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New Paradigms: "Wastewater Gardens", creating urban oases and greenbelts by productive use of the nutrients and water in domestic sewage

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Introduction

Humans have created two "anthropocentric biomes": cities and agricultural systems increasingly important in their impact on global biospheric processes (Allen, 1991). Making these newer ecosystems more sustainable should be a parallel and equally important task as the preservation of "natural" biomes (rainforests, coral reefs, etc.). The two anthropogenic biomes are intricately linked, most obviously in the movement of food from the farms and ranches to support urban populations. Yet this "nutrient export" is not returned to its source, and the treatment of the wastewater following water use in cities is very expensive, and discharge of treated and untreated sewage is a leading source of environmental pollution in aquatic and marine ecosystems. A first step in changing our approach to the "waste products" of our cities is to change our thinking, and to recognize wastewater as a valuable resource if properly utilized. The existing paradigm is to focus on the disease potential of domestic sewage and to expend considerable resources to remove it from residential areas to centralized locations where it can be "de-toxified." The wastewater is then typically chlorinated and then discharged into river or ocean waters for final dilution and absorption in the environment. The results have been enormous capital and maintenance costs in pumping and treating wastewater and environmental pollution caused by the discharge of large amounts of sewage into ecosystems that cannot productively process the nutrients remaining in the treated effluent.

The prevailing strategy of the indiscriminate mixing of all residential with industrial/commercial wastewater in urban environments also needs to be rethought. The mixing of industrial with domestic wastewater has led to the very costly and difficult issue of dealing with sludge disposal/reuse since industrial wastewater can contain harmful quantities of heavy metals, complex organochlorides and other environmentally harmful contaminants. In the context of new thinking to make our cities' infrastructure more sustainable, the current policy of not separating industrial from domestic wastewater must be challenged, and its hidden costs highlighted.

A new approach, using constructed wetlands, has been gaining momentum over the past decade that demonstrates that beneficial use of the water and nutrients contained in domestic wastewater can be implemented while safeguarding the public from accidental contact with the wastewater. These ecologically engineered systems, including the subsurface flow, highly biodiverse "Wastewater Gardens™" approach, enhance landscape beauty and are a way of sustainably greening urban areas by utilization of the renewable natural resources now exported at high expense. This approach also leads to increase of biological and landscape diversity, the establishment of useful vegetation (for domestic use or commercial sale) and can be used to increase wildlife-habitat around the human dwellings, or to create green belts in urban areas.

From Prevention of Disease to Reuse of Water and Nutrients

The recycling of nutrients is central to the challenge of transforming human economic activities in Earth's vaster biospheric life support system to a sustainable basis. Sewage treatment should do far more than simply preventing pollution and the degradation of natural ecosystems occasioned by the incomplete treatment and discharge of wastewater. Wastewater treatment should also accomplish the return of nutrients and water to productive use. An important development of the past few decades has been the use of natural and constructed wetlands for the treatment of domestic sewage and industrial wastewater (Reed et al., 1995, Kadlec and Knight 1996).

There has been increasing interest in using wetlands as interface ecosystems for wastewater treatment since early studies demonstrated their effectiveness at removal of nutrients and suspended solids. These included use of cypress swamps in Florida (Odum et al., 1977; Ewel and Odum, 1984) and peatlands in northern Michigan (Kadlec and Knight, 1996). Constructed wetlands using surface-flow or subsurface flow emergent vegetation or aquatic plant systems have gained increasing acceptance (Hammer, 1989; Mitsch and Gosselink, 1993; Reed et al, 1995). Since such natural or constructed wetlands are often limited by solar insolation and show increased rates of uptake in warmer climates, such systems may be expected to operate even more efficiently in milder Mediterranean, subtropical and tropical regions than in the continental US and northern European conditions where they were first developed.

There are three basic types of wetlands for wastewater treatment: surface flow wetlands, subsurface flow wetlands and aquatic plant wetlands. In surface flow wetlands, the wastewater runs through a shallow basin in contact with the underlying sediment. Both emergent (rooted) and floating plants can be used. In subsurface flow wetlands, the wastewater is kept below the surface of the wetland medium, generally gravel. Only emergent wetland vegetation can be used. Aquatic plant treatment systems utilize open bodies of water and can thus support only floating wetland vegetation. However, aquatic plant systems have declined in popularity due to poorer performance and necessity and costs of removing low-value vegetation (Bagnall et al, 1987, Reed et al, 1995, Kadlec and Knight, 1996). Surface flow wetlands require substantially more area than subsurface flow wetlands; This is because wastewater flows over and only contacts the top layer of the sediment whereas subsurface flow wetlands are designed to make the wastewater flow through the entire volume of the gravel substrate. This allows the surface area of each piece of gravel in a subsurface system to be colonized by microorganisms and to provide wastewater filtration, sedimentation and microbial interaction. For example, an informal "rule of thumb" in wetland design is that surface flow wetlands might require about 100 hectares (250 acres) for treatment of four million litres (one million gallons)/day wastewater loading, while a subsurface flow wetland might only require around 10 hectares (25 acres) for comparable treatment. Surface flow wetlands also have a potential for malodour, mosquito-breeding and accidental public contact because of the exposure of sewage water.

Numerous studies of subsurface flow wetlands for sewage treatment have demonstrated their advantages in situations of small on-site sewage loading, in areas where land is scarce, and in situations where avoidance of malodor and mosquito-breeding are important (EPA, 1993). A well-designed subsurface flow wetland also can provide inexpensive but highly effective sewage treatment. As is the case in the U.S. and Europe where this approach is rapidly spreading, the advantages of constructed wetlands are that because they rely on more natural methods, they are less expensive to build and operate than conventional sewage treatment plants. They can also produce a standard of treatment comparable or better than conventional secondary wastewater treatment (TVA, 1993, EPA 1993). A typical "package plant" or municipal sewage plant requires high capital investment, technical expertise and is energy-intensive to operate. Subsurface wetlands use little or no electricity and technology and require little technical supervision once installed (Green and Upton, 1992, Cooper, 1992 Steiner et al, 1992, Nelson, 1998a). Constructed wetlands use far more local and renewable resources than conventional sewage treatment. By using local resources rather than importing industrial products, in-situ utilization of the resources contained in wastewater in constructed wetlands is more conducive to sustainable economic enrichment (Odum, 1996, Nelson et al, 2001).

Experience in Developing Sustainable Treatment Wetlands

The authors' experience with constructed wetlands began in the late 1980s with the system developed for Biosphere 2, the large closed ecological system experimental facility in Arizona. Biosphere 2 was the first closed ecological system that was designed for recycling of all human waste products. In

Biosphere 2, the wastewater system functioned as part of the sustainable food production system through the production of forage for domestic animals, and by the utilization of excess nutrients remaining in the wastewater effluent for crop irrigation (Nelson, et al, 1994). The Biosphere 2 wastewater recycling system employed a two-stage process that began with anaerobic digestion in sealed holding tanks. Next the wastewater was passed for final treatment to a surface flow wetland (marsh) system.

The constructed surface flow wetland totaled 41 m^2 of surface area with emergent and floating plants and produced a total of 720 kg, dry weight, of emergent vegetation and 493 kg, dry weight, of floating vegetation during the two-year experiment. Fourteen plant species composed the primary autotrophic level in the wetland system. The constructed wetland system supported floating (aquatic) and emergent (rooted) wetland species. The aquatic plants colonized open-water channels and the emergents utilized upland soil areas in the wetland. The wetland system was housed in several fiberglass tanks and submersible pumps maintained water recirculation between tanks. Loading to the system was on a batch basis after the primary settling tanks became full. The system served as habitat for beneficial insects (e.g. “lady bugs”) and animals (such as the Colorado cane toad) within the Biosphere 2 agricultural biome (Nelson et al, 1999).

Following the Biosphere 2 experience, further development resulted in the development of a high biodiversity, subsurface flow approach, termed “Wastewater Gardens™” as a more effective approach. Locally available plants adapted to wetland conditions are selected to make a diverse and beautiful ecosystem. Even small systems may support 30-50 species of plants. The biodiversity indexes of some Wastewater Garden systems studied in Mexico were comparable to tropical forest systems and greater than many natural wetlands (Nelson, 1998a, b). Everything that is above the dry gravel is hygienic and safe to use, since there is no transmission path for pathogenic bacteria. For example, the fruits grown in Wastewater Gardens can be safely eaten by humans, fodder crops can be grown for animal food or trees grown for timber or fuel wood production (Nelson, 1995).

The system works by a gravity flow of wastewater from toilets, showers, and kitchens into properly designed and sealed septic tanks and then into specially designed, subsurface flow wetland cells. The gravel allows for adequate residence time for the wastewater and provides an enormous surface area where a wide variety of chemical, biological and physical mechanisms cleanse the wastewater by removing organic compounds, suspended solids and excess nutrients. The plants serve as aerators, pumping oxygen into their rhizosphere, thus allowing the wetlands to support both anaerobic and aerobic beneficial bacteria, enhancing wastewater use and purification.

In 1996, these systems were installed along the calcareous coastline of the eastern Yucatan peninsula. The challenge was to develop appropriate ecological interface systems to prevent human sewage from damaging coral reefs through eutrophication (Pastorok and Bilyard, 1985) and improve public health by preventing contamination of groundwater supplies, a leading cause of ill health in developing countries (U.N., 1995). Studies in geologically similar limestone coastlines (e.g., the Florida Keys and Caribbean islands such as Jamaica) have indicated that they are especially susceptible to eutrophication. Septic tank effluent flows rapidly through porous calcareous strata and does not allow sufficient retention time nor provide adequate soil sediments for microbial decomposition and plant uptake

. An area of 3-4 m^2 of Wastewater Garden per full-time resident proved capable of removing over 85% of BOD, between 75-80% of nitrogen and phosphorus were removed, and fecal coliform bacteria was reduced 99.8% without use of chemicals (Table 1). Two “Wastewater Gardens” covering 130 m^2 served to treat the black (toilet) and graywater (kitchen, shower, sinks) of 40 residents, and supported 65-70 varieties of wetland plants. Plant biodiversity was three times greater than in adjoining natural mangrove wetlands, and only 5% less than in the inland tropical forest areas (Nelson, 1998a and 1998b).

In the years since this research, the authors working with Planetary Coral Reef Foundation (www.pcrf.org) have implemented over many “Wastewater Gardens” in Mexico, Belize, the Bahamas, the United States, Europe, and Bali, Indonesia and in West Australia (e.g. Figure 2, more information/photos available at www.pcrf.org\wwg.htm). Recent results to date from the first pilot system in northern West Australia show effective treatment is being achieved (Table 2, Figure 3).

Advantages of High Plant Diversity in the Constructed Wetlands

Sewage treatment systems must be low-tech, low maintenance and minimal in their energy requirements to be affordable and practicable in developing countries, attributes which wetland systems exemplify. Natural and constructed wetlands rely on solar insolation as a main driving energy, and warmer climates improve treatment rates (8). Therefore, wetland treatment systems may be expected to operate more effectively in subtropical and tropical regions, or in arid regions with high solar insolation. In addition, wastewater interface ecosystems may benefit from the high species diversity found in tropical regions since diversity at the biotic and metabolic level increases the buffering capacity of ecosystems (Jorgensen and Mitsch, 1991). Allowing self-organization of plant, animal and microbial biota to develop cooperative mechanisms may develop better-adapted ecosystems to handle pollution and toxicity (Odum, 1991).

Plant diversity may benefit wastewater treatment by providing 1/ greater variety of root systems, allowing for greater penetration of the limestone gravel and supporting a wider range of associated microorganisms; 2/differing metabolic needs (e.g. nutrient uptake) may lead to greater capacity for absorbing wastewater constituents; 3/differing seasonal cycles of activity which may increase plant productivity year-round; 4/ greater ability to utilize the full spectrum of incident solar radiation by the inclusion of shade-tolerant as well as top canopy species and 5/ differing "specialist" capabilities (e.g. C_3 and C_4 photosynthetic pathways, or quantity of aerenchyma tissue in saturated conditions) allowing for greater system response to changing environmental conditions such as light, heat, and nutrient levels. Greater diversity also buffers against system failure should disease or herbivory decimate selected plant species in the constructed wetland.

Comparison of the Wastewater Garden Approach with Other Treatment Options

Wastewater Gardens™ are relatively low in cost, and low in requirements for imported goods and electricity as are other low-tech approaches such as use of surface flow wetlands and aerated lagoons. However, aerated lagoons and surface flow wetlands may not be suitable for use in regions with highly permeable soils or high water tables unless built with impermeable liners, as otherwise wastewater will be released to the environment before adequate treatment is effected.

Conventional sewage treatment plants are very capital-intensive. Three-quarters of overall costs are involved in the pumping required to move raw sewage to the centralized sewage plant (Southwest Wetland Group, 1995). Much of the cost for conventional sewage treatment is for purchased goods, which originates outside the region and frequently is imported in third world countries. Operation and maintenance costs are high, since such facilities require highly trained technicians and engineers. For example, our studies have shown that the Mexican Wastewater Gardens were one-third the per capita capital cost of a conventional sewage treatment plant at the University of Florida and operating/maintenance costs at $27/person/year are nine times higher (Nelson, 1998a, Nelson et al, 2001)

Electrical costs and maintenance are high for conventional sewage treatment plants since much of the system process relies on machinery. Maintenance and operation is also a problem in developing countries because of the lack of skilled operators, the high cost of imported machinery and parts, and the frequently more demanding climatic and environmental conditions. Treatment by high-tech sewage treatment plants decreases over time with poor maintenance of equipment and inadequate technical supervision (Reed et. al., 1995).

In addition, conventional treatment systems and package plants are designed to achieve secondary treatment standards (<30 mg/l of biochemical oxygen demand and total suspended solids), which may be inadequate for preventing eutrophication of marine and terrestrial environments. Large amounts of sludge are produced, which are difficult to dispose/use in a responsible manner.

Shallow-well injection following septic tank residence is low cost, but not very effective in reduction of organic compounds, nutrients or coliform bacteria or in preventing their impact on sensitive coastal marine ecosystems. Septic tank residence, with adequate holding time, only reduces influent BOD <50% (TVA, 1993). Wastes in partially treated wastewater are likely to accumulate in the groundwater or affect river, lake or coastal waters. In the Florida Keys, sewage injected into shallow wells on land was found less than one mile away in offshore waters (Shinn et al, 1992).

Aquatic plant treatment systems (Wolverton, 1987) and surface flow wetlands have the advantages of being low cost to build and operate, and have been applied in many ecosystems and climatic zones, using locally available wetland species. They often are designed for secondary/tertiary wastewater treatment, with lagoons or other settling devices accomplishing primary treatment before release of the wastewater. However, surface flow wetlands require more area than subsurface wetlands. This is because subsurface flow wetlands are designed to make the wastewater flow through the entire volume of their gravel substrate, as contrasted with surface flow wetlands where wastewater flows over the top of the soil bed. The cost of the medium (generally gravel) and liners usually makes the cost per area more for constructing subsurface flow wetlands, but this is offset by the smaller area and heavier loading that such systems receive. Thus subsurface wetlands are usually less expensive than aquatic plant systems or surface flow wetlands (TVA, 1993, Reed et al., 1995).

There may be applications where use of several approaches can be usefully combined. For example, in some constructed wetland systems, ponds have been used rather than septic tanks as the primary treatment stage to reduce construction costs. Constructed wetlands have also been used following conventional treatment or package plants to increase nutrient recycling and produce higher quality effluent water.

Environmental protection regulations in the Australia, Europe and the U.S. have made it more difficult to obtain permits for the use of natural wetlands for sewage treatment or disposal, despite the fact that there are numerous examples of successful historical and recent use of natural wetlands for this purpose. In addition, some wetlands with a relatively open hydrology are unsuitable as a primary mechanism of sewage treatment. However, these wetlands often have a substantial organic soil component, and as such they function as natural bio-filters. Perhaps the most appropriate use of such wetlands is as a final step in sewage treatment following primary and secondary treatment, such as was done with mangrove peat soils for some of the Mexican Wastewater Gardens (Nelson, 1998a, Nelson, 1998b). In developing countries, where wetlands are not well protected and are coming under increasing pressure for conversion, such use may assist in their preservation and utilization.

In contrast to conventional sewage treatment, constructed wetland approaches result in direct utilization of water and nutrients in the normally "waste"water for supporting plant growth and potentially producing beauty and utility as well. In addition, they prevent the downstream pollution effects caused by centralized sewage discharge. The increasing scarcity and cost of potable water should dictate against continuing to use potable water quality for irrigation of residential and urban landscapes. Such use often accounts for 2/3 or more of total residential water use (Tchobanglous, 1991). Correctly designed constructed wetlands and graywater recycling systems can be utilized for irrigation and creating green areas with conservation of potable water and better result (since they add "fertilizers" as well as water).

The Problems of Mixing Industrial and Residential Wastewater

One of the current practices that make adoption of constructed wetlands in urban environments difficult is the indiscriminate mixing of residential with commercial and industrial wastewater.

The nature of sewage sludge depends on the wastewater treatment process and on the source of the sewage. It can contain not only organic and inorganic matter, but also bacteria and virus, oil and grease, nutrients such as nitrogen and phosphorus, heavy metals and organochlorides. Some of the common hazards worldwide concerning the disposal of sludge relates not to the common constituents of residential or hotel wastewater, but to more toxic constituents which are primarily found in industrial and manufacturing wastewater. These substances include heavy metals, complex synthetic or organic compounds such as organochlorides and dioxins. These substances are both expensive to test since sludge varies in makeup over time; and pose hazards if disposed to land or ocean. Incineration is both energy consuming and expensive and can result in significant air pollution unless additional measures are taken which also increase costs.

Table 3 summarizes the standards currently being used by some countries regulating the maximum concentration of heavy metals in sludge used for land application. Some research on the buildup of such metals in the soil over time and their potential transmission through the food chain to plants, animals and people, but much remains to be learned about the extent of the hazard. The complexity of the subject is indicated guidelines such as those in effect in the United Kingdom where allowable concentration of heavy metals in the soil that has received sewage sludge, and maximum amounts of sludge that can then be applied annually both vary depending on soil pH. More research will be required to ascertain the rates of buildup in other soils and climatic conditions around the world.

These considerations suggest the advisability as a policy measure of avoiding the problem that is now, in the more developed countries, so intractable and expensive to remedy. This can be done by not mixing industrial and other wastewater together so that the concern about such toxic compounds can be avoided. Industrial and manufacturing wastewater poses different challenges from ordinary wastewater, and the problem can be confined, and the quantities of such materials greatly reduced, by treating such wastewater and sludge separately. It is also more equitable, and reflects a currently hidden cost of manufacturing processes that release potentially toxic elements, to require the industry to bear the costs of treating these wastes. This change of policy can be expected to also encourage market mechanisms that promote innovation and change of industrial/manufacturing practice to switch to less toxic options, and to encourage internal recycling and reuse of those compounds which cost more to detoxify.

By contrast, domestic wastewater sludge, since its major “impurities” are in fact valuable nutrients such as nitrogen and phosphorus, can be both effectively treated and reduced in volume in constructed wetlands (Reed et al, 1995, Kadlec and Knight, 1996) or composted to produce a valuable soil amendment (Tchobanglous, G., 1991). The return of nutrients from the urban areas to the soils of the agricultural areas from whence our foods derive is how the nutrient cycle would be most completely closed. Returning nutrient-laden wastewater is difficult and prohibitively expensive except to areas quite close to the urban populations. However, the sludge from the wastewater is a more compact product for shipping, and the return of such soil-building residues to the rural, food-producing soils would be another important step in maintaining the health and fertility of farm soils. To make this “export” from city to country feasible is another important reason to encourage the separation of residential from industrial wastewater. The safe return of this organic sludge to the agricultural soils will be seen in the future as another obvious step in the move towards sustainability of both anthropocentric biomes: city and agroecosystem with side effects of lessening dependence on chemical fertilizers and reducing energy consumption and pollution from fertilizer runoff and sewage disposal practices. Increasing the health of the anthropogenic biomes will reduce some of the stress currently placed on natural ecosystems.

Conclusion

The transition to sustainability in the urban ecosystem will require the development of ecological engineering solutions to the recycle and reuse of resources that are currently squandered. Ecological engineering, a new emerging discipline, seeks a symbiotic mix of man-made and ecological self-design that maximizes productive work of the entire system (including the human economy and the larger-scale environmental system). Allowing this process to self-organize may develop better adapted ecosystems that prevail because of their greater empower (Odum, 1994). By minimizing human manipulation the use of machinery, ecological engineering solutions aim to increase material recycling, enhance efficiency, reduce costs and maximize the contributions of ecological processes in the total system.

An important application of ecological engineering is the design of interface ecosystems, such as constructed wetland sewage treatment systems, to handle byproducts of the human economy and to maximize the performance of both the human economy and natural ecosystems (Mitsch and Jorgensen, 1991).

There is an urgent need around the world, but especially in tropical and developing countries for low-cost, low-tech solutions that employ natural systems to solve environmental challenges. New types of cultural landscapes can be created using the resources that are currently thrown away. In doing so, there is enormous potential for the creation of green urban oases: creating beauty, wildlife habitat, healing landscapes and generating useful products from the water and nutrients currently misnamed “wastewater”.

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Table 1. Comparison of removal efficiency and loading of Wastewater Garden subsurface flow systems with average North American surface and subsurface flow wetlands (Nelson, 1998a, Kadlec and Knight, 1996).

Parameter	Wetland system	In Mg/l	Out Mg/l	Removal %	Loading Kg/ha/d
BOD (Biochemical oxygen demand)	Surface flow	30.3	8.0	74	7.2
	Subsurface flow	27.5	8.6	69	29.2
	Wastewater Garden	145	17.6	87.9	32.1
Total Phosphorus	Surface flow	3.78	1.62	57	0.5
	Subsurface flow	4.41	2.97	32	5.14
	Wastewater Garden	8.05	1.9	76.4	1.7
Total Nitrogen	Surface flow	9.03	4.27	53	1.94
	Subsurface flow	18.92	8.41	56	13.19
	Wastewater Garden	47.6	10.0	79	10.3

In addition, there was a 99.8% reduction in coliform bacteria without using chlorine or other disinfectants.

Table 2. Results from the pilot program Wastewater Gardens at Birdwood Downs homestead, Derby, West Australia, September 2000 – December 2001.

Parameter	BOD-5 (Biochemical Oxygen Demand) mg/l	Total Suspended Solids(TSS) mg/l	Total Nitrogen Mg/l	Total Phosphorus mg/l	Total Coliform Bacteria Cfu/100 ml
Septic Tank	256	351	44	10.2	6,285,000

Wastewater Garden ™ discharge	12.5	19	25.6	7	116,000
Percent reduction	95%	95%	42%	32%	98.2%

Note: If nutrient reductions are presented on a mass flow basis (that is accounting for evapotranspiration of water in the Wastewater Garden which averaged 20% yearly), the total reduction in Nitrogen is 53%, and total reduction of Phosphorus is 45%. There are no requirements for nutrient levels at this installation, which is classified as residential on-site treatment. Increased nutrient reduction can be achieved with larger sizing per resident and modifications to system design.

Table 3: Maximum permitted concentrations of heavy metals in sewage sludge used for land application. (mg/kg dry solids) Source: Department of the Environment, United Kingdom(1989)

	Netherlands	France	Sweden	Japan	Australia New South Wales
Arsenic As	10	--	--	50	15
Mercury Hg	5	10	8	2	10
Cadmium Cd	5	40	15	5	8-20
Chromium Cr	500	1,000	1,000	--	500
Lead Pb	500	800	300	--	500
Nickel Ni	100	200	500	--	100
Zinc Zn	2,000	3,000	10,000	--	1,800
Copper Cu	600	1,000	3,000	--	1,200