composted and dehydrated in order to kill the pathogens and then it can be safely used as a rich soil amendment (Heinonen-Tanski and Wijk-Sijbesma 2005).

3. Potential resources

Nutrient and organic matter recycling

Whether in the form of wastewater, pure urine, or as dried composted faeces and food scraps, human domestic wastes are a very rich source of nutrients that can be recycled into productive agricultural landscapes, aquaculture operations, or simply into home gardens (Strauss 1996, Khalil and Hussein 1997, Jana 1998, Winblad et al 1999, Sawyer 2003, Heinonen-Tanski and Wijk-Sijbesma 2005). Every year a normal healthy person excretes approximately 5.7 Kg of nitrogen, 0.6 Kg of phosphorus, and 1.2 Kg of potassium. These numbers correspond to the amount of fertilizer needed to produce 250 Kg of cereal, which is the amount of cereal that one person needs to consume per year (Heinonen-Tanski and Wijk-Sijbesma 2005). Meanwhile, producing the same 5.7 Kg of nitrogen in the petrochemical fertilizer industry requires 10 Kg of oil; an increasingly unsustainable equation as global oil reserves continue to decline (Heinonen-Tanski and Wijk-Sijbesma 2005). Organic-matter content, is an equally important resource in human excreta (not shared by chemical fertilizers). Each day, humans excrete in the order of 30
g of carbon (90 g of organic matter), which if properly treated can be also used to restore and/or protect soil quality (Strauss 2001).


**Water recycling**

Wastewater recycling is becoming an important policy priority, as increasingly severe water shortages, coupled with declining groundwater supplies, affect places like the Mediterranean Coast, which are undergoing rapid desertification (Menegakis et al 2007). The use of recycled wastewater has been practiced (although not always carefully regulated) for over two decades in southern Europe and the Near and Middle East, in order to balance water shortages and meet increasing water demands of agriculture (Strauss 1991).

**Biomass production**

Plant nutrient uptake translates into biomass production. Under good sunlight conditions, wetland and aquatic plants can use the organic load and nutrient content in
wastewaters to stimulate vegetative growth (Koottatep and Polprasert 1997, Oron 1994). Treatment systems using aquatic plants and algae have proven to be very effective in removing organic matter, nutrients, pathogens and even metals from wastewaters, particularly in tropical and subtropical regions (Wolverton and McDonald 1977, Golueke 1977, Joseph 1978, Caicedo et al 2002, Zimmo et al 2002, Giraldo and Garzón 2002) but also in temperate regions under special design arrangements (Todd and Josephson 1996 Guterstam 1996, Craggs et al 1996, Peterson and Teal 1996). Aquatic Plant Biomass can be an important resource, potentially taking a variety of forms, such as: energy generation and biofuel production (Ramana and Srinivas 1997), carbon sequestration, wildlife habitat, food web support structure, and animal feed (Chará et al 1999, Sarria et al 1994).

Animal feed supplement and conservation land

The use of aquatic plants to treat wastewater and generate a source of protein for animal feed at the same time received considerable attention in the 1970s (Bagnall et al 1973, Otis and Hillman 1976, Golueke 1977, Wolverton and McDonald 1977, Joseph 1978). The biomass production rates and the actual content of protein in most aquatic plants are significantly higher than soy, which is a major source of animal feed and is a crop that takes up a significant amount of prime quality soils around the world (Chará et al 1999). In Colombia, a commercial plantation of soy produces 1.4 Tons of protein per hectare per year (Sarria et al 1994). In contrast, common aquatic plants in the tropics produce between 3 and 13 times more protein than soy does, using significantly less space (Chará et al 1999, Sarria et al 1994). *Duckweed* produces between 6.1-16.5 Tons of protein/ha.yr (Chará et al 1999, Oron 1994), *Azolla* produces 3.2-9.6 Ton protein/ha.yr
Giant Duckweed produces 3.5-6.5 Ton protein/ha.yr (Reddy and DeBusk 1985, Chará et al 1999), Salvinia produces 6.1-10.2 Ton protein/ha.yr (Reddy and DeBusk 1985, Chará et al 1999), and Water Hyacinth produces the highest yield of 13.4 Ton protein/ha.yr (Chará et al 1999).

In order to understand these numbers in terms of land use, it is helpful to correlate them with the amount of protein required by a certain animal-farming operation. In Colombia for example, from 1ha (10,000 m²) cultivated with soy, a farmer can obtain the amount of protein necessary to produce 4,880 Kg of live pig weight (74 pigs). If 30% of the soy-based feed is replaced with aquatic plants, the same 74 pigs can be produced, and 0.3 hectares (ca 3000 m²) of soy plantation could be liberated for other land uses. 1,465 out of the 4,880 Kg of live pig weight could be produced from 420 Kg of protein from aquatic plants, which could be grown in 467 m² of marginal tropical lands, leaving 2533 m² (of the 3000 m² liberated) of first quality land, available for human food production, forest regeneration, watershed protection, or a more multifunctional land use pattern like agroforestry, which in addition to all the above could also enhance the livelihoods of more families (Sarria et al 1994, Altieri 2002, Gliessman 1998).

Commercial non-edible crops

The same arguments presented for aquatic plants, nutrient uptake and biomass production, can be used in relation to the production of non-edible crops that can be commercialized or used as materials and fibers for different kinds of manufacturing and construction (e.g. bamboo). Wastewater can be seen as a fertilizer and a valuable
resource, and the advantage of using it on non-edible crops is that the health risks associated with the use of wastewaters would be minimized.

4. Challenges

Wastewater reuse, especially in agricultural settings is not a new concept. The theory and technical considerations are relatively well established (e.g. Sopper and Kardos 1973, D’Itri et al 1981, Metcalf and Eddy 1991) and there are several examples of wastewater reuse schemes being planned, implemented, upgraded and expanded in the Americas, Northern Africa, Southern Europe, the Near and Middle East, SouthEast Asia, and China (Strauss 2001). However, the implementation of safe wastewater reuse schemes still lags behind the theory, and reuse practices in agriculture range from uncontrolled use of raw wastewater for the irrigation of vegetables eaten uncooked to the irrigation of non-vegetable crops with secondary effluent (so-called restricted irrigation) and tertiary effluents from advanced wastewater treatment plants (Strauss 2001).

Public health concerns

Human health risks associated with wastewaters and poor sanitation have long been recognized. Waterborne diseases are very common in developing countries as untreated sewage is usually a focus of high concentrations of pathogens including bacteria, viruses, protozoans and helminths (Strauss 1998). Globally, close to 6,000 children die each day from diseases related to inadequate sanitation and hygiene, and lack
of access to safe drinking water; Ninety percent of these deaths being children under the age of five (WWAP 2006).

There are at least 30 types of infections of major importance for human health in projects related to wastewater reuse. Hence, concerns about the risk of contact with pathogens are completely legitimate and must be addressed when proposing a system for recycling human domestic wastewaters. However, it is also important to understand that these risks can be mitigated with several appropriate practices in addition to a reasonable level of treatment. Full treatment of wastewater flows to the guideline value of unrestricted irrigation (i.e. <1000 fecal coliforms/100 mL and <1 nematod egg/L) might often prove unfeasible for economic reasons, or even unnecessary, when wastewater is used for the cultivation of non-vegetable crops such as fruit trees, cereal crops, sugar cane, maize or cotton (Strauss 1991).

The use of human excreta and/or wastewater for agriculture or aquaculture can result in an effective threat to public health only if all of the following occurs: 1) an infectious dose of pathogens is transmitted to the fields/ponds, or the pathogens multiply in the field/pond to produce and infectious dose; 2) the infectious dose is transmitted to a human host; 3) the human host is effectively infected; and 4) the infection actually causes a disease (Strauss 1998). At each of these levels of potential risk there can be adequate practices acting as barriers to prevent actual disease. World Health Organization guidelines stipulate 4 measures as useful tools for reducing or avoiding the potential transmission of enteric diseases that might be caused by the use of excreta or wastewater
in agriculture and aquaculture: 1) wastewater or excreta treatment; 2) restriction of the crops grown; 3) choice of methods of application of the waste to the crops; and 4) control of human exposure to the wastes or to the waste-fertilized soils, crops, or fish ponds (see Strauss 1991, 1998, 2001). These measures act synergistically, so the more of them are simultaneously implemented the higher mitigation of risk can be achieved. However, the implementation of these measures can be challenging as it is constrained by socio-economic conditions and the institutional and governmental structures that regulate and enforce the restrictions on reuse of wastewaters in a particular place (refer to Strauss 1991 and 2001 for further detail).

Effective risks of wastewater treatment and reusing for public health are then classified as: 1) risks for the consumer (affecting consumers of edible crops that are irrigated and fertilized using wastewater), 2) risks for the workers (affecting workers at the treatment facility only), 3) risks for the nearby population (if there is any form of leakage at the treatment facility). Again, all of these potential risks can be prevented with appropriate treatment, hygienic practices to handle and cook foods, and the above-mentioned risk-mitigation measures. In any wastewater reuse scheme there are 3 main components that need to be monitored: the treatment unit, the irrigated soils, and the irrigated crops. In a wider context, humans can or must also be the focus of health monitoring: as excretors of the pathogens carried in the wastewater, as laborers or farmers using the treated wastewater for irrigation, and as consumers of the wastewater-irrigated crops. Parameters to be monitored include fecal coliforms (as indicators of pathogenic bacteria and viruses) and nematode eggs. Both of these must be monitored in
treated wastewater effluents used for irrigation, and in crops when irrigation touches the edible parts of the crop. In assessing the hygienic quality of soils irrigated with wastewaters, helminth eggs are the main parameter to be monitored. Fecal coliforms in this case are less relevant, since for the agricultural worker, soils are not an important transmission focus of bacterial infections, if treated wastewater is used. Besides health-related parameters, specific operational parameters related to the wastewater treatment processes must also be included in the monitoring schedule (Strauss 1991).

Chemical contamination is another important potential risk associated with human waste use, but this risk is harder to diagnose since its effects are chronic (gradually accumulate over time) and only visible in the long run; so, in order to prevent them, a precautionary principle has to be used, treating toxic chemicals in the best possible way before wastewater is reused (Strauss 2001). Understanding the risks associated with wastewater recycling is fundamental to adequately prevent them. This can be addressed with education, reliable information, participation and dialogue (Sawyer 2003).

Pathogen removal
All enteric pathogens naturally die off sometime after they are excreted from their human hosts. However, different pathogens have different survival periods, and survival also depends on environmental conditions such as humidity, average temperature, pH, and the ability to reach an intermediary host after they are excreted (Madera et al 2002, Campos et al 2002, Awuah et al 2002, Metcalf and Eddy 1991). Higher temperatures cause shorter survival periods of pathogens in the tropics than in temperate regions. In the
tropics, with average temperatures between 20-30 °C, enteric viruses, bacteria and protozoans live no longer than 50 days and as short as 5 days in wastewater sludge, after they have been excreted. Helminths (enteric worms) on the other hand, can survive and remain infectious as long as 12 months in wet sludge after they have been excreted, and therefore they pose the highest concern for public health (Strauss 1998).

There is a wide variety of disinfection methods, particularly used in drinking water treatment to reduce the risk of waterborne diseases (Kuo and Mou 1997, Metcalf and Eddy 1991). Chlorination is the most widely used disinfection method for both drinking and wastewater. However, this method also generates undesirable byproducts that pose other threats to human health. Therefore alternative disinfection methods have been researched and developed, including the use of other chemicals, ozonation, UV radiation, heat, and solar photocatalytic treatment (Kuo and Mou 1997).

The problem is that most of these disinfection methods are expensive and therefore beyond access to most small communities in developing countries. Affordable options for pathogen removal are required in order to improve safety in wastewater reuse schemes, which are practiced anyway in several developing countries including Mexico, Peru, Chile and Argentina (Strauss 2001, Esrey 2001, Vélez et al 2002, Fasciolo et al 2002).

Research done on waste stabilization ponds in Peru (Bartone 1985), Colombia (Madera et al 2002), and Brazil (Oragui et al 1987, Polprasert et al 1983) has shown that
an almost total reduction of pathogenic bacteria and viruses (from $10^8$ to $10^3$ per 100 mL) can be achieved within 2-4 weeks retention time in these type of treatment systems. Waste Stabilization Ponds are the most commonly used wastewater treatment system in rural areas of Latin America (Peña et al 2002, Biswas 1998) and their performance can be enhanced using aquatic plants (Awuah et al 2002).

Other natural systems for wastewater treatment can provide affordable and safe alternatives to deal with pathogens (Reed et al 1995) as long as they are adequately designed and implemented for a specific situation (Galvis and Vargas 2002, Restrepo 2002, Bastidas and García 2002). Long retention times in treatment reactors, and post-treatment slow filtration (e.g. in sand) can remove most pathogens from wastewaters (Reed et al 1995, Metcalf and Eddy 1991), but perhaps the most effective, low-energy and affordable way of eliminating them, is composting and dehydration of faeces without mixing them with water in the first place (Winblad et al 1999, Sawyer 2003).

Social and Cultural acceptability of human waste reuse

There are various forms of social, cultural and psychological resistance to the idea of reusing human excreta for any type of purpose (for some types more than others). However, while it is important to acknowledge this challenge, it is equally important to put in the right context and not overstate it (Winblad et al 1999, Sawyer 2003). It is commonly assumed that there is an intrinsic faecophobic nature in most communities and cultures, which would hinder a widespread use of human excreta as a resource. However, the use of human excreta as fertilizer for agriculture and aquaculture is an ancient
practice, which has been commonly used in many cultures and places around the globe up until two or three generations back, and is still practiced in the present time even in some of the most highly developed countries (Winblad et al. 1999, Esrey 2001, Rahman and Drangert 2001, Strauss 2001, Sawyer 2003, Heinonen-Tanski and Wijk-Sijbesma 2005).

Faecophobia in fact seems to be more related to modern urbanization along with the advent of waterborne sanitation systems - flushing toilets – (Sawyer 2003). The design, use and misuse of toilets and sanitation systems are deeply ingrained within a specific cultural context and then translated into individual attitudes and behaviors (Sawyer 2003), and such context in our western-modernist culture encourages us to “flush and forget” human excreta as something repulsive (Illich 1985), while some argue that hygienist-dominated modern medicine has over-dramatized the role of pathogens in health care (Sawyer 2003, Illich 1985).

The various forms of resistance to the idea of recycling human excreta can be overcome with education, participation and dialogue. Reliable information and successful examples are both crucial to build trust in the idea (Winblad et al. 1999, Sawyer 2003). Ron Sawyer, an experienced consultant and advocate of ecological sanitation, argues that once basic taboos are broken, people all over the world tend to be very interested in talking about toilets and sanitation, and do it in meaningful and constructive ways (Sawyer 2003). Specific methods and approaches to facilitate these conversations, and stimulate attitude changes among members of a peer group, have been developed and practiced in various local projects around the world, providing genuine and well-

Community empowerment to ensure long-term viability and permanence

In order to be effective, sanitation systems not only need to perform a high quality treatment, but they also must be widely accessible and appealing, which means, they have to be affordable, low energy-demanding, relatively easy to maintain and operate, and convenient to use. Designing and implementing an appropriate waste management system in a particular place is only the beginning. Ensuring long-term viability and permanence of the system involves social considerations in addition to technological solutions (Bastidas and García 2002, Galvis and Vargas 2002). A long-term commitment to maintain, monitor, and administrate a wastewater management system, first requires a community to recognize the importance of doing it, in terms of its own quality of life. But communities also need to feel confident about managing the system, and strengthen such confidence by actively participating in the processes of planning, designing, implementing and administrating their own waste management systems (Bastidas and García 2002). In other words, communities need to become more empowered in terms of autonomy, but also in terms of responsibility, skills and capacity for dealing with their own waste.

Having communities involved, the first consideration to ensure long-term viability is establishing who is responsible for the implementation and administration of waste management strategies. The second consideration is how will these strategies be
implemented and sustained over time. These considerations refer to governance structures and institutions, community organization structures and entities, the role of decentralization and local self-reliance, and the scale of action and jurisdiction of public administrative organisms, citizen’s organizations, industry and private sectors of the economy. They also refer to the *social fabric* that is built in the process (cooperation, solidarity and empowerment), as well as to the technical capacity, and the existence of appropriate regulations, law enforcement, and economic incentives to adequately manage waste. The third consideration refers to particular constraints, opportunities, and characteristics of the community, such as socio-economic conditions, cultural norms and paradigms, and the community’s perceived priorities for “development”.

5. Conclusions

Addressing water quality and wastewater management is not only a technological problem but also a socio-economic, cultural and political one. In that respect, it needs to be framed and addressed with a social science perspective. It is a problem that requires creative and synergistic solutions, which can be more effectively provided through transdisciplinary approaches that integrate ecological, technical, socio-economic, and psychological-behavioral considerations.

Tropical agroecosystems offer a multifunctional space in which synergies can be taken advantage of, in order to simultaneously address issues of water pollution, soil degradation, food production and people’s livelihoods. In that kind of space, productive
decontamination systems can be created to use and manage wastes, including human excreta, as valuable resources.

The use of human excreta and/or wastewaters as a resource requires consideration and mitigation of potential risks to public health and the environment. Understanding the risks properly is fundamental to adequately prevent them. This can be addressed with education, reliable information, participation and dialogue.

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References


A Case Study on the Use of Wetland Mesocosms for Sewage Treatment in Colombia

Sacha Lozano
Gund Institute of Ecological Economics, University of Vermont

1. Introduction

Most streams and coastal areas in Latin America receive direct discharges of domestic and/or industrial untreated wastewater and solid wastes, causing serious environmental and public health problems. In 2002, 25% of the population in Latin America (136,283,000 people) was not served with improved sanitation infrastructure, and only 10% (on average) of the wastewater collected in sewers received any type of treatment (Reynolds 2002). Most of the efforts to serve people with adequate sanitation have been made in urban areas with some 87 million more people connected between 1990 and 2002, and the portion of rural population served with some type of sanitation infrastructure increasing from 35% in 1990 to 44% in 2000 (WHO-Unicef 2004).

Some of the difficulties to provide a broader coverage of adequate sanitation in the region include: 1) financial limitations (Reynolds 2002); 2) technical difficulties associated to an atomization of the population in small and scattered urban and rural centers (Bastidas and Garcia 2002); 3) weak or corrupt governance structures and capacities (WWAP 2006); and 4) inadequate technological solutions (Restrepo 2002,
Galvis and Vargas 2002). Many of the existing approaches to sanitation are neither viable nor affordable to the vast majority of people, and many cities in the third world cannot access the necessary resources - water, energy, money and institutional capacity – to provide the population with improved sanitation systems (Winblad et al 1999). In addition to that, in Latin America, much of the infrastructure built for wastewater treatment has usually operated for some time, but then deteriorated due to a lack of active participation and involvement of the communities for which the systems have been built (Nunan and Satterthwaite 2001, Bastidas and García 2002, Restrepo 2002).

Considering all this, sanitation systems not only need to perform a high quality treatment, but they must also be widely accessible and appealing, which means, they have to be affordable, low energy-demanding, relatively easy to maintain and operate, and convenient to use. A long-term commitment to maintain, monitor, and administrate a wastewater management system, first requires a community to recognize the importance of doing it, in terms of its own quality of life. But communities also need to feel confident about managing the system, and strengthen such confidence by actively participating in the processes of planning, designing, implementing and administrating their own waste management systems (Bastidas and García 2002, Nunan and Satterthwaite 2001). In other words, communities need to become more empowered in terms of autonomy, but also in terms of responsibility, skills and capacity for dealing with their own waste.
Cinara Institute, Colombia

The Cinara Institute in Colombia is a regional leader in assisting rural and urban communities through participatory methodologies to develop organizational structures, technical skills, and physical infrastructure, to deal with their own waste in ways that are technically and environmentally sound, while affordable and appropriate to their local conditions (Bastidas and García 2002, Restrepo 2002, Galvis and Vargas 2002). Cinara’s transdisciplinary approach combines the technical expertise and practical thinking of engineers with methodological frameworks and theoretical insights from the fields of sociology, economics and biology. Every new sanitation project starts with a ‘participatory diagnosis’, including community surveys, water chemistry characterization, public health risk assessment, identification of local government structures, contact with local institutions and community leaders, workshops with people from the community, and visits to water sources and potential sites for water treatment plants. Once the situation, specific to the locality, has been well understood and described, a selection of technology takes place following a protocol that incorporates all the different variables (socio-economic, technical, geographic, financial, political, etc.) required to identify the most appropriate alternatives to the situation (Galvis and Vargas 2002).

What kind of treatment?

As mentioned before, part of the difficulty and limited impact of investments in sanitation solutions, in Colombia and other Latin American countries, has been an inadequate selection of technologies to treat wastewaters, particularly in small

communities (less than 30,000 people) (Galvis and Vargas 2002). Wastewater treatment systems range from mechanical, highly engineered, and highly energy demanding (usually more costly) to ‘natural’, low-energy, and usually more affordable systems (Metcalf and Eddy 1991, Reed et al 1995, Peavy et al 1985). Unfortunately, the government agencies responsible for providing sanitation solutions in the region, still tend to be attracted by overly expensive and high-energy-demanding systems that are considered “conventional” in “developed” countries, but are usually not appropriate or affordable for most situations in “underdeveloped” countries. An adequate selection of technology must consider not only technical aspects but also socio-cultural, institutional, economic and financial aspects in order to be effective in the long term (Galvis and Vargas 2002). Here, an ecological engineering approach can offer valuable contributions to strengthen community self-reliance and implement affordable and productive systems to safely address localized wastewater issues in Latin America.

Most of the successful wastewater treatment facilities in Latin America use natural systems, with some form of anaerobic pretreatment (e.g. septic tanks and anaerobic filters). Anaerobic systems can usually be more appropriate than aerobic systems in many situations in the tropics, but they can also be complemented with aerobic treatment units in order to have an overall better performance that takes the most benefit out of both types of bacterial metabolism. Natural systems can be divided in three broad categories: 1) Soil-based systems, which include subsurface infiltration, rapid infiltration/soil aquifer treatment, overland flow, and slow rate systems; 2) Wetland systems, which include free water surface and subsurface flow systems; and 3) Aquatic
systems, which include waste stabilization ponds and floating aquatic plant systems (Reed et al. 1995).

The present study aims at evaluating the performance and feasibility of solar-energy-based wetland *mesocosms* (Kangas and Adey 1996, Odum 1996) as a complementary aerobic unit to enhance anaerobic wastewater treatment, taking a rural locality of the Cauca Valley in Colombia as a case study. In doing so, it also aims at contributing new ideas from an ecological engineering perspective, to the work that the Cinara Institute does with small communities in Colombia, developing appropriate wastewater treatment technologies for the region.

2. Materials and Methods

Study Area

This study was carried out in Colombia, South America, in the rural community of La Vorágine, located 15 km from Cali, the third largest city in the country (ca 3°21’ N 76°33’ W). La Vorágine is located in the Pance River watershed, on the western branch of the north end of the Andes mountainous system (Fig. 1). The Pance River drains into the Cauca River Valley, which is one of the most productive and economically important agricultural lands in Colombia. La Vorágine is a recreational and tourist attraction area, visited by large numbers of people from the city of Cali during the weekends. The permanent population is only 500-600 people, but during the weekends a floating population of 5000-7000 people floods the area, stimulating economic activities related to tourism, recreation and catering (Cinara 1994).
Study Problem

La Vorágine has a system for collecting and treating domestic wastewaters to secondary standards since 1994. The design and implementation of this system was facilitated by the Cinara Institute through a process of community-based planning, involving the active participation of community members and the local board of water services\(^2\) (Cinara 1994a, 1994b). The system consists of a simplified collecting network (sewer)\(^3\) 1,500 m long, and a secondary treatment plant, serving both the permanent population (ca 600 people) and the tourists (5000-7000) that visit the area during the weekends. The plant was designed to treat a maximum load of 208 m\(^3\)/d (theoretical maximum during weekends) but the actual average load is only 65-70 m\(^3\)/d. The plant

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\(^2\) Junta Administradora de Acueductos  
\(^3\) Red de Alcantarillado Simplificado
consists of a Septic Tank, followed by an Anaerobic Filter and a Subsurface-Flow Constructed Wetland (Fig. 2) (Cinara 1994b). This plant has operated without major problems for 12 years under the administration, operation and maintenance of the local community.

In 1998 the performance of the plant was thoroughly evaluated in a Masters Research Project, which found the system being highly efficient in removing organic load and solids, but not very effective in removing nutrient loads and pathogens (Rivera 1998). According to the study, removal of organic load and solids occurs primarily in the first two treatment units (septic tank and anaerobic filter), which complementing each other, function as one anaerobic unit of separate phase. This means that during normal hydraulic loads, the complete anaerobic digestion of organic matter in the system occurs in two complementary phases: 1) hydrolysis and acidogenesis in the septic tank, and 2) acetogenesis and methanogenesis in the anaerobic filter.

On the other hand, the same study demonstrated that the constructed wetland was not enhancing in any significant way the characteristics of the effluent coming from the two anaerobic units. The goal of the constructed wetland was to remove nutrients and pathogens, but none of these two functions was being efficiently accomplished during the study period (Rivera 1998). The author suggested three reasons: 1) Low hydraulic retention time, 2) Anoxic conditions in the subsurface flow media, and 3) poor development of the Bulrushes (Cyperus payrus) that were planted on the flow bed, and therefore poor development of nitrifying bacterial populations associated to their root systems.
The discharge of partially treated wastewaters with high content of nutrients and pathogens into the Pance River has remained a concern to the local environmental and public health authorities. Therefore, after the study by Rivera (1998) was made, the community of La Vorágine began to explore different alternatives (and look for the financial resources) to improve and optimize the performance of this treatment plant. Recently, some additional holding capacity has been built into the constructed wetland, thereby increasing its hydraulic retention time. Unfortunately such increment is probably not significant enough as it is hindered by space limitations, and it does not solve the problems of anaerobic conditions in the flow media and poor development of the plants, so additional measures still need to be taken.

The goal of the present study was to explore other affordable alternatives, which favoring aerobic conditions (and relying mostly on sunlight as energy source) may contribute to remove more efficiently excess nutrient loads and pathogens from the anaerobically pre-treated effluent. Both nutrient and pathogen removal can be enhanced with longer exposure to sunlight, heat and high dissolved oxygen concentrations (Hench et al 2003, Romero 2001, Todd and Josephson 1996, Reed et al 1995). These conditions stimulate aerobic bacterial metabolism (necessary for nitrification), and also photosynthetic activity, which in turn produces more oxygen, takes up nutrients, and supports a food web that can also be partially responsible for pathogen removal.

Specifically, this study addresses the following questions: 1) Can a solar-energy-driven aquatic mesocosm, seeded in relatively translucent tanks, oxygenate anaerobically...
pre-treated sewage, and stimulate aerobic processes that enhance treatment quality in La Vorágine, Colombia?, 2) Can seeded mesocosms outperform unseeded mesocosms in enhancing water quality standards from anaerobically pre-treated sewage?, and 3) Is 48 hours a long enough retention time for these mesocosms to significantly enhance water quality standards from anaerobically pre-treated sewage?

**Ecological Design Considerations**

*Natural Wetlands, Biodiversity and Mesocosms*

Natural aquatic ecosystems, including wetlands, lakes and ponds, have processes inherent in their dynamics that make them capable of degrading or capturing and storing wastewater contaminants (Adey and Loveland 1998). This has been the basis for developing all forms of wastewater treatment (Metcalf and Eddy 1991, Reed et al 1995, Peavy et al 1985). However, in attempting to optimize the design and performance of wastewater treatment systems, complex biological processes are usually broken down, and organisms are removed from their ecological contexts, making necessary to artificially supply all the conditions that would otherwise be provided in a natural ecosystem. The more the natural ecosystem is broken apart, in search for those ‘specific organisms’ or ‘mechanisms’ thought to be primarily responsible for removing specific substances from the sewage, the more external energy, costs, and hazardous chemicals are required to sustain the process (Guterstam 1996).

A more systemic approach understands the irreducibility of certain properties of ecosystems (particularly in relation to capture, transformation, and transfer of energy and
matter), and recognizes the role of historicity and ecological succession in shaping and establishing (through self-organization and self-regulation) the complex dynamics and resilience that make an ecosystem capable of degrading, capturing and storing wastewater contaminants (Odum 1971, Kauffman 1993, Capra 1999). In an ecosystem, there is a close relationship between biodiversity, historicity, structure and function; and there is a minimum functional diversity required to ensure biological productivity, organizational integrity, self-regulation, and perpetuation of the ecosystem (resilience) (Swift et al 2004). The functional diversity refers here to a diversity of functional groups (‘sets of species that have similar effects on a specific ecosystem-level biogeochemical process’) that perform essential functions (such as primary production, decomposition and mineralization, and other elemental transformations) to maintain the ecosystem’s integrity (Swift et al 2004).

Understanding this relationship has been the basis to take the ‘mechanisms’, pathways, nutrient flows, and assemblages of organisms found in natural ecosystems, and effectively ‘design’ them into small-scale and relatively controlled constructed mesocosms (Kangas and Adey 1996, Odum 1996). A well designed mesocosm uses the natural abilities and self-regulation qualities of entire biological communities (functionally diverse) to break down macromolecules and metabolize organic nutrients typically found in wastewater and polluted water bodies, while providing an economic means for large-scale clean up (Todd et al 2003). In using mesocosms for applications such as wastewater treatment (Todd and Josephson 1996, Guterstam 1996, Craggs et al 1996, Peterson and Teal 1996), engineering helps to make the ecosystem more efficient
at a specified task, for example to "drive" primary production or export that production. But at the same time the designer relies heavily on the process of ecological succession (self-organization), which can be interpreted as an information process: ‘as time passes the initial information is expressed in the new organization manifested in the [eco]system. Within this organization there are implicit predictable changes in the environment, and the organization itself is capable of partially controlling the environment, so that gradually it becomes less necessary to implement costly and energy consuming changes in order to support a living community in a particular place. It can be said literally that the ecosystem has “learned” the changes in the environment and it anticipates them through internal cycles and patterns’ (Margalef, 1983). In this case, the mesocosm becomes a hybrid system, which is not necessarily a model of a particular natural system, but rather it is a means of achieving a goal or of performing a function (Kangas and Adey 1996).

This study is an attempt to follow this systemic approach in designing a mesocosm for polishing the anaerobically pre-treated effluent at the treatment plant in la Vorágine, in a way that is much less energy-demanding and more affordable (taking advantage of the tropical conditions) than other experiences with the use of mesocosms for wastewater treatment, previously implemented in temperate regions (Todd and Josephson 1996, Guterstam 1996, Craggs et al 1996, Peterson and Teal 1996).
Local Conditions

Average altitude in La Vorágine is 1,300 meters above sea level. Temperature fluctuates between 18 and 30 °C, with an average of 25 °C. There is a high incidence of sunlight all year-round, and two rainy seasons: one between March and June and another between September and December. Between July and August precipitation is less than 1500 mm. The topography at the site where the treatment plant is located is relatively flat, but it is surrounded by steep hills on both margins of the Pance River, and the landscape is dominated by dry mountainous forest and pasture (Cinara 1994a).

In the flat area of the Valley, where the Pance River drains, there are three kinds of wetlands associated to the hydrologic complex of the Cauca River Watershed: ‘madreviejas’, ‘lagunas’ and ‘ciénagas’ (Florez and Mondragón 2002). They differ in their proximity to the river, water depth and stratification, connectivity to other water bodies, and species composition of plant communities. Depending on these conditions, different types of microhabitats become available to different assemblages of species (Ramírez et al 2000). The microhabitats of interest for this study were the water body with its vegetation, and the shore with its vegetation. By collecting plants, substrate and water samples from these types of microhabitats, in various different sites, we expected to be able to recreate in the mesocosms a simplified version of the trophic structure that supports these living systems.
Experimental Design

Pilot Mesocosm Design and Construction

Twelve key factors have been described as principles required for the design of task-oriented mesocosms for wastewater treatment. These factors include: (1) mineral diversity, (2) nutrient reservoirs, (3) steep gradients, (4) high exchange rates, (5) periodic and random pulses, (6) cellular design and mesocosm structure, (7) subecosystems, (8) microbial communities, (9) photosynthetic bases, (10) animal diversity, (11) biological exchanges beyond the mesocosm, and (12) mesocosm/macrocosm relationships (Todd and Josephson 1996).

Trying to follow most of these principles, a pilot-scale mesocosm (220 gallons) was designed and constructed in August 2006 to treat 110 gallons/d (2-day hydraulic retention time) of pre-treated sewage coming from the anaerobic filter in La Vorágine treatment plant. Some additional design guidelines were considered in order to make the system affordable and feasible to scale up in the particular setting of La Vorágine. First, no electrical energy input (for aerators or water pumps) should be used; the aerobic process should be driven solely by solar energy (photosynthesis), biological reduction of BOD, water movement by gravity, and oxygen exchange with the atmosphere. Second, the design should enhance the conditions for high photosynthetic activity, taking advantage of high and year-round incidence of sunlight and warm temperatures. Photosynthesis would consume the high amounts of CO₂ coming in the effluent from the anaerobic filter, thereby buffering the acidity and favoring alkaline conditions necessary for nitrification to occur. Third, materials to build the system should be available in Cali...
at a reasonable price that the community would be able to afford when scaling up the system. Fourth, all plants and organisms to seed the mesocosm should come from local wetlands and aquatic ecosystems.

A four-cell design was devised using 55-gallon white plastic containers, which can be found at a relatively cheap price in various second hand stores in Cali, which collect them from different industrial sites. The containers were chosen to be relatively translucent, so that photosynthesis could occur in most of the water column. The mesocosm’s four cells (tanks) were connected in series and aligned along a moderately steep slope (Fig. 2). Water flow between the tanks followed a vertical meandering route with an inlet at the surface and an outlet closer to the bottom of each tank (Fig. 2). In this set up, the tanks acted as complete-mix reactors, and being connected in series, the whole mesocosm resembled a plug flow reactor (Romero 2001). Five replicates were built: three for seeded treatments, and two for experimental control (unseeded). An 80-gallon reservoir received the effluent from the anaerobic filter and distributed it at a controlled flow rate (ca 350 L/d) through five different piping lines to the three treatments and two controls (Fig. 3). The effluent from each of the five replicate mesocosms was discharged in the same leaching field where the rest of the effluent coming from the treatment plant was currently discharged.
Treatments were seeded with plants, substrate and water samples (containing plankton and microorganisms) collected in natural wetlands, located in lower lands (1000 meters above sea level) in the flat area of the Cauca Valley. The plant species used for initial seeding included: Water Hyacinth (*Eichornia crassipes*), Water Lettuce (*Pistia stratiotes*), Duckweed (*Lemna minor*), Giant Duckweed (*Spirodela polyrhiza*), Giant Salvinia (*Salvinia molesta*), Water Pennywort (*Hydrocotyle umbellata*), Broadleaf Arrowhead (*Sagittaria latifolia*), and Kidneyleaf Mudplantain (*Heteranthera reniformis*). All four cells in each mesocosm were intended to be aerobic, and each replicate treatment was seeded following the same procedure and distribution of plant species among tanks in order to homogenize as much as possible the initial conditions for the ecological succession in all replicates.
In all three treatment replicates the first tank was seeded with Water Hyacinth and some Duckweed; the second with Water Lettuce and some Duckweed; the third with even amounts of Duckweed and Giant Salvinia, plus one small Water Lettuce; the fourth with an even mixture of Duckweed, Giant Salvinia, Giant Duckweed, Water Pennywort, Broadleaf Arrowhead, and Kidneyleaf Mudplantain. Each treatment tank was also seeded with a small amount of substrate from the wetlands (for mineral diversity and benthic microfauna) and a sample of water from the wetlands (for planktonic diversity including algae and microinvertebrates).
Uneven Sunlight Exposure among replicates

Sunlight incidence was not fully controlled during the experiment, and therefore unpredicted differences in the exposure to sunlight among different tanks caused different ecological organization outcomes in each mesocosm. Two mesocosms (one unseeded and one seeded) were partially shaded during most of the day and totally shaded during a few hours each day. The second unseeded mesocosm was mostly exposed to direct sunlight but partially shaded for a couple of hours in the afternoon. The two remaining seeded mesocosms were not shaded at anytime during the day (Fig. 4). These uncontrolled differences undermined the homogeneity of the experimental replication, yet at the same time they allowed for comparisons between mesocosms with different conditions of sunlight exposure.

Chapter 3 - Figure 4. Schematic representation of uneven exposure to sunlight among the five replicate mesocosms, at different times of the day. Black circles indicate the maximum relative shade at any given time and grey circles indicate intermediate levels of shade. White circles indicate full exposure to direct sunlight.
**Water Sampling**

The pilot system was built and seeded in late August 2006 and then left to self-organize and stabilize, while processing a constant flow of pre-treated sewage coming from the anaerobic filter, during four months (September to December 2006). In January 2007 six water samples were taken during a three-week period at each of the following sampling points: one at the inflow point for all five replicates and five more at the outflow points of each replicate (Fig. 3), for a total of 36 water samples. Samples were taken on Mondays and Thursdays in order to have a representation of maximum and minimum loading peaks in the system (Sundays and Wednesdays respectively).

**Water Chemistry and Data Analysis**

Each water sample was tested for Biological Oxygen Demand (BOD$_5$), Total Kjeldahl Nitrogen (TKN), Ammonia, Phosphates, E. coli, and Helminth Eggs. Tests were conducted following standard procedures at the Cinara Institute’s Laboratory in Cali. Additionally, Dissolved Oxygen was measured in situ, in each individual tank, three times during each sampling day. The comparative overall performance of seeded vs. unseeded treatments, and among individual replicate mesocosms, was assessed through two sets of comparisons of water chemistry data using Analysis of Variance (ANOVA): 1) comparison among seeded (n=18), unseeded (n=12) and reservoir (n=6) effluents; and 2) comparison among effluents from each of the five replicate mesocosms (n=6 for each mesocosm), which self-organized with distinctive species compositions after four months of ecological succession.
3. Results

Ecological Succession and Biodiversity

In spite of efforts to homogenize the initial conditions when seeding each replicate mesocosm, the subsequent process of self-organization was naturally affected by unavoidable small differences in the conditions of each replicate, and/or uncontrolled events and interactions with the surrounding landscape. In order to document this process, an inventory of species and functional groups in each tank was carried out in January 2007 five months after the mesocosms were initially seeded (Table 1). Additionally, a photographic record of biomass production and apparent changes in the structure of biological communities establishing in each replicate mesocosm was kept between September 2006 and January 2007 (Fig. 5).

After five months of ecological succession each replicate mesocosm had a very distinctive structure, species composition, and dominance patterns of aquatic plant species (Table 1 and Fig. 5). Larger plants displaced duckweed in almost all tanks. Water Hyacinth dominated the first cell in all three seeded replicates and also the second cell in one of them. Water Lettuce dominated the second cell in two of the replicates, and after three months it also displaced Salvinia and Duckweed in the third cell of two replicates; Salvinia dominated the third cell in the remaining replicate. Finally, the fourth cell was different in all replicates: Broadleaf Arrowhead and Kidneyleaf Mudplantain dominated one of them. The second was dominated by Water Pennywort, and the third one had only a small amount of Duckweed after three months (Table 1 and Fig. 5).
Chapter 3 - Table 1. Inventory of species and functional ecological groups in five replicate mesocosms at La Vorágine sewage treatment plant, five months after seeding and processing pre-treated sewage continuously between September 2005 and January 2006.

<table>
<thead>
<tr>
<th>Species</th>
<th>Unseeded Shaded</th>
<th>Seeded Shaded</th>
<th>Unseeded Illuminated</th>
<th>Seeded Illuminated</th>
<th>Seeded Illuminated</th>
<th>Seeded Illuminated</th>
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<tr>
<td>PRODUCERS</td>
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<tr>
<td>Aquatic Plants</td>
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<tr>
<td>Eichornia crassipes</td>
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<tr>
<td>Pistia stratiotes</td>
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<td>Lemna minor</td>
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<tr>
<td>Spirodela polyrhiza</td>
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<tr>
<td>Wolffia columbiana</td>
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<td>Salvinia molesta</td>
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<td>Sagittaria latifolia</td>
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<tr>
<td>Hydrodictyon umbrillata</td>
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<td>Hydrodictyon verticillata</td>
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<tr>
<td>Heteranthera miniformis</td>
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<td>Algae</td>
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<td>Blue-Green</td>
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<tr>
<td>Oscillatoria tenuis</td>
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<tr>
<td>Yellow-Green</td>
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<tr>
<td>Tribonema spp.</td>
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<td>Green (Chlorophyta)</td>
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<td>Golden (Chrysophyta)</td>
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<td>CONSUMERS</td>
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<td>Zooplankton</td>
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<tr>
<td>Daphnia spp.</td>
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<td>Rotifers</td>
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<td>Protozoans</td>
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<td>Macroinvertebrates</td>
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<tr>
<td>Snails</td>
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<tr>
<td>Pomacea canaliculata</td>
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<tr>
<td>Pomacea spp.</td>
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<td>Insects</td>
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<tr>
<td>Ephemeroptera</td>
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<td>Coleoptera</td>
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<td>Odonata</td>
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<td>Heteroptera</td>
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<td>Spiders</td>
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<td>Salticidae</td>
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<td>Amphibians</td>
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<tr>
<td>Hyla spp.</td>
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<td>DECOMPOSERS</td>
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<td>Fungi</td>
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<tr>
<td>Alternaria spp.</td>
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<tr>
<td>Penicillium chrysogenum</td>
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<tr>
<td>Neospora sp</td>
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<tr>
<td>Bacteria</td>
<td></td>
<td></td>
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<tr>
<td>unidentified species</td>
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</table>

Note: Seeded Illuminated, Seeded Shaded, Unseeded Shaded, Unseeded Illuminated.
Chapter 3 - Figure 5. Photographic record of the ecological succession in five replicate mesocosms at La Vorágine sewage treatment plant, between September 2005 and January 2006.
In addition to changes in plant species composition and dominance patterns, various groups of bacteria, fungi, algae, plankton, macroinvertebrates and vertebrates colonized the different tanks and established themselves with distinctive patterns of species composition and dominance in each mesocosm (Table 1). The unseeded replicates were also colonized by various groups of organisms, primarily bacteria, fungi, algae, mosquito larvae, and plankton in some of the tanks (Table 1).

The white plastic containers let enough light pass through the walls, allowing photosynthesis and algal growth to occur even in the seeded tanks where the surface was covered by floating plants. Various kinds of algae grew both in the water column and attached to the tank walls and piping surfaces, in most of the tanks (Table 1). The kind and abundance of algae growing in each tank was related to sunlight incidence, and it varied between seeded and unseeded mesocosms. Also, a biofilm made of blue-green and yellow algae, three kinds of fungi (Alternaria spp., Penicillium chrysogenum, and Neurospora spp.), and unidentified bacteria was formed inside the hoses connecting all tanks.

Microinvertebrates, including zooplankton and protozoans were abundant in all seeded mesocosms and the unseeded replicate that was exposed to direct sunlight. Rotifers were only found in the two seeded mesocosms exposed to direct sunlight (Table 1). Presence of rotifers is an indicator of efficient aerobic biological treatment, as they consume bacteria and organic matter when the water is well oxygenated (Ramirez-Gonzalez and Vinia-Vizcaino, 1998) In one of the tanks, ‘clouds’ of Daphnia spp. (Cladocerans) were observed engulfing and presumably feeding on mosquito larvae.
Mosquito larvae and midges were present in most tanks but they were considerably less abundant in seeded mesocosms, where less free water surface was available. Conversely, a variety of other insect groups and spiders were present only in the seeded mesocosms.

Frogs (*Hyla spp.*) were well established and presumably reproducing (as evidenced by large numbers of tadpoles) in most seeded tanks and the two unseeded tanks with highest dissolved oxygen concentrations and sunlight exposure. Snails were a dominant group, also reproducing in some of the tanks of seeded mesocosms and they fed on floating aquatic plants and algae. Although snails play an important role in controlling algal blooms and filtering water, there is some concern that they may also act as intermediate hosts for helminth species in the system. More research is required in this respect to understand the role of the snail *Pomacea spp.* in magnifying pathogenic hazards and health risks to humans in the area of La Vorágine.

*Dissolved Oxygen*

Dissolved oxygen in the effluent coming from the anaerobic filter was consistently less than 0.5 mg/L during the entire study period. After flowing through the experimental mesocosms, this anoxic effluent was significantly oxygenated, reaching maximum levels of 4.6 - 5.7 mg/L, which corresponds to 63 - 76 % saturation at the altitude in La Vorágine (Table 2). There was a significant difference among mesocosms in their capacity to oxygenate the anoxic influent (F 4,45 = 3.10; p<0.02), and the highest average concentrations of dissolved oxygen were found in seeded mesocosms that were exposed to direct sunlight all day (Fig. 6). Oxygenation was partly related to water
movement and exchange with the atmosphere. However, the observed patterns in dissolved oxygen fluctuation among the different tanks and mesocosms, at different times of the day, suggest that photosynthesis played a more significant role than water movement in oxygenating the water. First, Dissolved oxygen (DO) concentrations were consistently higher and reached maximum levels in the mesocosms that were exposed to direct sunlight all day (Fig. 6). Second, there was a consistent tendency to increase DO from the first cell to the fourth cell in all replicate mesocosms, but the increment was significantly higher in the three mesocosms that were exposed to direct sunlight during most of the day (Fig. 7). Third, DO followed a typical daily pattern of photosynthetic activity (Adey and Loveland 1998) peaking around the early afternoon, in all but the first cell of all mesocosms (Fig. 7). However, this pattern, was more pronounced in the third and fourth cells, and especially in the mesocosms with direct sunlight exposure (Fig. 7). The first cell in all five replicate mesocosms remained practically anoxic, most likely because of the shade from the dense foliage and root system of Water Hyacinths, but also because of the bacterial activity in the root system that may have consumed any available oxygen in degrading the remaining organic matter present in the water.
Chapter 3 - Table 2. Dissolved oxygen concentrations by individual tank and treatment in five replicate mesocosms at the sewage treatment plant in La Vorágine, four months after initial seeding. % Saturation is relative to the maximum DO concentration in La Vorágine (7.43 mg/L), which is determined by altitude and temperature.

<table>
<thead>
<tr>
<th>Sampling Unit</th>
<th>DO (mg/L)</th>
<th>% Saturation DO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Min - Max</td>
</tr>
<tr>
<td>Unseeded Shaded</td>
<td></td>
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</tr>
<tr>
<td>1A</td>
<td>0.36 ± 0.12</td>
<td>0.13 - 0.49</td>
</tr>
<tr>
<td>1B</td>
<td>0.28 ± 0.10</td>
<td>0.16 - 0.46</td>
</tr>
<tr>
<td>1C</td>
<td>0.46 ± 0.36</td>
<td>0.13 - 1.18</td>
</tr>
<tr>
<td>1D</td>
<td>0.92 ± 0.63</td>
<td>0.09 - 1.82</td>
</tr>
<tr>
<td>Seeded Shaded</td>
<td></td>
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</tr>
<tr>
<td>2A</td>
<td>0.29 ± 0.09</td>
<td>0.13 - 0.47</td>
</tr>
<tr>
<td>2B</td>
<td>0.78 ± 0.75</td>
<td>0.12 - 2.25</td>
</tr>
<tr>
<td>2C</td>
<td>1.00 ± 1.01</td>
<td>0.09 - 3.49</td>
</tr>
<tr>
<td>2D</td>
<td>1.44 ± 0.98</td>
<td>0.09 - 1.34</td>
</tr>
<tr>
<td>Unseeded Illuminated</td>
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<tr>
<td>3A</td>
<td>0.22 ± 0.14</td>
<td>0.08 - 0.6</td>
</tr>
<tr>
<td>3B</td>
<td>1.16 ± 1.65</td>
<td>0.09 - 4.7</td>
</tr>
<tr>
<td>3C</td>
<td>1.54 ± 1.92</td>
<td>0.08 - 5.38</td>
</tr>
<tr>
<td>3D</td>
<td>2.08 ± 1.95</td>
<td>0.08 - 5.7</td>
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<tr>
<td>Seeded Illuminated</td>
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<tr>
<td>4A</td>
<td>0.51 ± 0.24</td>
<td>0.22 - 1.00</td>
</tr>
<tr>
<td>4B</td>
<td>1.61 ± 0.68</td>
<td>0.56 - 2.55</td>
</tr>
<tr>
<td>4C</td>
<td>2.46 ± 1.43</td>
<td>0.22 - 4.35</td>
</tr>
<tr>
<td>4D</td>
<td>2.65 ± 1.20</td>
<td>0.77 - 4.75</td>
</tr>
<tr>
<td>Seeded Illuminated</td>
<td></td>
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<tr>
<td>5A</td>
<td>0.68 ± 0.48</td>
<td>0.17 - 1.62</td>
</tr>
<tr>
<td>5B</td>
<td>1.45 ± 0.90</td>
<td>0.21 - 2.63</td>
</tr>
<tr>
<td>5C</td>
<td>2.38 ± 1.45</td>
<td>0.23 - 4.3</td>
</tr>
<tr>
<td>5D</td>
<td>2.60 ± 1.55</td>
<td>0.21 - 4.75</td>
</tr>
</tbody>
</table>

Chapter 3 - Figure 6. Average Dissolved Oxygen by treatment, and in each replicate mesocosm (sampling unit). Graphs show mean (small square), standard deviation (large box) and standard error (bars).
These patterns suggest a combined effect of sunlight exposure, time of the day (photosynthetic activity), and BOD in determining dissolved oxygen concentrations.

The maximum single measurement of DO was registered in the fourth cell of the unseeded (control) mesocosm that was only partially shaded during a couple of hours in the afternoon. However, the average DO over time was maximum in the two seeded mesocosms that were exposed to direct sunlight all day, suggesting a buffering capacity and more stable conditions presumably related to higher functional diversity in the seeded mesocosms (Tables 1 and 2).
Water Chemistry Analysis

1. Hydraulic Retention Time (HRT)

The flow rate in all mesocosms was calibrated in the same way, by adjusting the diameter of the pipes that connected the reservoir with the first cell of each replicate. Flow rate was designed to ensure a 48-hour hydraulic retention time (420 L/d). Nevertheless, as the system got established between September and December 2006, the flow rates became slower and slightly variable among replicates (265 – 355 L/d). This produced different effective hydraulic retention times in each mesocosm (Table 3). HRT varied from 60 to 80 hours, with maximum values in the unseeded and one of the seeded mesocosms that were exposed to direct sunlight (Table 3).

2. Biological Oxygen Demand (BOD)

Although most of the BOD is efficiently removed in the two anaerobic treatment units at La Vorágine treatment plant, the experimental mesocosms had a significant effect in further removing BOD from the anaerobic effluent. BOD was reduced from 85 mg/L average in the reservoir, to 45 mg/L and less than 30 mg/L in the unseeded and seeded treatments respectively (Table 3, Fig. 8). These averages were affected by a change in conditions during the last two sampling days, due to maintenance activities in the plant (sludge pumping from the septic tank), which caused a release of higher loads of organic matter into the experimental mesocosms. If the two samples affected by sludge pumping are not included in the analysis, the average BOD in the effluent reached a minimum of 16 mg/L, in one of the seeded mesocosms. There were not significant differences in BOD removal between seeded and unseeded treatments (table 3), however the unseeded...
A mesocosm that was shaded during most of the day presented the least efficient removal of BOD (Fig. 9).

3. Nitrogen (TKN, NH₃)

Significant removal of Organic Nitrogen and Ammonia occurred only in the two seeded mesocosms that were exposed to direct sunlight all day (table 3, Fig. 9). The largest nitrogen removal was obtained in a seeded mesocosm exposed all day to direct sunlight and containing two cells dominated by Water Hyacinth. In this mesocosm, TKN was reduced from 28 mg/L to 14 mg/L (on average), and Ammonia was reduced from 24 mg/L to 11 mg/L (on average). Excluding the two samples affected by sludge pumping, TKN was reduced to 12 mg/L and Ammonia to 9 mg/L in the same mesocosm.

4. Phosphorus

Phosphorus removal in each mesocosm exhibited practically the same behavior as nitrogen removal (table 3, Fig 9). Only the two seeded mesocosms exposed to direct sunlight presented a significant reduction in phosphate concentrations (Fig. 9). However, the maximum phosphate removal (which occurred in the same seeded mesocosm with two Water Hyacinth cells) was only from 9 mg/L to 5 mg/L (or 4.3 mg/L, if the samples affected by sludge pumping are excluded), which still leaves a eutrophic effluent being discharged, and therefore requiring further attention.
Chapter 3 - Table 3. Water chemistry evaluation of influent and effluent points in five experimental mesocosms at the sewage treatment plant in La Vorágine. The ANOVA evaluates differences among effluents only.

<table>
<thead>
<tr>
<th>Sampling Unit</th>
<th>BOD₅ (mg/L) mean ± SD</th>
<th>TKN (mg/L) mean ± SD</th>
<th>NH₃ (mg/L) mean ± SD</th>
<th>PO₄ (mg/L) mean ± SD</th>
<th>E.coli (CFU/100mL) mean ± SD</th>
<th>Helminths (# eggs/L) mean ± SD</th>
<th>Flow (L/d) mean ± SD</th>
<th>HRT (hours) mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Influent</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir</td>
<td>84.3 ± 37.6</td>
<td>28.4 ± 7.8</td>
<td>23.8 ± 8.7</td>
<td>9.2 ± 2.8</td>
<td>8E05 ± 6.1E05</td>
<td>60.3 ± 66.5</td>
<td>352.3 ± 67.5</td>
<td>56.1 ± 9.9</td>
</tr>
<tr>
<td><strong>Effluent</strong></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(1d) Unseeded Shaded</td>
<td>53.8 ± 45.7</td>
<td>22.8 ± 4.8</td>
<td>17.0 ± 5.1</td>
<td>7.5 ± 1.3</td>
<td>6.2E04 ± 4.9E04</td>
<td>28.3 ± 33.7</td>
<td>305.1 ± 71.8</td>
<td>65.5 ± 13.8</td>
</tr>
<tr>
<td>(2d) Seeded Shaded</td>
<td>30.3 ± 15.8</td>
<td>24.7 ± 6.1</td>
<td>21.2 ± 6.4</td>
<td>7.4 ± 0.7</td>
<td>5.0E04 ± 3.6E04</td>
<td>0</td>
<td>324.7 ± 70.4</td>
<td>61.4 ± 12.8</td>
</tr>
<tr>
<td>(3d) Unseeded Illuminated</td>
<td>33.6 ± 17.8</td>
<td>25.6 ± 3.2</td>
<td>20.3 ± 2.9</td>
<td>7.7 ± 1.1</td>
<td>4.9E04 ± 3.5E04</td>
<td>0</td>
<td>265.7 ± 97.5</td>
<td>80.9 ± 30.7</td>
</tr>
<tr>
<td>(4d) Seeded Illuminated</td>
<td>23.5 ± 14.9</td>
<td>14.9 ± 5.0</td>
<td>11.2 ± 3.7</td>
<td>5.1 ± 1.6</td>
<td>3.7E04 ± 2.9E04</td>
<td>0</td>
<td>296.9 ± 64.3</td>
<td>66.9 ± 13.0</td>
</tr>
<tr>
<td>(5d) Seeded Illuminated</td>
<td>34.5 ± 19.1</td>
<td>19.4 ± 2.1</td>
<td>17.0 ± 1.6</td>
<td>6.5 ± 0.8</td>
<td>5.5E04 ± 3.9E04</td>
<td>0</td>
<td>260.8 ± 55.1</td>
<td>76.5 ± 17.1</td>
</tr>
<tr>
<td><strong>ANOVA</strong></td>
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<td></td>
</tr>
<tr>
<td>p &lt; 0.34</td>
<td>1.18</td>
<td>1.18</td>
<td>5.69</td>
<td>4.97</td>
<td>5.17</td>
<td>5.17</td>
<td>5.17</td>
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<tr>
<td>NS</td>
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<td>Signif.</td>
<td>NS</td>
<td>NS</td>
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</tbody>
</table>
5. Pathogens

Helminth Eggs, averaging 60 eggs/L in the effluent coming from the anaerobic filter, were completely removed in all but the shaded unseeded mesocosm, in which an average of 25 eggs/L still remained (table 3, Fig. 9). E. coli concentrations were reduced by 1 log in all mesocosms (table 3). There were not significant differences in E. coli removal among mesocosms, but the largest removal was performed again in the seeded and well-illuminated mesocosm with two Water Hyacinth cells, from an average of 8E05 in the reservoir to a minimum of 3.5E04 (or 2E04, excluding the samples affected by sludge pumping) (Fig. 9). Although significant and better than the existing treatment, the reduction in E. coli concentrations was still far from ideal pathogen removal efficiencies, in order to produce a safe effluent for wastewater reusing schemes. Conventional discharge standards establish 1000 CFU/100mL as the maximum permissible level for safe reuse schemes. Achieving such removal efficiency using the experimental mesocosms evaluated in this study would require an additional mechanism to eliminate pathogens such as a slow filtration unit or a subsurface flow wetland attached to the end of the mesocosms. Additionally, more specific microbiological studies are required to confirm that the indicator of 1000 CFU/mL of E. coli is actually representing an accurate picture of the health risks associated to pathogen concentrations in wastewater reuse schemes.
Chapter 3 - Figure 8.
Comparative evaluation of six water quality parameters between the anaerobic influent (reservoir) and the effluents of two experimental treatments (seeded and unseeded mesocosms), at the sewage treatment plant in La Vorágine, Colombia.

Chapter 3 - Figure 9.
Comparative evaluation of six water quality parameters among the effluents of five replicate experimental mesocosms, with different treatments (seeded and unseeded) and different levels of exposure to direct sunlight (Shaded vs. Illuminated). U = Unseeded, S = Seeded.
Comparative efficiency of the experimental mesocosms

While being suggestive and consistent with field observations the presented results from this experiment should be interpreted with caution. Analysis of variance indicated significant differences in removal efficiencies at least between some of the individual mesocosms (table 3), but the robustness of this analysis was undermined by the sampling size (n=6), which may explain the high statistical error observed in the graphs. However, statistical error was also affected by two important factors: 1) Samples were taken on Mondays and Wednesdays, coinciding with the highest and lowest organic loads flowing through the treatment plant. Therefore, the collected data show the highest possible level of variability due to actual fluctuations in the conditions of the system; 2) during the last two sampling days, the conditions also changed due to maintenance and sludge pumping in the septic tank, increasing variability in the data. Having said that, the observed trends and differences in average removal efficiencies for all parameters, offer interesting and suggestive information about the performance of this kind of mesocosms.

The water chemistry results suggest that both unseeded and seeded mesocosms performed an important amount of removal in all the parameters evaluated. This result presumably highlights the role of hydraulic retention time, which fluctuated between 60-80 hours, significantly extending the sewage’s exposure to physical, chemical and biological treatment processes in the existing system. However, while hydraulic retention time clearly had a significant influence on the overall performance of the experimental mesocosms, it did not fully explain the different removal efficiencies among individual mesocosms for any of the parameters evaluated (Table 3 and Fig. 9). This may be
explained as the result of a hypothetical threshold beyond which differences in HRT do not determine significant differences in removal efficiencies. Alternatively, it may be explained by the complementary contribution of other important factors such as sunlight incidence, dissolved oxygen concentrations, and species composition and functional diversity in each mesocosm.

From the three mesocosms exposed to direct sunlight all day, the two seeded replicates presented consistently higher removal efficiencies in all parameters, and more stable dissolved oxygen conditions (higher averages and lower variances) (Table 3 and Fig. 9). Although the unseeded mesocosm that was exposed to direct sunlight during most of the day presented high levels of dissolved oxygen, its removal efficiencies were probably undermined by a lower functional diversity, compared to the seeded treatments (Tables 1 and 3). The most efficient removal in all parameters was performed by the fourth replicate (Table 3 and Fig. 9), which was a seeded mesocosm, exposed to direct sunlight all day, and containing two cells dominated by Water Hyacinth, one dominated by Water Lettuce and one dominated by Water Pennywort (Fig. 5). Among the aquatic plant species used in this experiment, Water Hyacinth has the highest rate of biomass production (2,190 ton/ha.yr of fresh matter, Chará et al 1999), which translates in higher nutrient uptake. Additionally, although annual biomass yields of Water Pennywort are lower than Water Hyacinth, Water Pennywort can have a higher nutrient uptake than Water Hyacinth under certain conditions. These factors combined may explain at least partially the overall higher nutrient removal in the fourth mesocosm.
When comparing the water chemistry results from this study with the reported performance of the existing constructed wetland at the treatment plant in La Vorágine (Rivera 1998), the seeded mesocosms presented higher removal efficiencies in all the parameters evaluated, in spite of having higher concentrations to treat coming from the anaerobic filter’s effluent, than in 1998 when Rivera did his study (Table 4). One obvious explanation to this difference is the significantly longer retention time allowed in the present study (Table 4). However, as Rivera also suggested it, oxygenation plays a very important role in enhancing the removal of nutrients and pathogens from the anaerobic influent, and this study corroborated his observation with the overall better performance of those mesocosms that were better oxygenated. Additionally, exposure to direct sunlight and warm temperatures (both conditions absent in the constructed wetland) also seemed to play a significant role in polishing the water. Finally, helminth egg removal although not measured in the study by Rivera, may have been negligible in the constructed wetland based on the results for the shaded-unseeded mesocosm in this study. This comparison suggests that the mesocosms evaluated in this study can potentially perform a much more efficient complementary treatment to the anoxic effluent coming from the anaerobic filter, than the existing constructed wetland at the sewage treatment plant in La Vorágine.
Comparative performance of the experimental mesocosms evaluated in this study and the constructed wetland evaluated in La Vorgane's sewage treatment plant by Lozano (2007).

<table>
<thead>
<tr>
<th>Sampling Unit</th>
<th>BOD₅</th>
<th>TKN</th>
<th>NH₃</th>
<th>PO₄</th>
<th>E.coli</th>
<th>Helminths</th>
<th>HRT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lozano (2007)</strong></td>
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<tr>
<td>Effluent from Anaerobic Filter</td>
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<td></td>
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<tr>
<td>(Influent to tertiary unit)</td>
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<tr>
<td>Effluent from mesocosms</td>
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<td></td>
</tr>
<tr>
<td>(1d) Unseeded Shaded</td>
<td>36.18</td>
<td>19.72</td>
<td>28.57</td>
<td>18.48</td>
<td>92.25</td>
<td>53.07</td>
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</tr>
<tr>
<td>(2d) Seeded Shaded</td>
<td>64.06</td>
<td>13.03</td>
<td>10.92</td>
<td>19.57</td>
<td>93.75</td>
<td>100.00</td>
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<tr>
<td>(3d) Unseeded Illuminated</td>
<td>60.14</td>
<td>9.86</td>
<td>14.71</td>
<td>16.30</td>
<td>93.88</td>
<td>100.00</td>
<td></td>
</tr>
<tr>
<td>(4d) Seeded Illuminated</td>
<td>72.12</td>
<td>47.54</td>
<td>52.94</td>
<td>44.57</td>
<td>95.38</td>
<td>100.00</td>
<td></td>
</tr>
<tr>
<td>(5d) Seeded Illuminated</td>
<td>59.07</td>
<td>31.69</td>
<td>28.57</td>
<td>29.35</td>
<td>93.13</td>
<td>100.00</td>
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<tr>
<td><strong>Rivera (1998)</strong></td>
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<tr>
<td>Effluent from Anaerobic Filter</td>
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<tr>
<td>(Influent to tertiary unit)</td>
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</tr>
<tr>
<td>Effluent from tertiary unit</td>
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<td></td>
</tr>
<tr>
<td>Constructed Wetland</td>
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</tbody>
</table>

| | Effluent from tertiary unit        |      |     |     |     |            |           |     |
| | (Influent to tertiary unit)        |      |     |     |     |            |           |     |
| | Constructed Wetland                |      |     |     |     |            |           |     |

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4. Discussion

The experimental mesocosms evaluated in this study offer a promising low-cost alternative to complement anaerobic wastewater treatment under tropical conditions. Although they still need to be adjusted and optimized in order to further enhance their performance, these mesocosms already exhibited a significantly more efficient removal of nutrients and pathogens, than the existing constructed wetland at the treatment plant in La Vorágine. Robust and functionally diverse biological communities were established in the mesocosms only a few months after seeding, and the main goal of oxygenating the anoxic influent coming from the anaerobic filter was satisfactorily attained, particularly in the seeded treatments. Following up with new iterations of design, new seeding, and re-accommodation of species within and among tanks, is necessary to optimize the conditions for higher efficiencies in nutrient and pathogen removal. In the same way, continue generating data from experimental treatment systems within Latin America, and not from somewhere else, is very important to inform the design of wastewater treatment systems that respond to the particular context, and consider what works and what doesn’t, in the wide majority of small communities who are underserved with sanitation infrastructures in the region. This case study offers data and some important insights to enhance domestic wastewater management in such communities.

Although anaerobic wastewater treatment has several advantages over aerobic treatment in the context of most Latin American small communities (Rivera 1998, Romero 2001), anaerobic and aerobic processes are not mutually exclusive, and instead they can be regarded as complementary, and designed creatively in combined wastewater
treatment systems (Cinara 1994b). In this context, photosynthesis is a key process, responsible not only for oxygenating the water and assimilating nutrients and organic matter, but also for supporting a functionally diverse biological community that can efficiently process all the different substances present in wastewaters, in a way that becomes increasingly robust and resilient over time as the dynamics of self-organization takes place. The compartmentalization of aerobic treatment units in various semi-translucent reactors, like the mesocosms in this study, can make an efficient use of limited available space, particularly in hilly areas, and perform a similar treatment quality as other natural systems, such as waste stabilization ponds, which while being capable of oxygenating anaerobic effluents, demand a lot of space and require a flat topography. Such semi-translucent reactors make use of year-round incidence of sunlight and warm temperatures, which are readily available resources in the tropics and can drive aerobic processes without needing air pumps or other devices that require electricity and therefore increment operation costs.

Multifunctional Approach to Wastewater Management

(anaerobic-aerobic) for wastewater treatment, combining septic tanks with aquatic plants and gravel/microbial filters, has also been studied by scientists in NASA since the 1970s (Wolverton 1988), and these type of systems have proven to be low-cost means for wastewater treatment, especially in tropical and subtropical areas (Wolverton 1984, Grau 1996). On the other hand, the use of aquatic plants to treat wastewater and at the same time generate a source of protein for animal feed, also received considerable attention in the 1970s (Bagnall et al 1973, Otis and Hillman 1976, Golueke 1977, Wolverton and McDonald 1977, Joseph 1978). Plant nutrient uptake translates into biomass production, and under tropical sunlight conditions, wetland and aquatic plants can use the organic load and nutrient content in wastewaters to stimulate significant vegetative growth (Koottatep and Chongrak 1997, Oron 1994). The biomass production rates and the actual content of protein in most aquatic plants are significantly higher than soy, which is a major source of animal feed and is a crop that takes up a significant amount of prime quality soils around the world (Chará et al 1999). If animal feed is supplemented with aquatic plants, not only money can be saved (enhancing rural livelihoods), but also extensive areas of land cultivated with soy could be liberated for other purposes including human food production and habitat restoration (Chará et al 1999, Sarria et al 1994).

Unfortunately, since most of the species that establish well in sewage-fed systems are remarkably robust and resilient, they can also create serious ecological imbalances when colonizing new environments. In consequence, these species are generally despised as nuisances, and the numerous qualities they have to offer are often overlooked. Aquatic plant biomass for instance can be an important resource, potentially taking a variety of
forms: 1) energy generation in the form of biofuel (Ramana and Srinivas 1997) and biogas (Wolverton and McDonald 1981, Jayaweera et al 2007); 2) carbon sequestration; 3) wildlife habitat and food web support structure; 4) animal feed supplements (Wolverton 1984, Chará et al 1999, Sarria et al 1994); and 5) production of non-edible crops that can be commercialized or used as materials and fibers for different kinds of manufacturing and construction (e.g. bamboo). Wastewater can be seen as a fertilizer and a valuable resource offering economic opportunities and useful byproducts.

Having all this research background and scientific validation, it is disconcerting that most local authorities responsible for addressing sanitation issues in Latin America, still prefer to consider mechanized and high-energy-demanding systems that are much more expensive but not necessarily more efficient than low-tech natural systems. On top of that, the cost over time of implementing high-tech ‘conventional’ systems usually ends up being 2 or 3 times higher than the initial investment (Grau 1996). Low-tech ‘natural’ systems can be more affordable to most sectors of the population, especially in tropical regions. However, the question still remains of how to implement low-cost eco-technologies for wastewater treatment more widely? This question certainly goes beyond technological considerations, and it extends into a complex socio-economic realm that needs to be approached with a social science framework, such as the one practiced by the Cinara Institute in Colombia.

Cinara’s work has grown over several decades in the context of a tendency to governance decentralization in Latin America (starting in the 1970s), the increasing
global attention and priority given to water related issues and sanitation, and the existence of community organization entities and structures in rural areas of Colombia, where sanitation coverage is limited and technically difficult due to low densities and scattered distribution of households in the landscape (Bastidas and García 2002). The forces that shape decentralization often times contradict each other, but at least they have created an opportunity for citizen’s participation and a more active role of the civil society in its own development processes. This opportunity has been used to some extent in Colombia to enhance self-reliance of small communities in relation to a range of issues including sanitation. Community involvement in sanitation projects constitutes the basis for their sustainability over time, while creating an important social fabric (Bastidas and García 2002). The challenge now is how to approach sanitation as a multifunctional process linking water quality, environmental protection, public health, economic opportunities and food security.

5. Conclusions

In the midst of financial limitations and a largely scattered distribution of the population in small localities, wastewater treatment in Latin America requires creative solutions that can be implemented easily in a decentralized administrative structure. The characteristics of La Vorágine—in terms of wastewater quality/quantity, and socioeconomic and biogeophysical contexts—are representative of many small rural communities all over Latin America, therefore this case study and specially the participatory methodology crafted by the Cinara Institute to develop community-based
sanitation infrastructure and administration, constitute an important reference that can be adapted to similar situations in other localities of the region.

The results from this study suggest that solar-energy-driven mesocosms seeded with plants, substrate and water from local wetlands can be an effective alternative for a complementary aerobic unit at the treatment plant in La Vorágine, Colombia. Given enough retention time, these mesocosms can oxygenate the water enough to stimulate aerobic processes that enhance the water treatment, by removing nutrients and pathogens that are not being efficiently removed in the existing constructed wetland.

Future research to improve and optimize the experimental mesocosms evaluated in this study should focus on: 1) phosphorus removal mechanisms, 2) evaluating different mesocosm designs, for example combining seeded with non-seeded tanks and having more cells in each mesocosm to see if higher oxygenation can be achieved, 3) pathogen removal mechanisms, and 4) the role of species like the snail *Pomacea sp.* as an intermediate host for helminth pathogens.

**Acknowledgements**

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specially, thanks to Chedorlaomer Villa from the ‘Asociación de Acueducto y Alcantarillado’ La Vorágine for all his work and support setting up and maintaining the experiments.

REFERENCES


CHAPTER 4

Integrating Ecological Design, Community-based Sanitation and Waste Management Solutions in Colombia.

Sacha Lozano
Gund Institute of Ecological Economics, University of Vermont.

1. Introduction

Generation of waste is a built-in and perhaps unavoidable property of our currently dominant economic system. From a thermodynamics perspective, all forms of human waste represent a high entropy state of matter, resulting after a gradual decay in embodied energy through the linear economic structure prevalent in current societal organization (Georgescu-Roegen 1971, MaxNeef 1992). If waste is left to accumulate, entropy will continue to increase until all available matter is in a low energetic state, economic production will cease, and the entire economic system will stop or collapse. In contrast, natural ecosystems never accumulate matter as “waste”, and instead, the planet as a living whole is constantly moving away from entropy by a multiple-scale recycling of every piece of matter, as long as the sun continues providing light and energy (Odum 1971). An ecological design approach to manage human waste, aims at learning how to participate more harmoniously within the planet’s recycling of matter, using renewable energy sources and mimicking nature’s low entropic states, to maintain the life-support systems that we and our economies are part of (Kangas 2004, Todd et al 2003)
It is now widely accepted that waste management and sanitation are not only technological problems, but they need to be addressed within a social science framework to overcome socio-economic, cultural and political obstacles to their solution (Biswas 2001, Bastidas and García 2002, Restrepo 2002). Alternative solutions to human waste management require creative and synergistic thinking, which can be more effectively provided through transdisciplinary approaches integrating ecological, technical, socio-economic, and psychological-behavioral considerations (Sawyer 2003, Winblad et al 1999, Bastidas and García 2002).

This paper focuses on domestic wastewater and human excreta, as a type of waste of major importance to ecological integrity, public health and economic development. I explore the integration between ecological design and community-based solutions to sanitation, and discuss opportunities and challenges of implementing ecological waste management in the particular bioregional and socio-economic context of a proposed agroecosystem, in a rural community of Colombia. In doing this, several arguments are presented to support the idea that assuming the responsibility of managing its own waste can be a powerful and transformative experience for a community to fundamentally change its perspective and understanding of its place within the planet. Furthermore, managing waste can be an integrative force linking economic, social and environmental considerations, and favoring human-scale development, genuine progress, and self-reliance in a community.
2. The Multiple Facets of Waste Management and Sanitation

Ecological Considerations

From an ecological point of view, generation of waste and its inadequate management, translate into water, air and soil pollution, which in turn poses serious threats to ecosystems integrity, wildlife biodiversity, and human public health (Winblad et al 1999, Mata 1994). Urban and peri-urban areas around the world are among the worst polluted habitats of the planet, with much of this pollution being caused by inadequate sanitation services (Winblad et al, 1999). In the Third World, sewage is commonly discharged into the environment at large without any treatment, causing serious environmental damage and public health hazards (WWAP 2006). As cities expand and population sizes increase, the situation tends to grow worse and the need for safe, sustainable, and affordable sanitation systems becomes even more critical (Winblad et al, 1999), just like the need to recognize waste management and sewage treatment as a priority in watershed restoration frameworks (Mata 2004).

Various natural ecosystems have processes inherent in their dynamics that make them capable of degrading or capturing and storing wastewater contaminants (Adey and Loveland 1998). However, our modern pattern of accumulation and concentration of waste for further treatment, usually undermines the capacity of natural ecosystems to process contaminants, and makes the use of costly treatment technologies necessary in order to prevent environmental damage (Graedel and Allenby 2003). An ecological approach to waste management and sanitation includes humans and their wastes within a
larger life-support system, and focuses on recycling materials (such as nutrients, water, and organic matter) in order to maintain a balance in the entire system (Winblad et al 1999, Allen and Behmanesh 1994). Such an approach requires a change in attitude towards what is perceived as ‘waste’ and the apparent convenience of ‘flushing it away and forgetting’ (Sawyer 2003, Illich 1985, Allen and Behmanesh 1994). Ultimately, it calls for a critical review and change in: patterns of land use, occupation and distribution; demographic patterns, including population growth, and rural vs. urban density; lifestyles, wealth distribution and consumption patterns; commoditization of nature; patterns of natural resource use; the way we use water, grow food, and most importantly the way we think about “waste”, and how we deal with it.

*Economic Considerations*

The forms of socio-economic and political organization currently in force in the world are essentially antagonistic to the achievement of a tripartite harmony between nature, humans, and technology (Max Neef 1992, Daly and Cobb 1989, Ehrlich and Ehrlich 1990). Many economists still refuse to recognize the fact that since the inevitable product of economic processes is waste, this, inevitably increases in greater proportion than the productive intensity of economic activity (Graedel and Allenby 2003). Hyper-urbanization and the increasing pollution that is concomitant with those centers considered to be the most highly developed are a proof that came as an unexpected and disconcerting surprise for all economic theories (Max Neef 1992). Therefore, the problem of waste management also requires a critical review and adjustment of current socio-economic thinking and development discourses in order to actually address root causes.
In currently prevalent economic thinking, dealing with waste (whether by reducing its production through increased efficiency, or by treating it before it is discharged) represents an extra cost—a burden—that undermines productive capital, unless it can be made profitable, or less costly, by some form of recycling or industrial ecology (i.e. selling undesired wastes to someone else who needs them as resources) (Graedel and Allenby 2003, Allen and Behmanesh 1994). Therefore, whenever adequate regulations do not exist, or are not properly enforced, the cost of managing waste is usually *externalized*, affecting the environment and/or other people, in one way or another. Because economics never assigned the natural environment—a system affected by entropy—its real weight, it has been possible for the discipline to remain enclosed within its mechanistic ivory tower, providing advice to dominant but intrinsically unsustainable socio-economic systems, and ‘subsidizing’ grave false assumptions with concepts like that of “externality” (Max Neef 1992, Daly and Cobb 1989). In contrast, increasingly widespread *ecological economics* and *industrial ecology* perspectives see waste management as a necessity to protect the life support system that provides natural, social, human and built capitals to any given community. Therefore, it is a cost that *must* be internalized in order to produce an undistorted picture of the economy (MaxNeef 1992, Constanza et al 1997, Graedel and Allenby 2003, Allen and Behmanesh 1994).

While such a fundamental change in our well-established economic systems (and most importantly in our mental paradigms) is only gradually taking place, there are several immediate economic considerations that need to be addressed in any waste management or sanitation project. The economic capacity of a community to deal with
human waste products depends primarily on its existing infrastructure and the availability of monetary capital, either from the government, international financing, locally available funds, or through private sector investment (WWAP 2006, Reynolds 2002, Biswas 2001). But it also depends on citizen’s capacity to pay for the service (Restrepo 2002, Galvis and Vargas 2002) and economic incentives that incorporate waste management within the local economy as a job generating and profitable opportunity.

Social Considerations: Governance systems and decentralization

Besides financial resources, a community’s capacity to adequately manage its waste is heavily constrained by its social organization capacity, governance structures, and the existence of an efficient and transparent administrative system, ensuring long-term viability of waste management programs and infrastructures (Bastidas and García 2002, Nunan and Satterthwaite 2001). In 1995, the World Bank estimated that an annual investment of 12,000 million USD during ten years would be required to elevate the levels of sanitation and water supply to acceptable levels in Latin America and the Caribbean (Reynolds 2002). Unfortunately, according to the UN WWD report the funding available for water and sanitation programs (from international organizations and the private sector) is declining, and only about 10% of the different types of official development assistance is actually directed to support development of water policy, planning and programs (WWAP 2006). On the other hand, the role of private investment in improving sanitation and water supply conditions remains highly controversial (for arguments in favor see Lee and Floris 2003; for arguments against see Hall and Lobina
and it usually finds strong opposition in most Latin American countries (Hall and Lobina 2002).

While privatization of water and sanitation services, has often failed to satisfy the expectations of national governments and donor countries (Nunan and Satterthwaite 2001, WWAP 2006), it has been also argued that financially strained governments with weak regulations are a poor alternative for addressing the issue of poor water resource management and inadequate supplies of water services (WWAP 2006). But the inefficiency of government structures may be an inherent failure related to the scale at which they often attempt to operate: National development strategies wrongly assume that a country is a homogeneous unity and, as a consequence, they often generate serious and harmful regional imbalances (MaxNeef 1992). Furthermore, they usually represent the interests of the dominant class. As a result, while the dominant class designs its own development strategy, the ‘invisible sectors’ are rarely benefited by private investments (Nunan and Satterthwaite 2001), and instead they are left alone to design their own ‘survival strategies’ (Max Neef 1992, Escobar 2001). Adding pressure to this situation, political corruption in Latin America costs the water sector millions of dollars every year and undermines water services, especially to the poor (WWAP 2006).

All these situations highlight the importance of governance in managing the world’s water resources and tackling poverty (Nunan and Satterthwaite 2001). Governance systems “determine who gets what water, when and how, and decide who has the right to water and related services”; and such systems are not limited to
‘government’, but include local authorities, the private sector and civil society (WWAP 2006). There is no truly effective or valid way of promoting human welfare and social justice if not through real and effective citizen’s participation (MaxNeef 1992). For instance, much of the infrastructure built for wastewater treatment in Latin America has usually operated for some time, but then deteriorated or ran into problems of poor maintenance, partly because of lack of capacity in the local institutions responsible for management and maintenance (Nunan and Satterthwaite 2001), but also due to a lack of active participation and involvement of the communities for which the systems have been built (Bastidas and García 2002, Restrepo 2002). Effective citizen’s participation and diversified regional development processes clearly constitute an important component of waste management and sanitation solutions in the region (Biswas 2001), and these can only come about as a consequence of local empowerment and decentralization (Max Neef 1992).

3. Community Self-Reliance and Multifunctional Wastewater Management

In Latin America, decentralizing tendencies started to manifest in the mid 70s in the context of globalization, technological change, market liberalization, privatization, etc. But also in the context of multiculturalism, a search for new identities, increase in poverty, increasing demands for participation coming from the civil society, a crisis of legitimacy in authoritarian and centralist political regimes, and a revitalization of the local, as a realm for pursuing a more democratic and sustainable development (Bastidas and García 2002). Although the forces that shape decentralization often times contradict
each other, at least an opportunity has been created for citizen’s participation and a more active role of the civil society in its own development processes. This opportunity can be used to enhance self-reliance of small communities in relation to a range of issues including sanitation and waste management, as it has been done to some extent in Colombia (Bastidas and García 2002, Restrepo 2002). Community involvement in sanitation projects constitutes the basis for their sustainability over time, while creating an important social fabric (Bastidas and Garcia 2002). The challenge is how to approach sanitation as a multifunctional process linking water quality, environmental protection, public health, economic opportunities and food security.

*Synergistic solutions to enhance local self-reliance and economic opportunities*

Although the chemical, physical and biological techniques to clean virtually every contaminant from human wastewaters are available to bring those waters to a safe drinking status, the costs of adequate detection and purification can be very high (Adey and Loveland 1998, Peavey et al. 1985). Existing approaches to sanitation are neither viable nor affordable to the vast majority of people. Many cities in the third world cannot access the necessary resources - water, money and institutional capacity – to provide the population with improved sanitation systems (Winblad et al 1999). Unfortunately, Third World countries, with a few exceptions, are fascinated by the temptation of following the road traced by the large industrial powers, forgetting that the only way to achieve and secure their identity and decrease their dependence, lies in promoting a creative and imaginative spirit capable of generating alternative development processes that may secure higher degrees of regional and local self-reliance (Max Neef 1992). As a
consequence, most local authorities responsible for addressing sanitation issues in Latin America, still prefer to consider mechanized and high-energy-demanding systems that are much more expensive but not necessarily more efficient than low-tech natural systems. On top of that, the cost over time of implementing high-tech ‘conventional’ systems usually ends up being 2 or 3 times higher than the initial investment (Grau 1996).

Managing wastewater [instead] as a resource in the appropriate context, can serve multiple functions, while generating economic opportunities: protein for animal feed can be produced locally (Bagnall et al 1973, Otis and Hillman 1976, Golueke 1977, Wolverton and McDonald 1977, Joseph 1978); some energy and fuel can be produced locally (Ramana and Srinivas 1997, Wolverton and McDonald 1981, Jayaweera et al 2007); money can be saved, and by replacing protein sources for animal feed, significant extensions of land currently devoted to mono-cropping, can potentially be used in a more multifunctional way, supporting the livelihoods of larger numbers of people (Sarria et al 1994, Chará et al 1999). Additionally, in situations where there are economic incentives like payment for ecosystem services, a multifunctional wastewater-recycling scheme can be a profitable activity. Productive decontamination systems installed in rural areas of Colombia to treat farm wastes have demonstrated that adequate treatment of pollutants can generate revenues (Chará et al 1999). In the same way, sewage-based aquaculture operations in India are the main source of income for many families (Jana 1998, Strauss 1996). From this perspective, instead of a sewage treatment plant, a waste treatment facility can be seen and designed as a nutrient and materials management system, or a
water-based farm with useful products and a viable economy as central to the design criteria (Kangas 2004, Todd et al 2003).

4. Case Study: Nashira, an ecological co-housing project in Colombia.

Nashira is a co-housing project, intended to support 88 low-income families in 3.2 hectares of land, collectively managed as a productive farm, in a semi-rural area of southwest Colombia. Low-income housing in Colombia, like in most Latin American countries, is usually located in marginal and unsafe areas (urban or rural), with very little or no green spaces, having difficult access to economically vibrant metropolitan areas, and frequently built with cheap –low quality– materials, and ugly alienating design. The Nashira Project is an unusual and innovative proposition for low-income housing, having community and place at the center, while offering privately owned households to its inhabitants, and economic opportunities through ecological stewardship of a collectively managed productive farm. This project was initiated three years ago by an association of single mothers and ‘women head of household’ (ASOMUCAF⁴), who have been working together for over ten years, helping each other to develop income-generating activities, and enhancing their ecological literacy through their productive enterprises.

Study Area

Nashira is located in Colombia, South America, in the rural community of El Bolo San Isidro (5 km southeast from the municipality of Palmira, 3°32’ N 76°18’ W), in the Cauca River Valley, between two of the three north-end branches of the Andes

⁴ http://www.awhf.org.co
mountainous system (Fig. 1). The Cauca Valley is one of the most productive and economically important agro-industrial regions in Colombia. Highly fertile soils offer great potential for diversified agriculture. However, sugarcane plantations dominate the landscape, and have taken over the valley’s natural wetlands and dry forests. Furthermore, over-extractive patterns of land use and poor waste management in the valley have created several environmental problems, including: water pollution in most streams and wetland systems; alterations to hydrological systems and the consequent decreasing in water availability; deforestation and soil compaction; soil erosion and salinization; and human occupation of unsafe flood-prone areas (Ramírez et al 2000). Most of the population at El Bolo San Isidro is involved in any of the main productive economic activities of the municipality of Palmira, which include: production and processing of sugarcane; production of concentrated foods; production of coffee, fruit crops, and some vegetable crops; pig, chicken and cattle raising; and manufacture industry (Pers. Comm.).
Nashira has been envisioned as an alternative model of land use and inhabitation in the low lands of the Cauca Valley, putting a strong emphasis on collective management practices to replenish biodiversity, soil fertility, water quality, and promoting community values and self-reliance, in order to enhance quality of life. This co-housing development has been designed to offer a healthy and enjoyable place to live in, and at the same time, function as an integrated farm with several productive activities, which will contribute to family-income generation. The project is currently in its third year of planning and implementation. So far, the work has been focused on setting up the production in the farm, and building up a sense of community among the 88 families, who meet every Saturday at the farm to attend workshops, discuss various maintenance and operation issues that come up, and to socialize. The productive activities already in place at the farm include: 1) horticulture (of common subsistence vegetables and herbs), 2) fruit orchards (oranges, limes, tangerines, avocados, and bananas), 3) medicinal plant gardens (currently elaborating and commercializing products from Noni fruit: *Morinda citrifolia*), 4) animal husbandry (chickens, ducks, common quails, guinea pigs, and goats), and 5) vermicompost (currently re-used in the farm, and also commercialized locally). The construction of the houses will start this year (2007), but before that can happen, Nashira must have an officially authorized plan for waste management and sewage treatment within the property.
The Community

While embracing the values of living in community and acting as stewards of their environment, Nashira is not and does not intend to be a commune. No religious belief, political ideology, or any form of idealization of ‘living in community’ unites this group of families. Their intention of living together is grounded on subsistence needs and the practicality and advantages of helping each other. Simply put, the project offers them, as low-income families with very low levels of formal education, a real alternative to acquire their own houses and significantly enhance their quality of life. This represents an unusual combination between affordable housing, cooperative work, environmental stewardship, and the ideals and principles of the co-housing model\(^5\), which is becoming increasingly popular – yet not necessarily affordable – in industrialized countries (Fenster 1999, Lloyd 2001). And as such, it also represents a social experiment, which regardless of its outcomes will serve as a model to either follow or improve.

The families that will live in Nashira come from several rural areas around El Bolo San Isidro, but also from the cities of Palmira and Cali (the two largest urban centers in the Cauca Valley). They are all low-income families, associated to ASOMUCAF’s single mothers program, and they were all selected to obtain housing subsidies from a governmental program. For three years they have attended several short courses and workshops on a variety of topics and practical skills, including: horticulture, farm animal husbandry, vermicompost, recycling, permaculture, entrepreneurship and

\(^5\) [http://www.cohousing.org](http://www.cohousing.org)
farm management. With an average of 3-4 people per household, the community will be conformed by 300-350 people.

Research Questions

In response to Nashira’s co-housing requirement to have a plan for waste management and sewage treatment before the construction of the houses can start, this case study aimed at exploring how could such a plan be incorporated as part of the farm’s collective management system, and furthermore become an economically productive activity for the community. Tropical agroecosystems offer a multifunctional space in which synergies can be used to simultaneously address issues of water pollution, soil degradation, food production and people’s livelihoods (Altieri 2002, Gliessman 1998). In this case, the basic idea was that nutrients, water and organic matter, present in domestic organic waste and sewage, can be recycled and re-used in the farm (directly or through various byproducts) to support agriculture and aquaculture operations, or to produce biofuels, while protecting the surrounding environment from untreated sewage discharges. Recycling human excreta is not a new idea, and the most important considerations for its safe practice have been relatively well documented (Winblad et al 1999; Esrey 2001; Rahman and Drangert 2001; Strauss 1990, 1991, 1996, 1998, 2001; Sawyer 2003; Heinonen-Tanski and Wijk-Sijbesma 2005). But there is still a major challenge to overcome in relation to social and psychological resistance to human waste recycling (Sawyer 2003, Illich 1985). This challenge can be addressed with clear and reliable information, open conversations, education and active involvement in concrete and localized successful projects (Sawyer et al 1998, Sawyer 2003). The main goal of this
case study was to address this challenge, and identify opportunities, economic potential, and obstacles to overcome, in implementing a multifunctional ecological system for sewage and waste management and recycling, in the particular bioregional and socio-economic context of Nashira’s co-housing project.

5. Exploring Methodologies for Community-Based Waste and Sewage Management

*Initial Exploratory Approach*

I first contacted Nashira in July 2006. Initially, I was only interested in learning more about the project, so I visited the farm regularly for a couple of months, and participated in various activities with the group, mainly as an observer. Gradually we started to build a closer relationship, and as I was working on a different research project to evaluate the use of mesocosms (Odum 1996, Kangas and Adey 1996) for sewage treatment in another rural locality in the Cauca Valley, Nashira’s project coordinators requested me to help them elaborate their own sewage and waste management plan. I proposed to have first a series of workshops with the community to start talking about waste, and explore how could waste management be optimally incorporated as a multifunctional system within the farm’s structure. The coordinators were interested in the workshops, and in September 2006 I had a first informal conversation with some of the participants, to get a sense of how the workshops could be organized, identify and prioritize topics of interest, and determine the appropriate level of depth in the

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6 Lozano, S. 2007. A Case Study on the Use of Wetland Mesocosms for Sewage Treatment in Colombia. Submitted to *Ecological Engineering*. 113
information to be presented. In December 2006 we re-established contact, and in January 2007 we had three half-day-long workshops: two informative sessions and one collective design exercise, to start envisioning the connections between the various productive activities, including the households, and closing the loops of waste production and resource use within the farm.

**Waste Management and Collective Design Workshops**

The first workshop was an introductory informative session about waste and sewage management and the concept of integrated farms, as practiced in Colombia. The goal was to introduce some basic concepts in order to start thinking about the design of a productive waste recycling system in Nashira. I used video and other audiovisual tools to present some examples of synergistic use of resources, waste management, and productive decontamination systems, in various integrated farms in the Cauca Valley (CIPAV 2006). Then we had a conversation about the concept of ‘waste’, and I introduced the concept of sewage as a mixture, primarily made of: water, organic matter, nutrients, and pathogens; and depending on the source, also containing various inorganic substances, organic pollutants, and metals (Metcalf and Eddy 1991). We discussed the importance of adequately treating sewage, and I briefly described sewage treatment as a combination of physical, biological and chemical processes that break down this mixture, by degrading, removing, or taking up its different components, so that water is cleaned up and made safe to discharge back into the environment. Lastly, I presented some examples of sewage treatment plants in rural communities of the Cauca Valley, and showed some
pictures of the experimental mesocosms for sewage treatment that I was evaluating at the
time in my own research.

The second workshop was partly another informative session, but it was much
more interactive than the first one. The goal was to elaborate an inventory of existing or
potential resources and ‘wastes’ in Nashira, and start making connections among them, in
order to integrate the various components of the farm’s system, while minimizing the
generation of non-usable ‘waste’. I first introduced the concept of ecosystem, and the
flow of matter and energy through the trophic network of producers, consumers, and
decomposers in natural ecosystems. Then we did a collective exercise of describing and
classifying the various components and productive activities of the farm (households and
humans included) as trophic groups in an ecosystem. Some of the components and
activities already existed in the farm, while others would be incorporated in the near
future. As producers we identified: horticulture gardens, fruit orchards, trees and shrubs
for animal feed, a bamboo grove, aquatic plants, plankton and algae in aquaculture ponds.
As consumers we identified: humans, chickens, ducks, common quails, guinea pigs,
goats, and fish. As decomposers we identified: vermicompost, biodigester, bacteria in
sewage treatment system, and elaboration of manufactures, crafts and various marketable
products. Stretching the analogy of the ecosystem, we discussed how the activities and
components classified as producers provide: food, medicine, oxygen, materials, and
fibers to the consumer group. The consumers, in turn, generate a series of products and
‘wastes’ that are used by the decomposers. And finally, the decomposers recycle matter
and energy, making it available again to both producers and consumers in the form of nutrients, organic matter, fuels and money (Fig. 2).

**Chapter 4 - Figure 2.** Ecological representation of the various components and activities within Nashira’s integrated farm, using the analogy of an ecosystem’s trophic structure.

Having done this exercise, we proceeded with a permaculture exercise of identifying *products* and *needs* of each component and productive operation in the farm (Hemenway 2000). The results of this exercise are summarized in Table 1. Based on the collectively identified products and needs, we started to make connections, trying to match products with needs, so that the different components of the farm complemented each other, and minimum or no waste was generated.
### Table 1a. PRODUCERS

<table>
<thead>
<tr>
<th>Horticulture</th>
<th>Fruit Orchards</th>
<th>Plants for Animal Feed</th>
<th>Aquatic Plants</th>
<th>Aquaculture Ponds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetables</td>
<td>Orange</td>
<td>Protein for animals</td>
<td>Protein for animals</td>
<td>Water</td>
</tr>
<tr>
<td>Medicine</td>
<td>Tangerine</td>
<td>Leaf litter</td>
<td>Leaf litter</td>
<td>Fiber</td>
</tr>
<tr>
<td>Healthy Food</td>
<td>Lemon</td>
<td>Nitrogen fixation</td>
<td>Water Absorption</td>
<td>Algae and plankton</td>
</tr>
<tr>
<td>Money</td>
<td>Avocado</td>
<td>Soil protection</td>
<td>Water Filtration</td>
<td>Fiber</td>
</tr>
<tr>
<td>Job</td>
<td>Mango</td>
<td>Erosion mitigation</td>
<td>Shade</td>
<td>Antibiotics</td>
</tr>
<tr>
<td>Community &amp; Learning</td>
<td>Clean Air</td>
<td>Wood</td>
<td>Leaf litter</td>
<td>Waste assimilation</td>
</tr>
<tr>
<td>Space</td>
<td>Leaf litter</td>
<td>Fiber</td>
<td>Clean Air</td>
<td>Fish habitat</td>
</tr>
<tr>
<td>Human labor</td>
<td>Wildlife Habitat</td>
<td>Shade</td>
<td>Wildlife Habitat</td>
<td>Animal protein</td>
</tr>
<tr>
<td>Weeding</td>
<td>Fresh Temperature</td>
<td>Medicine</td>
<td>Material for Crafts</td>
<td>Plant protein</td>
</tr>
<tr>
<td>Cleaning</td>
<td>Money</td>
<td>Nutrient uptake</td>
<td>Nutrient uptake</td>
<td>Heat sink</td>
</tr>
<tr>
<td>Plowing</td>
<td>Sunlight</td>
<td>Fast growth</td>
<td>Fast growth</td>
<td>Temperature and</td>
</tr>
<tr>
<td>Harvesting</td>
<td>Seeds</td>
<td>Saving money</td>
<td></td>
<td>moisture regulation</td>
</tr>
<tr>
<td></td>
<td>Soil</td>
<td>Sunlight</td>
<td></td>
<td>Wildlife habitat</td>
</tr>
<tr>
<td>Water</td>
<td>Nutrients</td>
<td>Soil</td>
<td></td>
<td>Money</td>
</tr>
<tr>
<td>Organic Matter</td>
<td>Pest control</td>
<td>Nutrients</td>
<td>Abundant Water</td>
<td>Water</td>
</tr>
<tr>
<td>Space</td>
<td>Pest control</td>
<td>Organic Matter</td>
<td>Organic Matter</td>
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</tr>
<tr>
<td>Human labor</td>
<td>Human labor</td>
<td>Nutrients</td>
<td>Space</td>
<td>Oxygen</td>
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<td>Coppicing</td>
<td>Human labor</td>
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<td>Harvesting</td>
<td>Harvesting</td>
<td>Processing</td>
<td>Coppicing</td>
<td>Good water quality</td>
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</tbody>
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### Table 1b. CONSUMERS

<table>
<thead>
<tr>
<th>Guinea Pigs</th>
<th>Ducks</th>
<th>Chickens</th>
<th>Common Quails</th>
<th>Goats</th>
<th>Fish</th>
<th>Humans</th>
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<tr>
<td>Meat</td>
<td>Meat</td>
<td>Meat</td>
<td>Meat</td>
<td>Meat</td>
<td>Meat</td>
<td>Work</td>
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<td>Eggs</td>
<td>Eggs</td>
<td>Eggs</td>
<td>Meat</td>
<td>Bones</td>
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<td>Manure</td>
<td>Feathers</td>
<td>Manure</td>
<td>Manure</td>
<td>Skin</td>
<td>Scales</td>
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<td>Urine</td>
<td>Fat</td>
<td>Sub-products for animal feed</td>
<td>Leather</td>
<td>Manure</td>
<td>Algae control</td>
<td>Organic litter</td>
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<td>Medicinal uses</td>
<td>Vitamins</td>
<td>Scavenger and foraging activity</td>
<td>Grazing activity</td>
<td>Leather</td>
<td>Aquatic plant control</td>
<td>Tools, systems and technology</td>
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<td>Money</td>
<td>Aquatic plant control</td>
<td>(= Weeding and plowing)</td>
<td>Money</td>
<td>Money</td>
<td>Mosquito larvae control</td>
<td>Construction</td>
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<td>Water movement</td>
<td>Money</td>
<td></td>
<td></td>
<td>Animal protein</td>
<td>Sense of community</td>
</tr>
<tr>
<td></td>
<td>Money</td>
<td></td>
<td></td>
<td></td>
<td>Water movement</td>
<td>Farm management</td>
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### Demands

<table>
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<th>Product</th>
<th>Demand</th>
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<td>Plant fiber and protein</td>
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<td>Fiber, grain and organic litter</td>
<td>Fiber</td>
<td>Fiber, grain and organic litter</td>
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<td>Antibiotics</td>
<td>Space &amp; Shelter</td>
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### Products

- Guinea Pigs
- Ducks
- Chickens
- Common Quails
- Goats
- Fish
- Humans
<table>
<thead>
<tr>
<th>Products</th>
<th>Vermicompost</th>
<th>Bacteria and Fungi</th>
<th>Medicinal Plant Products</th>
<th>Processed Bamboo Products</th>
<th>Recycled Paper Crafts</th>
<th>Restaurant</th>
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<tr>
<td>Organic matter</td>
<td>Organic matter</td>
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<td>Nutritional supplements</td>
<td>Wood</td>
<td>Recycling awareness</td>
<td>Organic food</td>
</tr>
<tr>
<td>Soil amendment</td>
<td>Organic waste</td>
<td>nutrients and</td>
<td>Herbal tea</td>
<td>Posts for construction</td>
<td>Marketable products</td>
<td>Community space</td>
</tr>
<tr>
<td>Protein (worms)</td>
<td>Manure</td>
<td>organic matter</td>
<td>Extracts</td>
<td>Furniture</td>
<td>Publicity about</td>
<td>Nashira’s mission</td>
</tr>
<tr>
<td>Fish and Pig food</td>
<td>Urine</td>
<td>Sewage treatment</td>
<td>Job and skill</td>
<td>Crafts</td>
<td>Nashira’s mission</td>
<td>Employment</td>
</tr>
<tr>
<td>Recycling of nutrients and organic matter</td>
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<td>Biofuel and biogas</td>
<td>Money</td>
<td>Construction material</td>
<td>Job and skill</td>
<td>Money</td>
</tr>
<tr>
<td>Ecological awareness</td>
<td>High temperature</td>
<td></td>
<td></td>
<td>Lamps</td>
<td>Market</td>
<td></td>
</tr>
<tr>
<td>Leaf litter</td>
<td>Human Labor</td>
<td></td>
<td></td>
<td>Job and skill</td>
<td>Money</td>
<td></td>
</tr>
<tr>
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<td>Worms</td>
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<td></td>
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<td>Space</td>
<td></td>
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<tr>
<td>Organic litter</td>
<td>Support media</td>
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<td>Marketing</td>
<td>Marketing</td>
<td></td>
</tr>
<tr>
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<tr>
<td>Air</td>
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<tr>
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<td>Worms</td>
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<tr>
<td>Lime</td>
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<tr>
<td>Shelter</td>
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**Table 1c. DECOMPOSERS**

<table>
<thead>
<tr>
<th>Products</th>
<th>Vermicompost</th>
<th>Bacteria and Fungi</th>
<th>Medicinal Plant Products</th>
<th>Processed Bamboo Products</th>
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<th>Restaurant</th>
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<tr>
<td>Protein (worms)</td>
<td>Manure</td>
<td>organic matter</td>
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<td>Furniture</td>
<td>Publicity about</td>
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<td>Lamps</td>
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<td>Job and skill</td>
<td>Money</td>
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<td>Manure</td>
<td>Worms</td>
<td></td>
<td></td>
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<tr>
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<tr>
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<td>Engineered environment</td>
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<td>Shelter</td>
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</tbody>
</table>

**Chapter 4 - Table 1.** Summarized results of permaculture design exercise (workshop No. 2). Members of Nashira’s co-housing project identified *needs* and *products* of the various existing and potential components of their integrated farm.

The third workshop was a design session, intended to follow up on the exercises from the second workshop. The goal was to translate into drawings and put on a scaled map of the property, all the information and ideas that had been gathered about products, needs, and connections, in the form of an integrated farm’s design, in which organic waste and sewage could be adequately managed as a resource, like in an ecosystem. We divided the group in four sub-groups, and I provided each of them with: 1) a sheet of paper (34x44 in), having a 1:250 scale drawing of the property’s contour line; 2) color markers, 3) glue; and 4) 88 square pieces of colored paper –representing the houses– also cut at 1:250 scale with respect to the actual proposed dimensions. Using these materials,
and all the information from the previous two workshops, each group had to produce a design for the spatial layout of Nashira’s *integrated farm*, including a waste and sewage management plan. This turned out to be a very ambitious exercise for the limited amount of time we had available, as the integrative design thinking and the use of spatial scale, proved very difficult to most participants. Nevertheless, each group produced a different, elaborate, and very interesting design proposal (Fig. 3). The exercise pushed them to think about integration and the spatial layout of connections and activities in the farm. But their designs not only talked about the farm; most importantly, they conveyed an impression of the heterogeneity among members of the group, and the way they think and see themselves as part of Nashira’s ecological co-housing initiative.

**Chapter 4 - Figure 3.** Four different representations of Nashira as an integrated farm supporting 88 households. Each representation was created through a collective design process by future inhabitants of the co-housing project.
For me it was also an important learning experience, and it helped me understand some language and communication challenges involved in trying to close the gap between academic theory and “real-life” practice (specifically in relation to community-based sanitation and waste management). Ecological waste and sewage management clearly requires technical knowledge and theoretical understanding of certain ecological and biochemical processes, which are difficult to grasp without a minimum level of formal academic education. So, unless that knowledge is made available to the non-expert person, ‘community-based sanitation solutions’ and ‘waste management self-reliance’ remain largely unfeasible. On the other hand, the theoretical concept of ‘community-based management’ – often idealized – has to confront the grounding reality of the community’s particular expectations, possibilities, and interests. If a community expects the government or ‘the experts’ to be the only agents responsible for waste management, there is little room for offering such a community the skills and knowledge required to manage its own waste. But if a community recognizes the importance of managing its own waste, in terms of enhancing quality of life, a collaboration between academic knowledge and the experience-based skills existing in the community, can be very fruitful. The challenge is to find a common design language, through which theoretical concepts can be simplified and intertwined with hands-on experience, so that integrative design thinking becomes a skill that is not exclusive of the expert but a contribution to community self-reliance. In the end, I realized that I had barely started a conversation, requiring follow up and continuous work to effectively begin to address the goal of a community-based sanitation and waste management plan, in Nashira, or in any other community. Only several months later I came across a social science methodology
called *Participatory Action Research (PAR)* and was able to articulate my experience as the initial stage of a PAR Cycle.

*The Participatory Action Research Cycle*

Participatory Action Research (PAR) is a well-established and versatile approach used in social sciences to address well defined ‘real-life’ problems in a community, and formulate appropriate and innovative solutions through a collaborative process involving a wide variety of stakeholders (e.g. academic researchers, members of grassroots organizations, local administrative structures, and regular citizens) (Carroll 2004). PAR is a cyclical active-learning process that involves *looking* (professional practice and research), *reflecting* (critical thinking), *acting* (developing solutions and instigating change) and *sharing* (expanding the network and impact of the proposed action) (Bacon et al 2005, Castellanet and Jordan 2002). This feedback-based cycle repeats over and over, involving the various stakeholders in an iterative manner, until appropriate solutions are effectively implemented. PAR is commonly used in Adaptive Integrated Management of natural resources and watersheds to address a variety of issues, including water pollution (Pound et al 2003, Castellanet and Jordan 2002).

Waste management design undoubtedly requires reliable technical knowledge, competency and expertise, in order to implement appropriate technological solutions. However, technical knowledge and expertise can most effectively be complemented with a PAR cycle that provides important and necessary feedback –from the potential users of the system– to develop technologies that are appropriate to the situation, from other than
technological points of view. PAR can help a community get started with its waste and sewage management plan and infrastructure, while ensuring the organizational structure and institutional support that is required for long-term viability of the proposed solutions. This kind of process is already practiced at the Cinara Institute in Colombia\(^7\), who facilitates community-based initiatives for water and waste management, in a process known as *Gestión Comunitaria* (Bastidas and García 2002).

While a completely participatory design process is not necessarily desirable, or even feasible in Nashira, establishing a PAR cycle could be an effective strategy to formulate and implement a sound plan for multifunctional waste and sewage management, which may then serve as a model for other small communities in the region. In the particular case of Nashira, the PAR cycle would also have to involve the assessment of economic opportunities in managing waste as a resource in the context of a co-housing agro-ecosystem.

6. Economic Potential

After having identified the potential feedbacks among the various farm components and activities, I tried to proceed with a more precise assessment of *products* and *demands*, in terms of quantity, required space, time, costs, and benefits from each component and activity. Much of this information was not available, since many of the proposed components and activities were not existing or operating yet, and for those

\(^7\) [http://cinara.univalle.edu.co](http://cinara.univalle.edu.co)
currently in place there were few recorded numbers. Table 2 summarizes a simplified benefit-cost analysis of five productive activities, currently operating within Nashira’s farm, for which recorded data was available.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Production</th>
<th>Costs</th>
<th>Market Price</th>
<th>Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicken meat</td>
<td>250 Kg/45d</td>
<td>50 USD (100 chicks)</td>
<td>1.5 USD/Kg</td>
<td>85 USD (in 45 days) 690 USD/year</td>
</tr>
<tr>
<td></td>
<td>240 USD (45d commercial feed)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guinea pigs</td>
<td>36 Kg/12 weeks</td>
<td>170 USD (concentrated food)</td>
<td>5 USD/Kg</td>
<td>10 USD (in 12 weeks) 40 USD/year</td>
</tr>
<tr>
<td>Common Quail Eggs</td>
<td>120 eggs/d</td>
<td>75 USD (150 quails/yr)</td>
<td>0.42 USD/dozen</td>
<td>1,093 USD/year</td>
</tr>
<tr>
<td>Tangerines</td>
<td>500 Kg/week</td>
<td>0</td>
<td>0.12 USD/Kg</td>
<td>1200 - 1500 USD/yr (depending on season yield)</td>
</tr>
<tr>
<td>Vermicompost</td>
<td>20 sacs/4 months</td>
<td>15 USD/4 months (cow manure)</td>
<td>12.5 USD/sac</td>
<td>700 USD/yr</td>
</tr>
</tbody>
</table>

**Market price References:**
- Chickens: [http://sisav.valledelcauca.gov.co](http://sisav.valledelcauca.gov.co)
- Guinea Pigs: [http://www.consumaseguridad.com](http://www.consumaseguridad.com)
- Common Quails: Pers.Comm
- Tangerines: Pers.Comm
- Vermicompost: Pers.Comm

**Chapter 4 - Table 2.** Benefit-Cost Analysis of five productive activities currently operating at Nashira Eco-Farm

A common claim among workshop participants was that the return on investment in animal husbandry within the farm was largely undermined by the cost of commercial/concentrate animal feed (Table 2). Commercial animal feed is usually made from soy-based products in order to supply their protein demands. This is a tendency that originates from agricultural practices in temperate regions, where soy cultivation is heavily subsidized; occupies extensive areas of land; and represents a relatively cheap source of protein. In the tropics however, there are many shrubs, trees and aquatic plants that have a significantly higher protein content and better protein quality than soy; can be
grown in relatively small extensions of land; and can be successfully used to supply
animal protein demands at a lower cost (Sarria et al 1994, Chará et al 1999, Reddy and
DeBusk 1985, Oron 1994). Furthermore, most of these aquatic plants can be used to treat
sewage and decontaminate polluted water, by effectively removing organic matter,
nutrients, pathogens and even metals from wastewaters, particularly in tropical and
subtropical regions (Wolverton and McDonald 1977, Golueke 1977, Joseph 1978,

In Colombia for example, from 1ha (10,000 m²) cultivated with soy, a farmer can
obtain the amount of protein necessary to produce 4,880 Kg of live pig weight (74 pigs).
If 30% of the soy-based feed is replaced with aquatic plants, the same 74 pigs (4,880 Kg)
can be produced at a considerably lower cost, and 0.3 hectares (ca 3000 m²) of soy
plantation could be liberated for other land uses (Sarria et al 1994, Chará et al 1999).
1,465 out of the 4,880 Kg of live pig weight could be produced from 420 Kg of protein
from aquatic plants, which could be grown in only 467 m² of marginal tropical lands,
leaving 2533 m² (of the 3000 m² liberated) of first quality land, available for human food
production, forest regeneration, watershed protection, or a more multifunctional land use
pattern like agroforestry, which in addition to all the above could also enhance the

Along the same lines, if only 30% of the animal feed in Nashira is replaced with
protein-rich shrubs, trees, and aquatic plants –which can be grown within the farm at a
negligible cost, while contributing to treat sewage and digest organic wastes– the
production of chickens and guinea pigs, could save a significant amount of money: according to the numbers provided by Nashira members, revenues from chicken meat could double in amount, from 690 USD/yr to 1,320 USD/yr; and guinea pig production could have seven times more revenues than it currently does (from 40 USD/yr to 280 USD/yr) (see Table 2). On the other hand, using fast-growing aquatic plants for sewage treatment can also provide significant additional volumes of nutrient-rich organic matter for compost production, thereby increasing the revenues from selling compost in the local market. This type of economic incentives may prove extremely effective in motivating a multifunctional management and recycling of sewage and organic wastes, especially in the context of a tropical agro-ecosystem, such as the one that is being developed at Nashira, where feedbacks to close waste-production loops can be easily established.

It is important then to be capable of making simple calculations to determine required quantities and space areas of each farm component and activity, in order to optimize their benefit-cost relationships. Making these calculations requires data collection and a minimum of mathematical literacy. But, while simple math and good communication skills should be enough to make the required calculations, and make the economic benefits easy to understand, there are more sophisticated tools that can be very useful from an ecological designer’s point of view, in order to propose a sound and economically beneficial plan for waste management and recycling: Leontief’s input-output model is one of such tools.
Economic input-output analysis

Input-output models represent the interdependencies and connections between different sectors of an economy, and serve to quantitatively analyze how each sector’s products feed into all other sectors, and how each sector’s demands are supplied, to a different extent, by the products offered by all the other sectors (Leontief 1986). This type of analysis has been used in industrial life cycle assessment and waste production analysis (Hendrickson et al 1998); water consumption and water pollutants discharge (Okadera et al 2006, Velázquez 2006); and linking economic and ecological models of natural ecosystems (Jin et al 2003).

In the context of an agro-ecosystem like Nashira, input-output analysis can be used to determine required inputs on each activity and component (quantifiable as specific amounts, monetary value, and area units), in order to optimize the farm’s economic outputs, while sustaining the entire productive system over time. Table 3 is a qualitative input-output matrix representing the potentially quantifiable connections and feedbacks among all the components and activities within Nashira’s integrated farm, including sewage and organic waste production (most of these connections were collectively proposed during the workshops, and detailed in table 1).

Quantifying these connections and feedbacks requires a significant amount of information and considerable effort to gather the necessary data. This makes the use of input-output analysis somewhat difficult, but at the same time, this type of analysis provides a powerful and comprehensive tool, available to the ecological designer in
making a thorough economic-potential assessment of multifunctional waste management plans. Making this information available and intelligible to communities with predominantly low levels of formal academic education, such as most rural communities in Latin America, would be a very important step to consolidate community-based sanitation and waste management plans in ways that are economically stimulating, and therefore feasibly replicated in the region.

Chapter 4 - Table 3. Qualitative input-output matrix illustrating connections and resource/waste flow among Nashira’s productive activities and inhabitants. ‘+’ denotes significant and monetarily measurable input from each farm component (in rows) into all the other components (in columns). ‘*’ show the components having a final demand outside the farm.
7. People’s perceptions, expectations and preferences

While the families taking part of Nashira’s co-housing project share various common characteristics, the community is still a heterogeneous pool of different mentalities, beliefs, intellectual and ideological backgrounds. In order to explore this heterogeneity, in relation to waste management issues and the potential for having a multifunctional system for sewage and organic waste recycling within Nashira’s farm, a survey was designed and implemented four months after the workshops had been completed. The survey was designed to inquire about perceptions, expectations and preferences related to waste and sewage management. Three types of questions conformed the questionnaires: 1) multiple choice, to choose only one answer; 2) multiple choice, to rank all possible answers according to personal preferences; and 3) open questions. Some of the questions were somewhat repeating, but taking different forms in order to detect inconsistencies in the responses and opinions.

According to the responses from 63 survey respondents, the prevalent attitude towards waste among Nashirans, was one of responsibility. Most respondents identified wastewater as a potentially valuable resource, and found wastewater recycling to be an acceptable practice, if done properly. The majority would also agree to implement a system to treat and recycle wastewater within Nashira’s farm (Fig 4).
Chapter 4 - Figure 4. Survey results summary.

Note: (Question 6) different shades in the bars represent the ranking position (1-4); and the proportion of each shade within each bar represents the percentage of surveyed population matching each ranking value to each answer option. The same applies to question 7, but instead of ranking 1-4, each shade represents: ‘yes’, ‘no’, or ‘no answer’ options.
However some inconsistencies were detected when comparing responses to different forms of the same question. When given multiple-choice questions with only one possible answer, most respondents tended to choose the “right answer” (the one I presumably wanted to hear), but when asked to rank several possible answers, or to write their own answers to open questions, different opinions emerged. For instance, when asked if they would agree with treating sewage within the farm using aquatic plants, which would then be used as animal feed (question 5, Fig 4), most respondents agreed with the idea (Fig 4), but when asked about their preferred alternative for dealing with sewage (question 6, Fig 4) most respondents preferred to either export it, or treat it within the farm without reusing it (Fig 4); the alternatives of recycling sewage within the farm, or using composting toilets in order to avoid producing sewage in the first place, were ranked only as the third option by the majority of respondents, while just a few chose either of those options as their first alternative (Fig 4). On the other hand, when asked about alternative options for recycled wastewater use within the farm (question 7, Fig 4) most respondents agreed with basically every option offered to them (Fig 4).

Responses to open questions provided more insights about the respondent’s genuine opinions and perceptions. The first open question asked for further explanation about the ranking choices made in relation to alternative options to manage Nashira’s sewage (question 6, Fig 4). Looking at the responses to question 6, there seemed to be an almost even opinion split between exporting the sewage and treating it within the farm, without reusing it. However, in answering the open question to further explain their ranking choices, most respondents clearly expressed a sense of responsibility and a strong
ethical position about dealing with their own waste. On the other hand, most respondents also manifested a concern about the health risks associated with treating and recycling sewage within the farm. Finally, while some respondents were enthusiastic about composting toilets, seeing them as an all-encompassing integral solution to the problem of sanitation and water recycling, most respondents declared having a lack of understanding or sufficient information about this kind of toilets, and therefore did not trust them.

The second open question asked them how would they recycle wastewaters in Nashira. Most respondents said they would reuse treated wastewater in irrigation systems within the farm. Only a few respondents manifested an opposition to the idea of recycling wastewater within the farm, and some proposed recycling in aquaculture ponds. Nobody mentioned the recycling of nutrients and organic matter. Finally, the third open question asked, in the hypothetical scenario that the community of Nashira decided to treat their own wastewaters within the farm, if they would participate in the operation and maintenance of the proposed system. With only a few exceptions, most respondents answered affirmatively, and their main motivations were: 1) a strong sense of collective well-being, mutual support, and a sense of responsibility to help enhance the life quality of the entire community; 2) the desire to learn, make sure waste is properly managed, and understand and supervise all the processes within the farm; 3) protection of their environment; and 4) economic benefits.
8. Conclusions: Opportunities and Challenges

Integrating ecological design and community-based approaches to waste management and sanitation solutions may prove to be an effective strategy to tackle sanitation and pollution problems, while enhancing people’s livelihoods and economic opportunities, in rural areas of Latin America. Such integration offers several opportunities and challenges that need to be balanced out. Some of the opportunities include: low cost alternatives for waste and sewage treatment; economic potential of a multifunctional waste management scheme; recycling of nutrients and organic matter, to restore soils, protect water, and support productive agriculture and aquaculture systems; and last but not least – on an educational level – using successful examples of eco-mimicry to convey the powerful message, that through waste recycling, it is possible to reconcile human systems, infrastructures, and activities, with the planet’s life-support dynamics. Challenges include: the need to rely on ecological and economic literacy; the social organization capacity and governance structures of communities; the financial capacity and economic opportunities; public health risks associated with manipulating human excreta; and the social and psychological resistance to the idea of recycling human waste.

The various forms of resistance to the idea of recycling human waste can be overcome with clear and reliable information, open conversations, education, and active involvement in concrete and localized successful projects. Economic incentives are also crucial in motivating a multifunctional management and recycling of sewage and organic
wastes, especially in the context of tropical agro-ecosystems, where feedbacks to close waste-production loops can be easily established.

Acknowledgements

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