1 Introduction

1.1 Closing nutrient and water cycles

Paradigm shift

The world is experiencing rapid growth in urbanisation and industrialisation. The pace, depth, and magnitude of these changes, while bringing about benefits to local people, have exerted severe ecological stresses on both local human living conditions and regional life support ecosystem. Urban sustainability can only be assured with a human ecological understanding of the complex interactions among environmental, economic, political, and social-cultural factors and with careful design, planning and management grounded on ecological principles (WCED, 1987; Mansson, 1992; Van der Ryn & Cowan, 1996). The city, with its water, wastewater and other infrastructures, sits within an industrial-urbanised ecology of individual entities arranged one to another and bound together in a web of energy and material flows. In an ideal world the “waste” residue from the metabolism of one of these entities should become the feedstock of another1 (Ausubel, 1992; Ekins & Cooper, 1993; Hallsmith, 2003).

It is now broadly agreed, as a principle that human activities on a global scale should be in harmony with the environment, for both present and future generations (WCED, 1987). “Sustainability” although a mantra for the 1990’s and beyond is a way in which society utilises the environment (Mitcham, 1995). The environmental load that follows from social activities should be “ecologically suitable”. This means that the functioning of regeneration systems, absorption capacities, and other parts of the ecosystems2 is guaranteed both quantitatively and qualitatively. The environment is seen as a set of resources for society. Sustainability therefore refers to the continued existence of the socially functional components of ecosystems; it limits the use that is made of these components (NWO, 1992; Daly, 1996; Van der Ryn & Cowan, 1996).

Conventional economics emphasises the seemingly self-generating flows of goods and money between firms and households in the marketplace. However it is blind to the irreversible unidirectional material flows that sustain the economy (Barbier, 1990; Rees, 1992; Daly, 1996; Wackernagel & Rees, 1996). The circular economic flows are actually sustained by the unidirectional throughput of ecological goods and services from and to the ecosphere (the “natural income” stream). All the energy and much of the matter that passes through the economy is permanently dissipated into the environment never to be used again. Trade and technology have enabled human-kind progressively to exploit nature far beyond sustainable levels so that present

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1 Urban ecosystems, designed ‘from scratch’ to imitate nature by utilising the waste products of each component as raw material or input for another are an attractive theoretical idea, but as yet most projects are at an infancy stage (Odum; 1983; Ayres & Ayres, 1996).

2 A natural ecosystem is a self-organising system consisting of interacting individuals and species, each programmed to maximise its own utility (survival and reproduction), each receiving and providing services to others, each therefore dependent on the system as a whole. The ecosystem normally maintains itself in a balanced condition, or evolves slowly along a developmental path. But such ‘dissipative systems’ remain far from (thermodynamic) equilibrium (Ayres, 1989).
consumption exceeds natural income (the “interest” on our capital). This leaves the next generation with depleted capital and less productive potential even as the population and material expectations increase (Wackernagel & Rees, 1996; Hawken et al., 1999; Chambers et al., 2000).

The world today is oriented towards “green”, “clean” and “compact” solutions where urban planning is re-thought from an “urban ecology” perspective. This brings local decentralised solutions (neighbourhoods) into focus as opposed to the conventional centralised water and wastewater systems (Lyle, 1985; Matthews, 1996; Kalbermatten & Middleton, 1998). It is not clear whether urban water management in its present form is sustainable or not (Cobb, 1995; Harremoes, 1997; Larsen & Gujer, 1997; Butler & Parkinson, 1997; Savenije, 2000). What is clear though is that too much water and non-renewable resources of high quality are taken from the eco-system and returned to the ecosphere as pollution (Daly, 1992; Hodges, 1993; Niemczynowicz, 1993). Overall it is argued that the present forms of agriculture, architecture, engineering and industry are derived from design epistemologies incompatible with nature’s own (Van der Ryn & Cowan, 1996; Smit 1996).

How can cities perform better with regard to resource use and waste management? Urban expansion has caused loss of fertile land and other ecological changes (Fazal, 2000; Morello et al., 2000; Hallsmith, 2003) despite the fact that urban areas occupy less than 2% of the total earth’s land surface (Miller, 1988). At present there is almost an explosion of seemingly novel technologies of potential strategic interest. How should these future technologies be judged to be better or worse than current arrangements? Does the form of present technology commit us to further developments that are incompatible with the needs of a sustainable city?

Cities, like organisms, are associated with flows of material and energy. Within the broad context of the global cycles of certain principal materials, the ways in which futuristic urban water and drainage system might introduce minimal distortion to these “natural” material cycles is an important subject of exploration lately (Ayres & Ayres, 1996; Herrmann & Klaus, 1997; Grotteker, 1998). Specifically, the cycles of Carbon (C), Nitrogen (N), Phosphorus (P) and Sulphur (S) bearing materials, together with those of heavy metals, synthetic organic chemicals and pathogens, have to be examined carefully. These represent the principal categories of pollution associated with the activities of a city. Much of the analysis points towards the desirability of returning the non-aqueous output fluxes of the urban drainage system to the land, as opposed to the aquatic environment (Lijklema & Tyson, 1993; Beck et al., 1994; Staudenmann et al., 1996).

The principal nutrients (P and N) flow in a circular, closed loop system in nature, but human activities use and dispose nutrients in a linear, open-ended system (Walker, 1991; Vitousek et al., 1998; Gijzen & Mulder, 2001; Smil, 2001). The danger is that once one closed loop system is opened, it may force open other closed loop systems elsewhere in the ecosystem (Esrey, 2000). Short-cutting or closing the P-cycle in the urban environment is closely related to closing of water cycles (Savenije, 2000).

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3 Urban Ecology is a neologism intended to call attention to a biological analogy; the fact that an ecosystem tends to recycle most essential nutrients, using only energy from the sun to ‘drive the system’. This analogy to a complex web of potentially synergistic and symbiotic relationships is appealing (Ayres, 1989).
There is still much debate however, on whether robust municipal systems can achieve 100% source control treatment and reuse technologies as in industry, from an economic, engineering and ecological resilience point of view (Ayres & Ayres, 1996; Matthews, 1996; Jeffrey et al., 1997; Otterpohl, 2001).

New solutions in terms of water management, sanitation and management of organic wastes for the 21st century cities (Cosgrove & Rijsberman, 2000) are perceived to be source orientated, local and small scale, non-mixing, ecologically sound closed loop systems approaching the life-support system of a spaceship⁴ (Beck et al., 1994; Roelofs, 1996; Van der Ryn & Cowan, 1996; Nelson, 1997; Otterpohl et al., 1997; Crites & Tchobanoglous 1998; Ross et al., 2000; Lens et al., 2001). Since cities need to close the open loop of limited resources such as P, urban agriculture seems to be a viable option by reusing and transforming the by-products of human metabolism especially, which, usually are dumped as polluting waste into the bio-region (Smit & Nasr, 1992; Hodges, 1993).

There is a growing agreement among engineers, planners, and activists that: ‘Large scale end-of-pipe wastewater treatment facilities create a spectacular example of technology that must change in order to provide a sustainable, global solution. Several non-conventional, ecologically sound wastewater treatment technologies do exist and they are ready for implementation. The strongly entrenched connection of urban residuals with pipes, culverts, conduits, concrete, and tanks has enabled the society to forget that ultimately the interest must lie in studying the relationship between all types of land use (which determines water use and vice versa) and receiving water quality (Lyle, 1985; Lijklema & Tyson; 1993; Gumbo, 2000a, 2003a).

The Bellagio principles

The pressures of humanity on a fragile water resource base, and the corresponding need for environmental and freshwater protection requires that human excreta and other societal wastes (solid and liquid) be recycled and used as a resource. The so-called Bellagio principles, following a Water Supply and Sanitation Collaborative Council (WSSCC) meeting of experts in Bellagio (Italy), underpin the basis for this new approach to environmental sanitation (SANDEC & WSSCC, 2000; Schertenleib, 2001).

There are two main concepts emanating from the Bellagio principles, which make the basis of this dissertation. Firstly, Household Centred Environmental Sanitation (HCES) puts the household at the focal point of environmental sanitation planning and; secondly, the Circular System of Resource Management (CSRM) that emphasises conservation, local recycling and reuse of resources (SANDEC & WSSCC, 2000; WSSCC, 2000). The house, the most familiar habitat has been used

⁴ For space missions, high tech solutions such as vapour compression distillation, reverse osmosis, or multi-filtration are considered for the recovery of water from urine and faeces (Silverstone, 1993; NASA, 1994). In short-term missions, however, human wastes are usually stored for post flight treatment or disposed using an overboard-vacuum-system. On long-term space missions it is necessary to close not only the water cycle but also the food and nutrient cycle, for this purpose bio-regenerative life support systems have been designed (Alling et al., 1993a; 1993b; NASA, 1994; Nelson, 1997; Allen, 2002). The only example of full-scale implementation is Biosphere 2 (Nelson, 1997; Alling et al., 1993b).
as a good starting point in many ecological designs. The rural or village homestead is viewed as once the centre of a largely self-sufficient system that produced a family’s livelihood, its food and fibre, and its tools and toys (Van der Ryn & Cowan, 1996). Therefore rethinking home metabolism has become the focus of ecological design (Olkowski et al., 1979; Sowman & Urquhart, 1998).

Implementation of the HCES and CSRM approaches for environmental sanitation requires integration between excreta disposal, wastewater disposal, solid waste disposal, and storm water drainage (Cosgrove & Rijsberman, 2000; SANDEC & WSSCC, 2000; WSSCC, 2000). Firstly, the HCES makes the household the focal point of environmental sanitation planning, reversing the customary order of centralised top-down planning (Hodges, 1993; Zeeman & Lettinga, 1998; Schertenleib, 2001). The approach argues that only problems not manageable at the household level should be ‘exported’ to the neighbourhood, town, and city and so on up to larger jurisdiction. Secondly, the CSRM, in contrast to the current linear system, emphasises conservation, recycling and reuse of resources as illustrated in Figure 1.1 (Schertenleib, 2001). Many water supply and sanitation problems would be resolved by this new paradigm, which places all aspects of water and waste within one integrated service delivery framework (Larsen & Gujer, 1997; Niemcynowicz, 1997; Esrey et al., 1998; Schertenleib & Gujer, 2000; Schertenleib, 2001).

Figure 1-1 The concept of household centred environmental sanitation (HCES) and circular system of resource management (CSRM)
Source: Adapted from Schertenleib (2001)
1 Introduction

Land and water demands by humanity

Sustainability requires living within the regenerative capacity of the biosphere. One approach is to identify spatial and physical dimensions of urban demands on the natural capital and also to explore the extent to which surrounding rural areas are affected by cities (Wackernagel & Rees, 1996; Fazal, 2000). In an attempt to measure the extent to which humanity satisfies this requirement, Wackernagel et al., (2002a, 2002b) used existing data to translate human demand on the environment into an area required for the production of food and other goods, together with the assimilation of wastes generated, under the predominant management and production practices in any given year (see Box 1.A: Land as a finite resource). Not only human demand on nature, but also nature’s supply changes over time because of innovations in technology and resource management, changes in land use, and cumulative damage of past impacts (Wackernagel et al., 2002a).

According to the exploratory assessment by Wackernagel et al., (2002a, 2002b) indications are that human demand on nature may well have exceeded the biosphere’s regenerative capacity since the 1980’s (Box 1.A). The accounts of biologically productive space presented by Wackernagel et al., (2002a) are based on six human activities that require biologically productive space. They are (i) growing crops for food, animal feed, fibre, oil, and rubber; (ii) grazing animals for meat, hides, wool, and milk; (iii) harvesting timber for wood, fibre, and fuel; (iv) marine and freshwater fishing; (v) accommodating infrastructure for housing, transportation, industrial production, and hydro-electric power; and (vi) burning fossil fuel. The calculated human demand and existing capacity in year 2000 for each category is shown in Table 1.1.

Table 1-1 Summary of humanity’s area demands, and earth’s biological capacity in 2000

<table>
<thead>
<tr>
<th>Area</th>
<th>Equivalent factor $^a$</th>
<th>Average global area demand</th>
<th>Equivalent existing bio-capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global $m^2/m^2$</td>
<td></td>
<td>$m^2$ per person</td>
</tr>
<tr>
<td>Growing crops</td>
<td>2.1</td>
<td>5 300</td>
<td>5 300</td>
</tr>
<tr>
<td>Grazing animals</td>
<td>0.5</td>
<td>1 000</td>
<td>2 700</td>
</tr>
<tr>
<td>Harvesting timber</td>
<td>1.3</td>
<td>2 900</td>
<td>8 700</td>
</tr>
<tr>
<td>Fishing</td>
<td>0.4</td>
<td>1 400</td>
<td>1 400</td>
</tr>
<tr>
<td>Accommodating infrastructure</td>
<td>2.2</td>
<td>1 000</td>
<td>1 000</td>
</tr>
<tr>
<td>Fossil fuel and nuclear energy</td>
<td>1.3</td>
<td>11 600</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>23 300</td>
<td>19 100</td>
</tr>
</tbody>
</table>

$^a$ To make aggregation reflect differences in bio-productivity, areas are expressed in standardised global $m^2$, which correspond to $m^2$ with world average bio-productivity.

Source: Adapted from Wackernagel et al., (2002a)

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$^5$ Biologically productive space is the land and water area that is biologically productive. It is land or water with significant photosynthetic activity and biomass accumulation. Marginal areas with patchy vegetation and non-productive areas are not included. The total biologically productive space adds up to 0.10 billion Mm$^2$ and hosts over 95% of the planet’s terrestrial biomass production.
**Box 1-A Land as a finite resource**

Adapted from Redefining Progress (2002) and Wackernagel et al., (2002a; 2002b)

The surface area of the planet is about 0.51 billion Mm$^2$. Of this, less than 0.13 billion Mm$^2$ is land. About two-thirds of this, at most, could be classed as productive in the sense that it can support 10% or more forest cover, is permanent pasture, or arable land. The remainder is inhospitable desert, ice-covered, and rock.

If an upper estimate of 0.10 billion Mm$^2$ usable land is assumed, and a year 2000 global population of 6 billion, then this gives an average ‘Earth share’ of about 17 000 m$^2$ per capita (an area 165 metres by 100 metres). A figure which will reduce to just over 10 000 m$^2$ by 2050 if the United Nations medium-term population predictions of around 9 billion are realised. Adding to this the productive regions of the oceans, takes the year 2000 average ‘Earth share’ to around 19 000 m$^2$, this includes a very modest 12% allowance for other species and conservation; WCED (1987) (see Table 1.2). This shrinking space must service all human needs (food, materials, recreation, living space, energy) and be capable of assimilating all wastes (arguably the most pressing being the sequestration of greenhouse gases).

Based on current global average yields, and ignoring the massive energy inputs common with modern agriculture, around half the year 2000 ‘Earth share’ was used to provide meat and vegetables alone to the human population. Available data suggests that humanity is drawing down the planet's capital account rather than living within the interest. Whereas the available ‘Earth share’ is 19 000 m$^2$, the average global citizen has a footprint of 23 000 m$^2$ - an overshoot of 37%.

**Table 1-2 The year 2000 global ecological footprint**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (in billions)</td>
<td>6</td>
</tr>
<tr>
<td>Ecological footprint$^6$ (000’s m$^2$)</td>
<td>23</td>
</tr>
<tr>
<td>Bio-capacity$^7$ (000’s m$^2$)</td>
<td>19</td>
</tr>
<tr>
<td>Ecological deficit$^8$ (000’s m$^2$)</td>
<td>4</td>
</tr>
</tbody>
</table>

The latest estimates from Wackernagel, et al., (2002b), based on 1995 data suggests that consumers in developed countries have very large feet. The United States has a per capita footprint of 96 000 m$^2$, Australia 94 000 m$^2$ and Canada 72 000 m$^2$. Wackernagel et al., (2002b) also calculate the ‘Available Bio-capacity’ within a country. Where this is higher than the Footprint then it is theoretically possible for that country to meet its own bio-productive needs. Of the three nations mentioned, Australia and Canada have theoretically ‘spare’ bio-capacity. The US uses around twice its nationally available bio-capacity with a deficit of 41 000 m$^2$/person. An average US citizen consumes at five times the total ‘Earth share’.

There are two main ways in which deficits are resolved. First, a country trades with others that have a surplus of resources - as in the case of fossil fuel use (stored energy of ‘Paleozoic summers’), where use of ancient bio-productivity leads to present-day pollution (Sturm et al., 2000). Second, and more significantly, ecological natural capital is diminished and/or renewable resources are ‘used’ at unsustainable rates (Chambers et al., 2000; Sturm et al., 2000). Examples include soil degradation, deforestation, over-fishing, and over-grazing.

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$^6$ Ecological footprint is a measure of how much productive land and water an individual, a city, a country, or humanity requires to produce all the resources it consumes and to absorb all the waste it generates, using prevailing technology. This land could be anywhere in the world. The Ecological Footprint is measured in ‘global area units’.

$^7$ Biological capacity: the total biological production capacity per year of a biologically productive space, for example inside a country. It can be expressed in "global m$^3$", i.e. the equivalent area of space with world-average productivity.
Infrastructure for housing which include transportation, industry, and hydroelectric power results in built-up land (Sowman & Urquhart, 1998). The space occupied by this infrastructure is the least well documented, because low-resolution satellite images are not able to capture dispersed infrastructure and roads. Wackernagel et al., (2002a) use an estimate of 0.003 billion Mm² (approximately 2% of global land area), a minimum estimate of the extent of infrastructure worldwide today, and assume that built-up land replaces arable land, as has been documented for the United States.

It is in cities that a considerable (and growing) proportion of the world’s population lives and a much higher proportion of all resource use and waste generation is concentrated. The form and structure of any city influences it global impact (Hardoy et al., 1992; Rees, 1992). Many cities and economies in the North achieve sustainable development goals within their own region by drawing heavily on the environmental capital of other regions or nations and on the global sink for their wastes (see Box 1.B: The manure problems in the Netherlands). Through trade and natural flows of ecological goods and services, all urban regions appropriate the carrying capacity of distant ‘elsewheres’, creating dependencies that may not be ecologically or geopolitically stable or secure (Rees, 1992; Chambers et al., 2000; Sturm, 2000).

World Bank predictions indicate that over the next 25 years production of food must increase by a factor of at least three, yet present statistics show that total grain production per capita is decreasing, with no signs of change. In order to reverse this trend, huge amounts of water and nutrients will be required to increase food production. This will require expansion of agriculture, which can be achieved with increasing use of finite fossil fertilisers and pesticides, more artificial impounding reservoirs for irrigation, potentially bringing economic burden, environmental pollution and a further decrease of clean water resources (Niemczynowicz, 1997a; 1997b; Falkenmark et al., 1998; Savenije, 1999). Meanwhile the global fertiliser use has soared from less than 14 Mt/a in 1950 to about 140 Mt/a as macro nutrients (N, P & K) in year 2000 (Steen, 1998; Johnston & Steen, 2000).

Ecological agriculture can be viewed as a component of sustainable agriculture which includes all agricultural systems that promote the environmentally, socially and economically sound production of food and fibres (Rees, 1992; Nasr, 2000). These systems take local soil fertility, culture and biodiversity as a key to successful production (Tilth, 1982; Hands et al., 1995; IFOAM, 2000). By respecting the natural capacity of plants, animals and the landscape, it aims to optimise quality in all aspects of agriculture and the environment (Halweil, 2001). Sustainable agriculture dramatically reduces external inputs by refraining from the use of chemo-synthetic fertilisers, pesticides, and pharmaceuticals. Instead it allows the powerful laws of nature to increase both agricultural yields and disease resistance. Sustainable agriculture also calls for efficient use of ‘green water’⁹. Of all water resources, green

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⁸ Ecological deficit: the amount by which the Ecological Footprint of a population (e.g. a country or region) exceeds the biological capacity of the space available to that population. The national ecological deficit measures the amount by which the country’s footprint (plus the country’s share of biodiversity responsibility) exceeds the ecological capacity of that nation.

⁹ The concept of green water was first introduced by Falkenmark (1995). The storage medium for green water is the unsaturated soil. The process through which green water is consumed is transpiration. Green water is a very important resource for global food production. About 60% of the
water is probably the most under-valued resource. Yet it is responsible for by far the largest part of the world’s food and biomass production (Savenije, 1999).

### Box 1-B The manure problem in the Netherlands
Adapted from Van Ruiten (1998)

Increasingly intensive methods of stock farming have resulted in a surplus of animal manure in the Netherlands (a developed country in western Europe with a population of about 15.9 million and land area of about 34 000 Mm²), which primarily means a surplus of minerals (nitrogen and phosphorus). Above all, the emergence and growth of ‘land-independent’ (intensive) stock farming establishments in the sandy regions of the southern, eastern and central Netherlands has made a major contribution to this state of affairs. The reason is that the soil type in these regions is not suitable for a high level of production of ‘land dependent’ agricultural crops, and the cultivated area per farm is small. The import of cheap raw materials for livestock feeding and the good infrastructure have encouraged the development of intensive stock farming in these regions. As a counterweight to the import of mostly pig and cattle feed, there are substantial exports of products (meat, eggs, milk, cheese, etc.). However, the excreted minerals remain in the soil. The result is a net increase in the amount of minerals within the country’s borders.

A surplus of minerals causes environmental pollution in the form of contaminated soil, groundwater and surface water. In addition, unpleasant odours are emitted. Although the signs of the negative effects were already recognised in the 1960’s, it was not until the 1970’s that measures were gradually introduced to limit the loss of minerals into the environment. Although the emission of nitrogen is just as harmful from an environmental point of view as the emission of phosphorus, the Dutch government has always geared its legislative and regulatory measures to phosphate (P₂O₅). The significance of this is primarily practical. Nitrogen is more difficult to incorporate in an analysis of inputs and outputs, due to its presence in the form of volatile compounds such as ammonia (NH₃) and nitrogen gas (N₂). In the course of the years, the limiting measures taken by the government have been steadily tightened up (phased approach) and the amount of research work into proposed problem solutions has simultaneously increased. In its search for solutions the government has elected for a three-pronged policy of geographically spreading (from regions of surplus to regions of shortage), limiting minerals in cattle feed, and treating and processing manure.

At the end of the 1980’s the Dutch government urged the stock farming sector to take 25 000 Mg P₂O₅ (equivalent to about 6 Mt of pig manure) out of the market by 1995 through processing. A large number of initiatives were started at the major ones involving: Processing pig slurry into fertiliser granules; Concentrating liquid fraction of sow and veal calf manure; Drying chicken manure into fertiliser granules. With the exception of the processing of veal calf manure (total processing capacity 660 000 Mg/a) and slurry (evaporation plants with a total processing capacity of 160 000 Mg/a), these large-scale initiatives ultimately led to nothing, despite the enormous amounts of time and money invested.

There were various causes for these large-scale failures, such as an excessively high processing price in relation to competing options such as geographically spreading; insufficient support from the sector; problems with the choice of location and licences; and uncertainty with regard to the market for the end product. In addition, in 1995 the EU prohibited the continuation of subsidies for large-scale manure processing and long-distance transportation, and this had an extremely disadvantageous effect on the competitive position of the various problem solutions.

world staple food production relies on rainfed irrigation, and hence green water. The entire meat production from grazing relies on green water, and so does the production of wood from forestry. In Sub-Saharan Africa almost the entire food production depends on green water (the relative importance of irrigation is minor) and most of the industrial products, such as cotton, tobacco, wood, etc (Savenije; 1999, 2000) (see also Chapter 4).
Box 1-B The manure problem in the Netherlands (conti)

Surpluses also occur in some regions of other countries, for example in Flanders, Brittany, northern Germany and the Po delta. Although this problem is gradually attracting more attention in these regions, partly under the influence of European legislation, far less effort has been devoted to solving it than in the Netherlands. On the basis of the most important manure flows, the emphasis is on the following categories of animals: cattle, veal calves, pigs and chickens. According to the data from the CBS (Dutch Central Bureau of Statistics) the number of animals in 1997 is shown in Table 1.3. It should be noted that the cattle, with the exception of veal calves, are held on the land (grazing animals). Veal calves, along with pigs and chickens, are raised in indoor establishments. This is important with regard to the form in which the manure becomes available (see Table 1.4). The type of stall plays an important role - for example, farmyard manure (solid) versus slurry (semi-liquid).

Large amounts of cattle feed, and therefore of phosphate, are imported for the livestock industry. A considerable proportion of this phosphate is excreted by the animals. In principle, the amount of excreted minerals can be calculated from the produced amount of manure and its composition (Gerritse & Vriesma, 1984). In the case of the mineral phosphate, and on the basis of the data in Table 1.4, the phosphate as P$_2$O$_5$ excreted by the Dutch livestock in 1997 is shown in Table 1.5. The table shows that cattle make the biggest contribution to phosphate excretion (about 50%).

A considerable proportion of the phosphate excreted in the manure is used to fertilise grassland and arable land (placement in farm where produced and distribution; Farm surplus = Production - In-farm placement). A small proportion is exported or processed. In view of the fact that not all manure can be disposed of in this way, a national manure and phosphate surplus arises. This is illustrated in Table 1.6. The amount of manure that can be spread on cultivated land inside the Netherlands depends on the legal standards drafted by the government for this type of use. Since the early 1990’s these standards have been tightened up. In 1997 the standards for spreading on grassland, maize silage and other arable land was 13.5, 11.0 and 11.0 g/m$^2$ as P$_2$O$_5$, respectively (Van Boheemen, 1987; Van Ruiten, 1998).

From Table 1.6 it is clear that a national surplus (National surplus = Farm surplus – Distribution + Export or processing) was created in 1997. In future as a consequence progressive tightening up of the manure policy, more manure surplus would need to be taken out of the market or the number of animals reduced.

<table>
<thead>
<tr>
<th>Livestock</th>
<th>Number (000’s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle</td>
<td>4 410</td>
</tr>
<tr>
<td>Veal calves</td>
<td>740</td>
</tr>
<tr>
<td>Pigs</td>
<td>15 190</td>
</tr>
<tr>
<td>Chickens</td>
<td>93 110</td>
</tr>
<tr>
<td>Othera</td>
<td>2 160</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Livestock</th>
<th>Slurry</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle</td>
<td>56.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Veal calves</td>
<td>2.5</td>
<td>-</td>
</tr>
<tr>
<td>Pigs</td>
<td>16.2</td>
<td>-</td>
</tr>
<tr>
<td>Chickens</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Other</td>
<td>1.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>77.8</td>
<td>2.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Livestock</th>
<th>Mt as P$_2$O$_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle</td>
<td>0.096</td>
</tr>
<tr>
<td>Veal calves</td>
<td>0.003</td>
</tr>
<tr>
<td>Pigs</td>
<td>0.058</td>
</tr>
<tr>
<td>Chickens</td>
<td>0.029</td>
</tr>
<tr>
<td>Other</td>
<td>0.006</td>
</tr>
<tr>
<td>Total</td>
<td>0.192</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option</th>
<th>Capacity (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>0.192</td>
</tr>
<tr>
<td>In-farm placement</td>
<td>0.118</td>
</tr>
<tr>
<td>Farm surplus</td>
<td>0.088</td>
</tr>
<tr>
<td>Distribution</td>
<td>0.071</td>
</tr>
<tr>
<td>Export or processing</td>
<td>0.014</td>
</tr>
<tr>
<td>National surplus</td>
<td>0.003</td>
</tr>
</tbody>
</table>
Agricultural management can successfully mimic natural ecosystems, with - for instance - the use of mulches, green manure crops, legume covers, alley cropping and appropriate crop rotations (Hands et al., 1995; Gruhn et al., 2000). Sustainable agriculture adheres to globally accepted principles, which are implemented within local social-economic, geo-climatical and cultural settings. Cumulative negative nutrient balances heighten the impact of climatic factors, insecure tenure arrangements, and land and demographic pressures on soil fertility (see Box 1.C: Human-induced soil degradation). In Sub-Saharan Africa net annual nutrient depletion was estimated at 2.20 g N/m²; 0.25 g P/m² and 1.5 g K/m² during 1982 to 1984 (Stoorvogel et al., 1993).

**Box 1-C Human-induced soil degradation**
Adapted from Gruhn et al., (2000)

Soils in many countries suffer from declining fertility. Their physical and chemical structures are deteriorating and the vital nutrients for plant growth are slowly being depleted. By some estimates, the annual cost of environmental degradation in some countries ranges from 4 to 17% of gross national product (GDP). Three-quarters of the area degraded by inappropriate agricultural practices, overgrazing, and deforestation is in the developing world. Tables 1.7 and 1.8 illustrate the extent and human-induced causes of soil degradation in Africa, Asia, and South America (WRI, UNEP, & UNDP 1992; Oldeman, 1992).

<table>
<thead>
<tr>
<th>Region</th>
<th>Degree of degradation (land area in 10⁶ Mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Light</td>
</tr>
<tr>
<td>Africa</td>
<td>204</td>
</tr>
<tr>
<td>Asia</td>
<td>46</td>
</tr>
<tr>
<td>South America</td>
<td>245</td>
</tr>
</tbody>
</table>

Source: Oldeman et al., (1992)

<table>
<thead>
<tr>
<th>Region</th>
<th>Deforestation</th>
<th>Overexploitation</th>
<th>Overgrazing</th>
<th>Agriculture</th>
<th>Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>14</td>
<td>13</td>
<td>49</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>Asia</td>
<td>40</td>
<td>6</td>
<td>26</td>
<td>28</td>
<td>1</td>
</tr>
<tr>
<td>S. America</td>
<td>41</td>
<td>5</td>
<td>28</td>
<td>26</td>
<td>-</td>
</tr>
<tr>
<td>World</td>
<td>29</td>
<td>7</td>
<td>34</td>
<td>28</td>
<td>2</td>
</tr>
</tbody>
</table>

Source: Oldeman (1992)

It is suggested that the lack of manure, and excessive exploitation of soil and water resources beyond their population-carrying capacity, have been major factors in the collapse of several ancient civilisations. Cases in point are the Roman Empire, the Sumerians in Mesopotamia and the Mayans in Central America, where soil disintegration was caused respectively by salinisation and deforestation – two of the major threats of today (Ponting, 1991; Johnston, 1995; IFA & UNEP, 1998).

The urban food system is so far not sufficiently reflected in the urban planning process in many countries (Jarlov, 2000; Nasr, 2000; Argenti, 2000; Pothukuchi & Kaufman, 2000). The urban food system connects to many other urban systems – notably the agricultural sector, the economy and ecological systems. Urban people
are not passive food recipients; in many locations they are actively involved in food production (Argenti, 2001; Balbo et al., 2001).

Agriculture in urban areas can mitigate negative impacts on surrounding and more distant biodiversity (the urban footprint). The lead feature of urban agriculture, which distinguishes it from rural agriculture, is its integration into the urban economic and ecological system (the urban ‘ecosystem’) (Smit, 1996; Mougeot, 2000). Urban agriculture produces food and energy crops close to the market demand, some within the neighbourhood. This proximity of production to consumption reduces traffic, storage, and packaging as sources of the pollution that erodes biodiversity (Smit, 2000; Hallsmith, 2003).

It is argued that urban agriculture is inherently more biodiversity-prone than modern rural agriculture, by being more sustainable, less chemically dependent and more biologically friendly. Urban agriculture occurs on smaller sites and typically has a more diverse or integrated crop mix (Smit, 2000). Urban agriculture may close open nutrient and energy loops. Perhaps the most effective example is modifying urban wetlands to food, fuel and recreation instead of filling them with waste and converting to built-up uses. Further research might be worthwhile on differences in biodiversity in different climate zones, associated with urban versus rural farming.

1.2 Urban agriculture

Significance

The poor throughout most of Africa have experienced increasing difficulties over recent years as a result of the imposition of structural adjustment programmes. One of the main coping mechanisms has been increased self-help in satisfying basic households needs (Matshalaga, 1997; Argenti, 2000; 2001). Food is one of these basic needs and urban agriculture, both legal and illegal, has grown as a consequence of the difficult economic climate. As yet relatively few studies have attempted to asses the role that urban agriculture plays or might play in social or environmental terms (Drakakis-Smith, 1992; UNDP, 1996; FAO, 1999c).

Urban farming is often minimised as being merely “kitchen gardening” or marginalised as a leftover of rural habits. Certain myths still predominate e.g. urban agriculture means household and community gardening, urban agriculture is a temporary activity, urban agriculture is a marginal activity or means of survival, urban agriculture pre-empts “higher” land uses and cannot pay full land rent, urban agriculture competes with and is less efficient than rural farming, urban agriculture is unhygienic, urban agriculture causes pollution and damages the environment, urban agriculture is unsightly and aesthetically inappropriate in the city and the “garden city” is an archaic, utopian concept that cannot be created today (UNDP, 1996; Nugent, 1997).

10 Urban agriculture is defined as the production of crops and or livestock on land, which is administratively and legally zoned for urban uses. This activity is done within these zones or at the periphery of urban areas i.e. land likely to be rezoned from rural agriculture to urban land.
In 1996 the UNDP estimated that some 15% of food production in the world comes from urban agriculture (farming, horticulture, animal husbandry, fish ponds, etc.). Nearly 1 billion people are engaged in urban agriculture, 200 million producing food for markets (UNDP, 1996; Bakker et al., 2000; IDRC, 2003; RUAF, 2003). In cities such as Lusaka and Dar es Salaam as much as 50% of the food is produced within the city. Shanghai, which has a population of 11 million, produces 100% of its fresh vegetables in community gardens (Yeung, 1993; Yi-Zhang, 1999). For city dwellers, community gardens are another option for farm-fresh food. It has been estimated that having market gardens located throughout suburbs and cities could cut the dollar cost of food by 70%. Given that half of the world population soon will live in urban areas, it could be expected that re-circulation of nutrients in urban areas will be featured high on the agenda in the near future (Hayward, 1997). However despite many benefits, urban agriculture is still an ill-understood industry (Mbiba, 1995; Ruel et al., 1999; Bakker et al., 2000).

Many questions arise (Drescher, 2000; FAO, 1999c): Where are urban agricultural activities concentrated and why? Who is involved? Is it for psychological or cultural reasons (hobby, leisure, growing your own cultural food, growing organic food)? What kinds of crops are grown and by which groups of city dwellers? What contribution does the product make to nutrition and food security? What type of land tenure system has to be adopted to ensure sustainability? What kinds of soils do urban agriculturalists prefer? How available is water and what is its quality? How far does the producer have to travel to market the products grown? What are the risks to human health? What are the possible environmental impacts from urban agriculture? How can harmful health and environmental impacts be mitigated? What are the possibilities and limitations for integration of urban agriculture in urban planning and zoning?

Urban agriculture constitutes an important component of sustainability in terms of ensuring that people have sufficient income and food, both of which sustain other aspects of household life such as health and education (Maxwell et al., 1998; Martin et al., 2000; Nugent, 2000). The World Food Summit held in Rome in November 1996 gave priority to the development of urban and peri-urban agriculture as well as improving the efficiency of food supply and distribution systems and linkages between production and consumption areas, with the aim of facilitating access to food by low-income households and hence improving food security in developing countries and countries in transition (Armar-Klemesu, 2000). The Habitat II Conference in 1996 drew attention to the high urbanisation levels and the rapid urban growth rates in developing countries and countries in transition, and stressed their direct relationship with urban poverty.

Historically, public support for access by the poor, to urban land for food production has arisen for economic and cultural reasons (schreber gardens, allotment gardens). In the post-World War II period, urban farming examples include the Gorbachev reforms in Russia (Moldakov, 2000), Mozambique’s zonas verdes, Cuban hidroponicos, (Bourque & Canizares, 2000; Cruz & Medina, 2003) Mongolian school gardens (Yeung, 1993), South Africa’s provincial urban small-scale farms (Jarlov, 2000), and ‘community gardens’ in France and the USA.
Urban agriculture draws on the often unmanaged and ‘un-recovered’ urban waste stream inherent to a majority of cities in the developing world and attempts to redirect these resources toward the production of food and fibre in an economically and environmentally sound fashion. Food production schemes can be augmented and enhanced by recycling human and solid waste (Furedy, 1996) if low-cost and reliable waste recovery technologies and approaches can be demonstrated and proven feasible\textsuperscript{11} (Tilth, 1982; Smit & Nasr, 1992; Gardner, 1998; Rose, 1999).

**Feasibility**

In many countries, an important and so far unsolved problem is how to devise appropriate methodologies to integrate agricultural activities in cities into urban planning processes. To what extent are various functions of city life - such as farming - included in the urban planning process (Drescher, 2000; Quon, 1999; Jacobi et al., 2000)? The ultimate objective of an urban plan is to create a liveable city – relatively free of conflicts among dwellers and uses, providing for the needs of its citizens, and maintaining its natural resources. The role of urban and peri-urban agriculture in a city plan is to contribute to those ends (Mougeot, 2000). In most of the world’s cities, little is known about the actual extent to which inner city areas are used for agricultural purposes (Drescher & Iaquinta, 1999).

In many urban centres, open space for agriculture is limited and the faster the urbanisation, the more limited that space becomes. For this reason, the efficient protection of open spaces in inner cities is an important issue. However, despite the lack of open spaces for agriculture in urban areas, there is huge, unused potential for this activity in many cities of the world\textsuperscript{12} (Fernades & Varley, 1998; Balbo et al.; 2001). Strips of land at the sides of roads, railways and power lines; along river banks and on seasonally flooded land; and on other partially unproductive areas could be legally used for agriculture, in many cities of the world, providing it is carried out in a proper, environmentally sound way (Dowall & Giles, 1996; Drescher, 2000).

Despite traditions in some countries, access to land must be distinguished from availability of land; land may be available or present in a city but not accessible to farmers because of political or social constraints to its use or redistribution (Mbiba, 1995; UNDP, 1996; Meadows, 2000). Generally, agriculture in urban areas suffers greater ecological and economic pressures than rural agriculture, requiring more intensive and better controlled production to stay competitive and secure. When land availability is restricted, urban farmers tend to be opportunistic, and find creative ways to use the smallest plots or strips of land and water. This leads to farming on land originally set aside for other purposes, on land that is hazardous and therefore unusable, or land that has been abandoned or contaminated by past uses, sometimes

\textsuperscript{11} The International Federation of Organic Agriculture Movements (IFOAM) specifies that manures containing human excrement (faeces and urine) shall not be used on vegetation for human consumption, except where all sanitation requirements are met. Certification bodies or standardising organisation should establish sanitation requirements and procedures, which prevent transmission of pests, parasites and infectious agents (IFOAM, 2000)

\textsuperscript{12} There are lots of interesting ideas for intensive gardening. One of the most inspiring ideas is “The Productive Homestead” by Dr Gus Nilsson in Gaborone in Botswana. He claims that a 1000 m\textsuperscript{2} plot including a house can feed a family and pay for the building of the home over a 20-year period. The effective adoption of this system, however, depends on the level of education attained by the people (Esrey et al., 1998).
without the farmer even being aware of the hazard (UNDP, 1996; Smit, 1996; Dubbeling, 2000). Such opportunistic use may result in unregulated production and processing that may be hazardous to consumers. Planners can assist poor families (De Zeuw et al., 2000; Balbo et al., 2001).

**Negative impacts of urban agriculture**

Today, as in earlier times, agriculture in the city poses a range of possible negative impacts. Irrigation with polluted water, animal waste in the streets, or spraying chemical insecticides can be injurious to man and the community biosphere (Birley & Lock, 1999; Flynn, 1999; Smit, 2000). Converting park-like open space to monocropping can diminish biodiversity of the site. The management of an ecologically sustainable or ‘biogenic’ city, which conserves biodiversity, will require a much higher level of environmentally sophisticated management than current practices (Van der Ryn & Cowan, 1996).

Several reviews or studies of health issues have tended to highlight the health risks of urban agriculture (Birley & Lock, 1999). This has served to reinforce the perceptions of many governments and municipal authorities that urban agriculture is a (marginal) activity that has substantial health risks and should not be supported (Lock & De Zeeuw, 2001; Lock & Van Veenhuizen, 2001). According to Lock & Van Veenhuizen (2001), the main health risks associated with urban agriculture are summarised in Box 1.D.

**Box 1-D Overview of major health risks in urban agriculture**

Lock & De Zeeuw (2001)

<table>
<thead>
<tr>
<th>Crop production</th>
<th>Communicable diseases</th>
<th>Non-communicable diseases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crops irrigated with untreated (or inadequately treated) domestic wastewater or fertilised with improperly produced compost may be infected with bacteria (shigella, typhoid, cholera), worms (like tape and hookworms), protozoa, enteric viruses or helminths (ascaris, trichuris)</td>
<td>Crops may take up heavy metals and other hazardous chemicals from soils, irrigation water or sewage sludge polluted by industry</td>
<td></td>
</tr>
<tr>
<td>In Africa, mosquitoes that are the vector for malaria may breed in clean, shallow irrigation water and crop land with serious water-logging. Incidence of malaria mainly relates to wet rice and ridge cultivation of yams and sweet potatoes</td>
<td>Crops grown close to main roads or industry, and food purchased from street vendors may be contaminated by air-borne lead and cadmium</td>
<td></td>
</tr>
<tr>
<td>Mosquitoes that are the vector for filariasis and dengue may breed in standing water heavily polluted with organic materials (drains blocked by organic refuse, latrines, septic tanks)</td>
<td>If waste materials are not separated at source, the resulting compost may contain heavy metals, which can be taken up by crops</td>
<td></td>
</tr>
<tr>
<td>Food may be contaminated with bacteria due to poor hygienic conditions in informal food preparation and marketing, causing diseases such as salmonella and E-coli</td>
<td>Occupational injury of agricultural workers is an important source of disability including musculoskeletal disorders or poisoning by agrochemicals</td>
<td></td>
</tr>
</tbody>
</table>
Environmental reasons have often been used to criticise urban agriculture and in many instances to prohibit it. In Zimbabwe the main criticism is that it causes soil erosion and subsequent siltation of water supply sources (ENDA, 1995; Mbiba, 1995; Bowyer-Bower *et al.*, 1996; Bowyer-Bower & Tengbeh, 1997). A review of available literature reveals that very little field research has, in fact, been undertaken to provide empirical substantiation of these claims. Without such evidence, potentially damaging environmental impacts may be ignored, or actions (often costly and unpopular) taken that if investigated could be found to be unnecessary (Drakakis-Smith, 1992; ENDA, 1995).
Bowyer-Bower & Tengbeh (1997) identified four main categories of potential environmental effects of widespread urban agriculture on public land in Harare. These are listed in Box 1.E together with their implications on the quality of urban life and cost of urban management.

### Box 1-E Potential environmental impacts of urban agriculture

Adapted from Bowyer-Bower & Tengbeh (1997)

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
<th>Primary effects</th>
<th>Quality of life and environmental costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Change in the hydrological regime of the area</td>
<td>More runoff; more flooding; less infiltration</td>
<td>Flood damage to property, transport routes etc.; apparent drying of wetter areas</td>
<td>Costs of maintaining urban infrastructure are affected</td>
</tr>
<tr>
<td>2. Soil erosion</td>
<td>Lowering of the land surface; deposition of eroded sediments; particulate pollution of the air</td>
<td>Clogging of city drains; nuisance to transport; health problems</td>
<td>Increasing costs of maintaining urban infrastructure; loss of aesthetic quality of urban space; increasing the health-hazard of urban living</td>
</tr>
<tr>
<td>3. Chemical pollution</td>
<td>Eutrophication; vegetation or crop toxicity; water quality</td>
<td>Algal blooms; potential health hazards; threat to wildlife</td>
<td>Increasing costs of water treatment for safe urban water supply; loss of aesthetic quality of urban space</td>
</tr>
<tr>
<td>4. Vegetation change</td>
<td>Reduced plant species diversity; change in dominant plant type e.g. from open grassland to tall maize and weeds; loss of ground cover</td>
<td>Loss of species habitat; loss of biodiversity; loss of aesthetic quality of open land, loss of land for recreation; increased incidence of crime; cause of soil erosion</td>
<td>Aesthetic quality of urban space affected; loss of an urban amenity (recreational space); gain of an urban amenity (cultivation); increasing the crime-hazard of urban living by providing hiding habitats for muggers</td>
</tr>
</tbody>
</table>

### 1.3 The eco-city concept

**Introduction**

The eco-city-building concept is aimed at improving the city’s structural coupling, metabolism process and functional sustainability through cultivating an ecologically vivid landscape (eco-scape), totally functioning production (eco-industry) and systematically responsible culture (eco-culture) (Van der Ryn & Calthorpe, 1991; Girardet, 1992; Smit, 1996). It is a healthy human ecological process towards sustainable development within the carrying capacity of the local ecosystem through changing production mode, consumption behaviour and decision instruments based on ecological economics and system engineering (Mansson, 1992). Institutional integration, scientific incubation, entrepreneur’s investment and citizen’s incentives as
provided by government are the key in eco-city development (Van der Ryn & Calthorpe, 1991; Todd & Todd, 1994, Tjallingii, 1995).

The eco-city network is inspired by transformative environmental movements through their political wings (exemplified by the Greens) almost in every part of the world. The “Greens” share the age-old longing for the genuine community, where face-to-face interactions create a web of political, economic, social, and cultural life (Roulofs, 1996). Green theory, which emphasises on ecology, owes much to the Club of Rome’s (1972) *The Limits to Growth*, Schumacher’s (1973) *Small is Beautiful*, Ebenezer Howard’s (1965) *Garden cities of tomorrow* and Daly’s (1977) *Steady-State Economics*. The sustainable city concept is meant to remedy most of the modern metropolis and suburb’s ills through re-creation of locally or bio-regionally based economies (Hallsmith, 2003). Today, many planners and related professionals have joined the environmentalists in the eco-city movement, and advocate both environmental protection and social justice (Roulofs, 1996). Local governments world-wide have enacted formal environmental policies, which are seriously enforced (Satterthwaite, 1999, UNEP, 2002).

Several models influence eco-city designers of today, some utopian and bordering on fantasy villages proposed by a Frenchman Charles Fourier (1772-1837). Fourier believed that 1 620 people should live in communities (called phalansteries) to share the work, the wealth, the fun, and the enormous variety of tastes and passions in the combined order. Growing food (in gardens and orchards), cooking, and eating would be major activities in his new world. Sex, in all the non-violent varieties imaginable by this diverse crowd, was also an important feature. Manufacturing would be reduced to bare necessities, such as fine glassware for *le vin* and tureens for *potage*. His compact scheme for a totally full life would also encourage resource conservation, reduce pollution, and facilitate the utmost in conviviality (Roulofs, 1996). Fourier’s vision was reincarnated in the 1960’s and 1970’s in Collenbach’s (1975) novel, *Ecotopia*, which in turn influenced bio-regionalism and the USA green political movement. In Ecotopia all materials are recycled, including sewage sludge used as fertiliser. Towns are decentralised and built around public transit hubs. Energy production and the economy are bio-regional, with only a tad of imports and exports.

One of the earliest attempts to create a model eco-city dwelling is described in Olkowski *et al.*, (1979) *The integral urban house: Self reliant living in the city*. The integral urban house project in Berkeley, USA involved transforming a typical urban house into a self-reliant life support system involving food production, wind and solar energy, composting, grey water recycling, and a host of other "revolutionary" integrated systems concepts.

Urban eco-villages have been created in various parts of the world e.g., in Denmark; Vancouver, Canada; Munich, Germany; Davis in California and Ithaca in New York, USA; The Halifax eco-city project in Adelaide, Australia; Stockholm, Sweden; The Green roof (*Het Groene Dak*) in Utrecht, the Netherlands; and many others are either in planning or construction stages. Most of them have adopted a radical approach by abandoning the private household in favour of communal living another legacy of Fourier (The Catalyst, 1993; Tjallingii, 1995; Roulofs, 1996).
The joint UNCHS (Habitat) and UNEP Sustainable Cities Programme (SCP) initiative is presently working in more than 40 cities around the world (UNEP, 2002). The primary focus of the Sustainable Cities Programme is at the city level, with country, regional and global levels being recognised. According to UNEP, (2002), a sustainable city is a city where achievements in social, economic, and physical development are made to last. It has a lasting supply of the natural resources on which its development depends (using them only at a level of sustainable yield). A Sustainable City also maintains a lasting security from environmental hazards which may threaten development achievements (allowing only for acceptable risk) (Satterthwaite, 1999; Hallsmith, 2003).

The “Melbourne Principles on Sustainable Cities” governing the design and function of sustainable cities were formulated in Melbourne Australia in 2002 by a group of experts and launched in the same year during the World Summit on Sustainable Development in Johannesburg. The Principles provide cities with a framework to develop a consensus around a sustainable development policy and programs (UNEP, 2002).

**Feasibility of eco-city concept**

Eco-city concepts are theoretically interesting, however in practice the model is fraught with controversies and contradictions and even the advocates differ about the goals. There are disagreements and dilemmas on self-reliance of cities and the actual urban form (Rees, 1992; Roulofs, 1996). Are all resource imports and waste exports necessarily exploitative? Some believe that ultimately there should not be a clear separation between town and country (Harremoes, 1996; Chambers *et al*., 2000). Nonetheless there are some common widely shared objectives which include resource conservation, waste reduction, toxic reduction, social justice, participatory process, health and cultural vitality. These objectives are espoused in the 1987 United Nations “Brundtland Commission” report *Our Common Future* (WCED, 1987; Mansson, 1992).

According to Kalbermatten & Middleton (1998), the “City of the future” would be a city of neighbourhoods. This urban renaissance will include the provision of water supply, sanitation, solid wastes and storm drainage services at the lowest economically efficient level, by neighbourhood or combination of neighbourhoods. The emphasis will be on resource conservation and recycling, synergism between services, commercialisation of services (whether through public or private ownership), and multiple use of facilities for maximum public benefit (Beck & Cummings, 1996).

Even when considering single services, there is evidence that economies of scale limits may have been reached - bigger is not necessarily better. As services become more integrated or inter-related, and especially if they are increasingly turned over to communities to manage, decentralised smaller packages of services will probably be found to be more appropriate (Schumacher, 1973; Lens *et al*., 2001).

Urban ecosystem management should be based on a network of small-scale, “closed” water and nutrient cycles (Beck & Cummings, 1996; Lens *et al*., 2001) associated with a variety of patches, spatially and temporally connected in the landscape by
water and nutrient flows. Control and prediction of water and nutrient movement may depend on the number, size, shape, sequence and configuration of patches in a landscape. This is a level of complexity well beyond most current landscape-, erosion- and water and nutrient cycling- models (Tiessen, 1995).

In as yet no city in the world has demonstrated that it can sustain itself by drawing only on the resources within its boundaries. What is sought in sustainable development is not “cities that sustain themselves” but cities (and rural areas) where the inhabitants’ development needs are met without imposing unsustainable demands on local or global natural resources and systems (Hardoy et al., 1992). In the context of this study, the most essential concept of eco-city development is the closing of nutrient cycles, the short-cutting of cycles and the implementation of this process at the household and neighbourhood scale, both technically and in terms of environmental feasibility of such systems.

The question is how to achieve mastery and control with the attribute of “engineering resilience” and at the same time “ecological resilience” (Somlyody, 1995; Beck, 1997). The complexity of ecological systems is daunting and so too is the complexity of urban social systems. There are overwhelming calls globally – in the slogans of eco-cities (green or sustainable cities), clean technology, clean households, source control of pollution, recycling and recovery of valuable materials, consumption emission, closing material cycles, cross-sectoral and other, improved integration etc. - to consider revolutionising the urban water and sanitation systems in particular. A number of questions still emerge. Is it more than one of the many buzzwords, which can not really be defined? Can it be used operationally? How is it done? It is also becoming a frequent belief that “low-tech” approaches are “naturally” better than “high-tech”. That may not be the case at all. Low-tech solutions maybe technically simple, but they can be “ecologically” complicated and frequently difficult to operate (Beck, 1997; Chen & Beck, 1997; Harremoes, 1997).

1.4 Ecological sanitation and organic waste recycling

Global sanitation problem

In spite of the efforts during the International Drinking Water Supply and Sanitation Decade (1981-1990)\(^\text{13}\) (Cairncross, 1992; Evans et al., 1990) still 1.2 billion of the world's population lack access to safe drinking water and about 2.4 billion lack adequate sanitation (UNDP, 2001, 2003). WHO’s Collaborative Council Working Group on Sanitation (WHO, 1996a, 1996b) concluded that the progress of sanitation in the developing countries is hindered by basic misconceptions and myths stating that, water supply is always needed for good sanitation. Another myth originates from the assumption that water is need for to flush the toilets (Niemczynowicz, 1997a; WMO, 1997; Savenije, 2000).

Conventional sanitation in the form of waterborne sanitation has offered limited solution to this global sanitation crisis particularly in dry and soil-nutrient deficient environments (Hardoy et al., 1990) suggesting a need for a new paradigm (Niemczynowicz, 1993, 1997a; 1997b; Savenije, 2000).

\(^{13}\) So declared by the General Assembly of the United Nations; thereinafter, referred to as ‘the Decade.’
Over the period 1990-2000, access to improved sanitation increased globally from 51 to 61%, resulting in 1 billion additional people with access to sanitation. Despite these gains, in year 2000 about 2.4 billion people, 80% of them in Asia, still lacked access (Cosgrove & Rijsberman, 2000; MDG, 2000; UNDP, 2003). The gap between rural and urban areas still remains extremely wide, especially in Eastern and South-Central Asia, where coverage in rural areas is only about one quarter of the population, while urban coverage is 70% (WHO, 1996). The Millennium Development Goals\textsuperscript{14} (MDG Goal 7 Target No. 10\textsuperscript{15}) championed by the United Nations, World Bank, International Monetary Fund (IMF) and the Organisation for Economic Development (OECD) has set up an ambitious target of halving the proportion of the world’s population without improved sanitation\textsuperscript{16} by 2015. This will require reaching an additional 1.7 billion people, a challenge for greater financing and more effective sanitation programs (MDG, 2000, United Nations, 2002).

The Millennium Development Goals set targets\textsuperscript{17} for reductions in poverty, improvements in health and education and protection of the environment. They commit the international community to an expanded vision of development that vigorously promotes human development as the key to sustaining social and economic progress in all countries, and recognises the importance of creating a global partnership for development (Cosgrove & Rijsberman, 2000). The goals have been commonly accepted as a framework for measuring development progress (MDG, 2000; UNDP, 2003).

The sanitation practices that are promoted today fall into one of two broad types: ‘flush-and-discharge and forget’ or ‘drop-and-store’ (Franceys et al., 1992; Pickford, 1995; Drangert et al., 1997; Winblad, 1997; Esrey et al., 1998; 2001). Over the past hundred and fifty years flush-and-discharge has been regarded as the ideal technology, particularly for urban areas (Winblad, 1997). Many municipalities in developing countries, often with the help of international financing, have copied this model (Niemczynowicz, 1993, 1996; Drangert, 1997). For those without access to flush-and-discharge the conventional alternative has been a ‘drop-and-store’ device, usually a pit toilet, based on containment and indefinite storage of human excreta. Drop-and-store is often regarded as an inferior; temporary solution compared with flush-and-discharge (Winblad, 1997, 2000).

\textsuperscript{14} The Millennium Development Goals and targets come from the Millennium Declaration signed by 189 countries, including 147 Heads of State, in September 2000. The goals and targets are inter-related and should be seen as a whole. They represent a partnership between the developed countries and the developing countries determined, as the Declaration states, “to create an environment – at the national and global levels alike – which is conducive to development and the elimination of poverty.”

\textsuperscript{15} Goal 7 of the MDG’s refers to ensuring environmental sustainability and Target 10 reads: “Halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation.”

\textsuperscript{16} The definition of \textit{access to improved sanitation facilities} and methods for assessing it are more contentious than those for water, with national definitions of “acceptable” sanitation varying widely.

\textsuperscript{17} Proportion of the population with access to improved sanitation refers to the percentage of the population with access to facilities that hygienically separate human excreta from human, animal and insect contact. Facilities such as sewers or septic tanks, pour-flush latrines and simple pit or ventilated improved pit latrines are assumed to be adequate, provided that they are not public, according to the World Health Organization (WHO) and United Nations Children’s Fund’s (UNICEF) \textit{Global Water Supply and Sanitation Assessment 2000 Report}. To be effective, facilities must be correctly constructed and properly maintained (MDG, 2000).
The major question in sanitation today is? How can a rapidly growing city short of money and water and with limited institutional capabilities achieve safe, non-polluting sanitation for all its inhabitants (or even recover its resources)? Conveniences like flush toilets are totally dependent upon the electrical grid and completely reliant on a constant water supply. When the electricity is out and water is unavailable, how does one flush the toilet? Supplying the clean water, treating the sewage, and providing all the delivery and collection requires sophisticated systems whose cost strains the resources even in wealthy countries (Niemczynowicz, 1993, 1996).

The historical background for the waterborne sanitation in cities needs to be outlined in order to give the rationale for the technical solutions that have been inherited from last centuries (Niemczynowicz, 1993; Hayward, 1997; Larsen & Gujer, 1997; Niemcynowicz, 1997a; Otterpohl et al., 1997). The key element is maintaining the hygienic conditions in the cities. The success is illustrated by the absence of water borne diseases in the modern developed city (Butler & Parkinson, 1997; Harremoes, 1997).

**History of conventional waterborne sanitation**

Methods of waste disposal date from ancient times, and sanitary sewers have been found in the ruins of the prehistoric cities of Crete and the ancient Assyrian cities. Storm-water sewers built by the Romans are still in service today (Herschel, 1973; Goubert, 1989; Drangert, 1997). Although the primary function of these was drainage, the Roman practice of dumping refuse in the streets caused significant quantities of organic matter to be carried along with the rainwater runoff through the Cloaca Maxima to the river Tiber emptying into the Mediterranean Sea (Herschel, 1973). The one million citizens of Rome imported much of their food from neighbouring countries and did not have to worry about the reuse of nutrients in the effluent. After the decline of the Roman Empire, advanced sewer systems initially fell into oblivion.

Toward the end of the Middle Ages, below-ground privy vaults and, later, cesspits were developed. When these containers became full, sanitation workers removed the deposit at the owner's expense. The wastes were used as fertiliser at nearby farms or were dumped into watercourses or onto vacant land (Gotaas, 1956; Del Porto & Steinfeld, 1999).

In England, Chadwick's report in 1842 had advocated for combined hygiene and recycling of nutrients by application of wastewater on agricultural fields through the use of the ‘pail system’. However the unique conditions in London made it possible to flush all human waste via the perennial River Thames into the North Sea (Gayman, 2000). As with the Romans, with cheap imported fertilisers, the English then were not concerned about a decline in soil fertility (Asano & Levine, 1996; Drangert, 1997).

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18 Chadwick's Report on Sanitary Conditions: Edwin Chadwick (1803-1890) had taken an active part in the reform of the Poor Law and in-factory legislation before he became secretary to a commission investigating sanitary conditions and means of improving them. 'Report from the Poor Law Commissioners on an Inquiry into the Sanitary Conditions of the Labouring Population of Great Britain. London, 1842, pp 369-372.
In the first half of the 19th century Europe experienced epidemic Cholera, called the Asian disease, because it migrated in waves from Asia to Europe e.g. in 1853 the epidemic reached Copenhagen, Denmark, with the result that 7% of the population died in two month (Doudoroff & Adelburg, 1970; Hunter, 1997). Nobody knew the real cause. Not until after the discovery of bacteria by Pasteur, in 1880 did real understanding of the mechanisms of transmission of water borne diseases have an impact on the application of technology. Before that, the “experts” were divided into two camps. The two concepts were Miasma versus Contagionism. Miasma was the belief that diseases are the result of a foul environment (mostly air). Contagionism was the belief that some (as yet unknown agent) cause a contamination that could be transferred by infection through contact (Gayman, 2000). John Snow during the Cholera epidemic in Soho, London 1855, made one of the first real epidemiological investigations that indicated transmission via water (from the Broad Street pump); however his approach was not recognised until much later. This era can be referred to as the ‘great sanitary awakening’ era (Taras, 1981; Goubert, 1989; Winblad & Kilama, 1985).

In the 19th Century the concept of miasma prevailed: the cities had to be cleaned up. Clean water, air and food had to be provided and waste had to be carried out of the cities in an organised fashion. Therefore the introduction of water supply and sewerage was based on a false concept, a misunderstanding of the issue (Gayman, 2000). Development of municipal water-supply systems and household plumbing brought about the modern sewer systems. Despite some reservations that sanitary sewer systems wasted resources, posed health hazards, and were expensive, many cities built them in Europe and in the USA (Taras, 1981; Goubert, 1989; Niemczynowicz, 1996).

At the beginning of the 20th century, a few cities and industries began to recognise that the discharge of sewage directly into the streams caused health and environmental problems, and this led to the construction of sewage-treatment facilities (Asano & Levine, 1996). At about the same time, the septic tank was introduced as a means of treating domestic sewage from individual households both in suburban and rural areas (Gayman, 2000). Because of the abundance of diluting water and the presence of sizable social and economic problems during the first half of the 20th century, few municipalities and industries provided wastewater treatment ‘The sewer overfloweth’ (Del Porto & Steinfeld, 1999).

During the 1950’s and 1960’s, the USA and most European governments encouraged the prevention of pollution by providing funds for the construction of municipal wastewater treatment plants, water-pollution research, and technical training and assistance. New processes were developed to treat sewage, analyse wastewater, and evaluate the effects of pollution on the environment (Metcalf & Eddy, 1995). In spite of these efforts, however, expanding population and industrial and economic growth continued to cause pollution and health difficulties in both the developed and developing countries (Young, 1985; Del Porto & Steinfeld, 1999).

Up until the 1990’s emphasis has been on reclamation and reuse of water in wastewater and not the contained nutrients (Harremoes et al., 1991; Asano & Levine, 1996; Nakazato, 1997). From the 1970’s technology and research has been advanced for removing nutrients from wastewater (notably biological nutrient removal in
activated sludge treatment works) so as to mitigate eutrophication of fresh water lakes. In arid areas like Windhoek in Namibia reclamation of wastewater for potable reuse has been achieved with minimal potential for health risks (Harhoff & Van der Merwe, 1998).

Human excreta have traditionally been used for crop fertilisation in many countries (Night Soil Fertiliser Industry; Del Porto & Steinfeld, 1999). Medical science in the 19th Century posed no barriers to the use of human wastes directly on the soil. The Massachusetts sanitary commission of 1850 argued that, when applied ‘in the open country’, the wastes where “diluted, scattered by winds, oxidised in the sun: vegetation incorporated its elements”. Miasmas and contagions would be dealt with by nature (Del Porto & Steinfeld, 1999). In China human and animal excreta have been composted for millenia and is still widely practiced (King, 1973; Matsui, 1997). In 1952 an estimated 70% of all human excreta produced in China was collected and used as fertiliser and this represented about a third of all fertiliser use in the country (Gotaas, 1956; Winblad & Kilama, 1985; Matsui, 1997). Whilst in Japan it is recorded that recycling of urine was introduced in the 12th century (Matsui, 1997; Shiming, 2001).

In the 1970’s alternative dry sanitation systems exemplified by the Clivus Multrum were developed and marketed in Sweden and the USA in particular (Winblad & Kilama, 1985; Del Porto & Steinfeld, 1999, Jenkins, 1999). In Sweden initially, these were intended for use in summer cottages rather than in apartments, but this earlier interest among ecologically minded individuals has now broadened into a public concern. The Swedish Environmental Protection Authority (SEPA) has approved a number of these dry systems and the current regulations make the user responsible for maintaining the system (Drangert, 1997).

Wastewater and sludge has also been widely used in agriculture in the last two centuries (Smith, 1996). However, when raw sewage was used in Berlin in 1949, it was blamed for the spread of worm-related diseases. In the 1980s, it was said to be the cause of typhoid fever in Santiago, and in 1970 and 1991, it was blamed for cholera outbreaks in Jerusalem and South America, respectively (Metcalf & Eddy, 1995). The economic value of human excreta has gradually been outweighed by the demands for hygienic and aesthetic conditions. Incidentally, the production of synthetic fertilisers began at the turn of the last century and accelerated after the Second World War (IFA, 1999; IFA & UNEP, 2002).

It is realised that sanitation is not just a ‘technical fix’ but an intricate interplay of norms and attitudes among professionals as well as users. The reasons for installing an improved collection of excreta may vary, and often include status, convenience, hygiene and improved health (Lens et al., 2001). Rarely is improved nutrition mentioned, since re-circulation of nutrients is hardly practised or contemplated (Staudenmann et al., 1996; Esrey et al., 2001). Sanitation in its global sense should include collection, sanitisation and beneficial use of human excreta, sullage or grey water and solid waste. In broad terms sanitation calls for the holistic management of

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19 Phosphorus bound to the sludge makes the sludge interesting as phosphorus fertiliser. Unfortunately not only P is bound to the sludge, but also toxic compounds that derive from the wastewater (Ekvall, 1995).
both the water cycle and the food cycle to avoid health and environmental repercussions.

**Ecological sanitation**

According to many water professionals, researchers, environmentalists and public health experts a new paradigm in sanitation has emerged based on three fundamental aspects: 1. rendering human excreta safe; 2. preventing pollution rather than attempting to control it after polluting and; 3. using the safe products of sanitised human excreta for agricultural purposes. This approach can be characterised as ‘sanitise-and-recycle’ and can be called ‘ecological sanitation’ or ‘eco-san’ for short. It is a cycle - a sustainable, closed-loop system. It treats human excreta as a resource. Human excreta are processed on site or off-site (commonly applying dehydration and decomposition techniques) and then, if necessary, further processed off site until they are completely free of disease organisms. The nutrients\(^{20}\) contained in the excreta are then recycled by using them in agriculture (Winblad, 1996; Drangert *et al*., 1997; Otterpohl *et al*., 1997; Esrey *et al*., 1998; Winblad, 2000; Esrey *et al*., 2001; Werner, 2001).

The principles underlying eco-san are not novel. The Swedish ecosan programme is based on “collection, containment, sanitisation and use of excreta” (Jonsson *et al*., 2004). In different cultures sanitation systems based on ecological principles have been used for hundreds of years (Matsui, 1997; Del Porto & Steinfeld, 1999). Ecological sanitation systems are still widely used in parts of East and South-East Asia (mainly China, Japan and Korea) (Polprasert *et al*., 1981). In Western countries this option was largely abandoned as flush-and-discharge became the norm but in recent years there has been a revival of interest in ecological sanitation. With ecological sanitation it is preferable to avoid mixing (Winblad, 1996; Winblad, 2000; Esrey *et al*., 1998; 2001; Werner, 2001):

- Human urine (*yellow water*) and faeces (*brown water*)
- Human excreta and water (dry-sanitation systems are preferable)
- **Black water** and **grey water**
- Household organic wastes and industrial wastes
- Wastewater and rainwater

According to this concept, by not mixing human excreta and flushing water the sanitation problem is limited to managing a comparatively small volume of urine and faeces. This leads to savings in water, savings on pipe networks and treatment plants, employment creation and preservation of the environment (Winblad, 1996; Winblad, 2000; Esrey *et al*., 1998; 2001; Werner, 2001). Domestic water use can also be reduced by recycling grey water for washing cars, flushing toilets, and watering gardens i.e. non-potable water uses (Whelans, Maunsell & Palmer, 1993).

The purpose of ecological sanitation systems is the closing of the water and nutrients cycles, taking into account that the main task of sanitation is to assure highest

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\(^{20}\) In this dissertation plant nutrients refer to all types of nutrients, whether organic or inorganic, that combines with energy from the sun to result in plant growth. The word “fertiliser” will usually refer to chemical or inorganic fertiliser unless it is explicitly qualified with the adjective ‘organic’. Therefore, plant nutrients include both organic and inorganic fertilisers.
hygienic standards in a cost-effective, environmental sustainable way (Esrey et al., 2001; Simpson-Herbert, 2001), saving both water and energy and keeping soils fertile. There is a fundamental connection between agricultural development and actions to be taken in the sanitation sector and organic waste management (UNDP, 1996; Savenije, 1998).

**Feasibility of ecological sanitation**

The plant nutrients stemming from human metabolism contained mainly in urine is of particular interest in ecological sanitation (Olsson; 1995; Larsen & Gujer, 1996; Herrmann & Klaus, 1997; Jonsson et al., 1998; Johansson et al., 2000). Ways of recovering the resources in urine, which include – diversion, separation, absorption and combined processing with faeces, vacuum toilet systems, waterless urinals (some toilet pedestals are shown in Figure 1.2) – are currently under intensive investigation and piloting in numerous settlements around the world (Del Porto & Steinfeld, 1999; Jenkins, 1999; Morgan, 2000; Clark, 2001; Hoglund, 2001; Vinneras, 2002; Werner et al., 2003). There are different possibilities to design sanitation systems, in accordance with the Bellagio Principles. One option is certainly the installation of on-site dry sanitation systems using ecological toilets with or without urine diversion (Esrey et al., 1998; Morgan, 1999; Jenkins, 1999, Del Porto & Steinfeld, 1999). Figure 1.2 (b) shows a non-flush urine diverting toilet seat from Zimbabwe (note the ash container on the right: ash is used as a desiccant and to facilitate composting, an optional air freshener container can also be seen to the left).

The focus on urine is because it contains the bulk of the plant nutrients in domestic wastewater, approximately 80% of nitrogen, 55% of phosphorus and 60% of the potassium (see Table 1.9 and Figure 1.3), furthermore, this is provided in the correct forms for uptake by crops - nitrogen as urea, phosphorus as super-phosphate and ionic potassium, with urine also being free from heavy metals and usually sterile and less objectionable to handle. The plant availability of the nutrients Nitrogen (N), Phosphorus (P) and Potassium (K) in source separated urine is high (Lentner et al., 1981; Kirchmann & Pettersson, 1995; Larsen & Gujer, 1996) and the concentrations of different heavy metals are low (Jonsson et al., 1997; 2004). Furthermore, after being stored the hygienic quality of the source separated urine improves considerably (Blumenthal et al., 1989; Cairncross et al., 1995; Hoglund et al., 1998; Hoglund, 2001).

The arguments favouring the ecological sanitation approach are convincing at least from an agricultural point of view. The average global cereal output is about 0.1 kg/m² (FAO, 1986; 1999a; 2001). This implies that the land area needed to produce an average adult person’s annual intake²¹, of say, 250 kg of cereals would be 2 500 m² (Drangert, 1997). This varies substantially between different agricultural zones and whether irrigation or dry-land farming is contemplated: from some 500 m² in irrigation agriculture to as much as 5 000 m² in dry-land farming on marginal land (Drangert, 1997). In a year, each person excrete the fertilisers needed to grow the 250 kg of cereal they require over the same period of time, with urine accounting for around 90% of this fertiliser value (Drangert, 1996; 1997; Lienert & Larsen, 2003).

²¹ There are many different suggestions of the area needed to feed a person. The span is generally between 100 and 800 m². The requisite area differs with the climate, the soil, the access to water and fertiliser and the diet of the family – vegetarians need less area.
Figure 1-2 Some types of ecological sanitation toilet receptacles
(a) Urine diverting non-flush dry toilet concrete used and manufactured by Mvuramanzi Trust in informal settlements in Harare; (b) Porcelain non-flush urine diverting dry-toilet seat designed by Aquamor, Harare, Zimbabwe; (c) and (d) Double-flush urine-diverting toilet seat, the Nordic 393U from Gustavsberg and Dublette from BB Innovation and Co AB; (e) Chinese urine-diverting squat pan; (f) Swedish vacuum toilet system.
Photographs: Gumbo (1998 to 2002)
Table 1-9 Elemental composition and volume of domestic wastewater expressed per adult person per day (p.d)\(^{22}\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Urine</th>
<th>Faeces (^a)</th>
<th>Grey water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Range</td>
<td>Value</td>
<td>Range</td>
</tr>
<tr>
<td>Volume (^b)</td>
<td>litres/p.d</td>
<td>1.2</td>
<td>0.6-1.5</td>
<td>0.15</td>
</tr>
<tr>
<td>Weight (^b)</td>
<td>g/p.d</td>
<td>1200</td>
<td>600-1500</td>
<td>150</td>
</tr>
<tr>
<td>Total solids</td>
<td>g/p.d</td>
<td>60</td>
<td>20-150</td>
<td>45</td>
</tr>
<tr>
<td>Total nitrogen</td>
<td>g/p.d</td>
<td>11</td>
<td>4-16</td>
<td>2</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>g/p.d</td>
<td>1</td>
<td>0.5-2.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Potassium</td>
<td>g/p.d</td>
<td>2.5</td>
<td>1-5</td>
<td>0.5</td>
</tr>
<tr>
<td>BOD(_5)</td>
<td>g/p.d</td>
<td>7.5</td>
<td>2-14</td>
<td>14</td>
</tr>
<tr>
<td>COD</td>
<td>g/p.d</td>
<td>15</td>
<td>4-28</td>
<td>35</td>
</tr>
</tbody>
</table>

a) Values exclude flush water. Flush water volume ranges from 15 to 80 l/p.d with an average value of 30 l/p.d.

b) Density assumed to be 1.0 kg/dm\(^3\)


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Figure 1-3 Content of major plant nutrients and volume in typical domestic wastewater

To grow 250 kg of maize requires 5.6 kg of nitrogen, 0.7 kg of phosphorus and 1.2 kg of potassium and urine provides 5.6, 0.4 and 1.0 kg respectively (\textit{The urine equation}, Drangert, 1996; Hellstrom & Karrman, 1996; Jonsson, 1997; Niemczynowicz, 1997a; Niemczynowicz, 1997c).

Other points in urine’s favour are that (see Box 1.F: Concise facts on human urine as fertiliser), when collected in ‘no-mix’ toilets that keep urine and faeces separate, flushing can be carried out with only 100 millilitres (Herrmann & Klaus, 1997; Niemczynowicz, 1997c).

\(^{22}\) There is a wide range of variability in the content of excrement and water use from person to person and place to place. Factors include nutrition, climate, health, age, lifestyle and levels of service for water and sanitation. For example, vegetarians produce higher quantities of faeces with higher water content than those who eat meat (Lentner \textit{et al}., 1981; Feachem \textit{et al}., 1983; Del Porto & Steinfeld, 1999).
Vinneras, 2002). As a result, the yearly volume of urine and flush water will only be about 0.7 m³ per person, so that transportation costs are likely to be low.

**Box 1-F Concise facts on human urine as fertiliser:**
*Separation, collection, storage, transportation and application*

Adapted from Johansson *et al.*, (2000)

- Human urine is a quick acting fertiliser that can replace mineral fertiliser in crop production.
- The relationship between nitrogen, phosphorus, potassium and sulphur is well-balanced and, with appropriate doses, broadly corresponds to the needs of most crops.
- The odour problems in connection with urine separation toilets do not appear to be greater than with other toilets.
- Transport systems and technology for the storage of urine are currently available on the market
- Nitrogen losses during transportation and storage can be kept very low if the urine is stored in non-ventilated tanks²³.
- A high temperature, low dilution and high pH levels promote sanitisation of the urine mixture. Recommendations are now available for storage times and suitable crops.
- Urine in itself presents a negligible hygienic risk.
- Faeces that enter the urine bowl can contaminate the urine.
- Many pathogens are killed during a storage period of about 6 months.
- Nitrogen losses in the form of ammonia in connection with application are normally less than 10% (usually 5%) (Jonsson *et al.*, 2004).
- Conventional techniques for applying liquid manure work well for human urine too. New technology is also of interest e.g. umbilical hose systems.
- There is a noticeable odour while urine is being applied, but this subsides within 24 hours. At a short distance from the field the odour is not a problem
- The risk of nitrogen leaching into water is no greater than when mineral fertiliser is used.

In general it can be said that pathogen survival depends mainly on time-temperature combinations. When the temperature is high enough for a certain period of time, pathogens will die (see Figure 1.4; Feachem *et al.*, 1983; Mara & Cairncross, 1989). It is bacteria in faeces, which produce urease, which is responsible for conversion of urine to ammonia gas thereby creating odour problems (Esrey *et al.*, 1998).

It is obvious that the open space available in densely populated urban areas my not allow 100% in-situ recirculation of all human excreta (mainly urine and including the organic fraction of solid waste), even if all open space was allotted to agriculture (Drangert, 1997). Drangert, (1997) proposed a relationship between outdoor space and plant uptake of nutrients (see Figure 1.5). There is a biochemical limit to what plants can absorb and soils can retain nutrients and another limit to what is administratively allowable. In between these limits there is a ‘feasibility gap’ where interesting combinations of local recirculation and export to distant sites can be found. The capacity for 100% local recirculation depends on the population density. In very densely populated areas like Khayelitsha in Cape Town, South Africa or Dzivarasekwa Extension in Harare, Zimbabwe where less than 10 m² of open space per person are available, it would require strong efforts by skilful and keen horticulturalists (Drangert, 1997).

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²³ One method to reduce this risk is to prevent the decomposition or urea to ammoniacal nitrogen by adding small amounts of acid to the fresh urine before storage (Vinneras, 2002).
In China the old tradition of human manure (humanure) use in agriculture still continues (see Box 1.G: Overview of some ecological sanitation projects) and a range of new toilet receptacles have been developed (King, 1973; Jiang, 2001; Shiming, 
In Mexico around 100,000 urine separation toilets have been distributed (Clark, 2001; Esrey et al., 2001; Cordova & Knuth, 2003), and in Africa a number of projects are being implemented in other countries notably Mvula Trust and CSIR in South Africa (Austin, 2003; Holden, 2003), WaterAid and ESTAMOS in Mozambique (Breslin & Dos Santos, 2001), SUDEA in Ethiopia (Faul-Doyle, 1999; Terrefe & Edstrom, 1999; 2001), OSIENALA in Kenya (Munyirwa & Onganga, 1999) and a number of NGO’s in Uganda a country which has adopted ecological sanitation on a wider scale (Schattauer et al., 2001; Nyiraneza, 2001). In Zimbabwe and many other similar case studies full utilisation of separated urine is yet to be achieved (Faul-Doyle, 1999; Morgan, 1999; Guzha, 2001).

**Box 1-G Overview of some ecological sanitation projects**

**Sweden**
The Understenshöjden eco-village in Sweden is situated in the suburb of Björkhagen, south of Stockholm. The village meets high ecological standards with regard to waste management, construction materials, energy systems and the outdoor environment. Ecological sanitation was introduced in 1995 to 44 apartments with 160 residents. Urine-separating toilets (wall hung Dubletten models) were installed. The urine is collected in two series connected tanks of 40 m$^3$ each. When the first tank is full, the urine mixture overflows into the other one. About once a year the urine is transported to holding tanks at Lake Bornsjön in Salem where it is stored for about 6 months. The remaining toilet waste and grey water is treated in a local biological treatment plant before being released for tertiary treatment in a system of ponds and ditches (Johansson et al., 2000).

The Palsternackan housing estate situated in Enskede south of Stockholm has 51 rental apartments with 160 residents commissioned in 1995. The Dubletten urine-separating toilets are used. The urine is collected in three subsystems of roughly equal size, each connected of 30 m$^3$ capacity tanks. The tanks are emptied once a year and the urine is transported to holding tanks at Lake Bornsjön where it is stored for about 6 months. The remaining wastewater (faeces, flush water and grey water is discharged into the Stockholm wastewater system (Johansson et al., 2000; Vinneras, 2002).

At Lake Bornsjön three 150 m$^3$ ‘balloon’ tanks made out of rubber are used for storage. The tanks are airtight (minimal nitrogen losses during storage), require little construction work (can be easily re-located), and are reasonably priced. A farm close to the tanks uses the urine solution by means of a feeder hose to grow spring barley for forage.

In the Understenshöjden and Palsternackan there were some starting problems: odour problems through improper connection. Groundwater was leaking into pipes, because they were not watertight. Blockage of the urine collection separation system by hair and other objects and precipitation of urine. However the toilets were found not to be smelly compared to conventional flush toilets. Although a little more work was required for cleaning. Well motivated and informed residents contribute to the efficient functioning of the system and hence the recovery rate of the nutrients in urine (Fittschen & Niemczynowicz, 1997; Johansson et al., 2000).

**Zimbabwe**
Mvuramanzi Trust a Zimbabwean NGO has been making ecological sanitation trials since 1998. About four different technologies have been developed to date and are being used in a number of community trial projects. Before introducing ecological sanitation practice among communities the Trust carried out a basic base line knowledge attitude and practice survey. The survey showed that people in Zimbabwe and the region were using urine and faeces as fertiliser or for medicinal purposes. Trials on crops showed that urine and sanitised faecal matter are useful ingredients to plant growth and improved harvest (Morgan, 1999; Esrey et al., 2001; Guzha, 2001).
1 Introduction

Box 1-G Overview of some ecological sanitation projects (conti)

During the experimental trials Mvuramanzi Trust came up with the following ecological sanitation technology designs which are being used in rural and peri-urban situations (Guzha, 2001):

1. *Compost latrine*: The compost latrine consists of two vaults $1 \text{ m} \times 1.2 \text{ m} \times 3 \text{ m}$ long these vaults are separated by a dividing wall. The vault is fitted with an access opening through which the digested excreta can be empty. A compost toilet normally has two non-urine diverting squat or and pedestal leading to each vault. One such squat and vault is used at a time whilst the other one is closed. Organic materials such as leaves, ash, soil, saw dust and grass is added into the toilet as the people uses the toilet. Earthworms may also be added to the mix, these together with fly-maggots help to digest the matter. The contents are left for six months to mature before being used as manure.

2. *Abhor-loo “Tree toilet”*: The Abhor-loo consists of a movable bottom slab and a portable upper structure; the movable components are placed on a 0.7 m shallow pit lined with bricks to prevent the pit from collapsing. Users are encouraged to add ash, leaves and other organic material as they use the toilet. The mixture of soil, ash, urine and faecal matter forms a rich mix of compost. When the pit becomes $\frac{3}{4}$ full a layer of top-soil is added and a choice fruit tree is planted. The toilet is used to furnish orchards and have been used extensively to address sanitation and deforestation problems in some peri-urban informal settlements. Communities are planting bananas, guava, marlberry and mango trees.

3. *Fossa Alterna*: This operates like an Abhor-loo, it consists of movable upper structure and slab which is placed on top of 0.7 m pit, in the case of the Fossa Alterna twin pits are used. The materials used to make the supper structure ranges from plastic sheets, hessain and wood. The family is encouraged to add organic matter, ash and soil to the human excreta as they use the toilet. When the first pit is $\frac{3}{4}$ full it is covered top soil is added, short term plants like maize and flowers may be planted into the pit the plant roots helps in breaking down the faecal matter facilitating decomposition. The matter can be left for six months or so to allow for composting to take place, after the 6 months the rich organic manure is recovered and used in agriculture.

4. *Sky-loo Urine Diverting toilet*: Sky-loo refers to a step up toilet built with a vault above the ground to minimise the possibility of ground water contamination especially in areas where the water table is very high. A wooden or brick super structure is placed on top of the vault. The faecal matter drops directly into the vault or into the plastic dish place in the vault. The Sky-loo urine diverting toilet is fitted with a urine-separating pedestal that diverts urine and ensures that urine and faeces do not mix. The separation of urine and the addition of soil and ash accelerate drying of faeces and create an environment that hinders multiplication of pathogenic bacteria. The diverted urine go through a network of pipes into a small soak away where a tree is planted to absorb some of the nitrates from the urine to prevent contamination of underground water.

Germany

In the ecological housing estate Flintenbreite in Lübeck vacuum toilets are installed in combination with anaerobic digestion with co-treatment of organic waste in a semi-centralised biogass-plant. Grey water is treated in a decentralised vertical flown constructed wetland. Storm water is retained in an infiltration constructed wetland. The project began in 1999. Until 2003 28 houses with 95 inhabitants had been constructed. The vacuum system has been running for 2 years without any technical problems. The flushing system is optimised and uses 0.7 litres for flushing. The average drinking water consumption is around 77 litres per capita per day. Problems and their reasons can be identified very easily. The vacuum toilets have been well accepted by the inhabitants and are now viewed as more hygienic than conventional flushing toilets (Otterpohl *et al.*., 1997; Otterpohl 2001; Wendland & Oldenburg, 2003).
Box 1-G Overview of some ecological sanitation projects (conti)

In the ecological village ‘Braamwisch’ in Hamburg composting toilets were installed in 1999. The Biolett system was installed in 15 houses whilst the TerraNova composting toilet was installed in 18 houses with. An additional 7 houses had a normal flush toilet with rainwater used for flushing. Co-composting of kitchen refuse together with the faeces and urine was selected. The major motivation of the inhabitants or users was contribution to the environment sustainability though the use of composting toilets. The composting process was rather complex and needed much attention. The users had to take the initiative themselves and solved some of the problems through ‘learning by doing’. The grey water system composed of mechanical pre-treatment in a septic tank and biological treatment in reed bed soil filters of about 2 m² per person (Bijleveld, 2003).

China

Under the influence of the long tradition (dating back almost 5 000 years; King, 1973), human excreta is always used as fertiliser for crops in China (Shiming, 2001; Wenhua & Rusong, 2001). The main application methods are (1) direct usage for crops and fruits as basal or top application after fermentation in a ditch for a certain period, (2) composting with crop stalk for basal application, (3) direct usage as feed for fish in ponds. Even human waste generated in the cities and towns has been very valuable for farmers. Before 1949, there were private companies in Wuhan, Beijing, and other cities to control the commercial selling of human excreta (Shiming, 2001). Although the tradition of using human waste still continues, the percentage of human excreta used is decreasing due to a host of reasons, among them: increased urbanisation, reduced capacity to use the waste in peri-urban farms, transportation logistics, unsanitary methods of treatment, handling and application of excreta. It is estimated that in year 2000 an average of 31% of the absolute amount of human excreta generated in Beijing, Xian, Shanghai, and Changchun was collected and applied on farm land (Shiming, 2001).

With financial assistance from the Sida-funded EcoSanRes programme a pilot ecological sanitation project was introduced in 1998 in a large number of villages. The project was well received by villagers as well as by the government. The original pilot project covered 70 households, the following year 2 000 households were provided with ecosan systems, in year 2000 another 8 000 households. By the end of 2001 a total of 30 000 households in Guangxi are had ecosan toilets with urine diversion. The urine-diversion squatting pan was designed during his programme and patented in China. Many of the toilets were built inside the dwelling, and often upstairs. Apart from toilets for individual households a total of 7 ecosan school toilets have been built (Jiang, 2001).

Netherlands

In 1993 the housing estate ‘Groene Dak’ in Utrecht in The Netherlands installed two Clivus Multrum composting toilets. Grey water was treated in oxidation beds or reed beds. Despite a lot of effort and motivation the composting toilets never worked. There was too much moisture and an anaerobic environment, probably due to little aeration. This lead to problems of flies, spiders and smell nuisance. A very strong energy consuming ventilator was installed to mitigate the smell problem. In 2000 the toilets were removed because the composting process had failed. The removal of the black cake got national attention because of a suspected danger of explosion. The composting toilets were replaced by water saving toilets connected to the sewer system (Bijveld, 2003; translated from URL: www.groenedak.nl).

At the Twaalf ambachten in the province Noord Brabant in The Netherlands around 20 users have used the Paper Leaf Toilet, a sort of composting toilet. Composting is not done in or under the toilet. The bucket with faeces and paper is mostly emptied on the compost pile in the garden. The urine flows into the sewer or into a constructed wetland. Most of the users used the toilet because of environmental concerns, some because they had no connection to the sewer system. In the beginning problems occurred due to a construction failure in the first model. After some improvement most of the users where satisfied. However some felt emptying the container was not very pleasant and hygienic (Bijveld, 2003).
In Sweden, recycling of nutrients produced in sanitation systems to agriculture without increasing concentrations of conservative pollutants in soils is being given special attention (Johansson et al., 2000). This requires non-flush dry, double-flush, micro-flush, foam flush, vacuum flush and urine-diverting solutions, and changes in, for example, construction of houses and layout of cities (Fittschen & Niemczynowicz, 1997). In Sweden more than 50,000 non-flush dry systems have been sold in 42 models from 22 manufacturers (Drangert, 1997; Esrey et al., 1998). They cost scarcely more to buy and can cost less to install than a non-diverting toilet plus its sewer connection. Many other countries around the world have come up with a variety of proprietary urine separating and composting toilets. In Zimbabwe, two NGO’s, Mvuramanzi Trust and Aquamor have developed a number of such toilet seats and about 7,000 have been installed mostly in rural and urban squatter settlements (Morgan; 1999; Esrey et al., 2001; Guzha, 2001).

The popular Swedish WM-Ekologen (now Wost Man Ecology AB) dehydrating toilet costs about US$ 360. The total on-site installation cost including a seat-riser; fan, processing vault, transport container and a 1 m$^3$ urine tank is about US$ 750 (Johansson et al., 2000). The Mvuramanzi Trust non-flush dry toilet seat version (which is a hybrid of South African and Mexican design) costs about US$ 10 and the full installation including the superstructure is about US$ 70 (Morgan, 1999; Guzha, 2001).

**Urban organic waste recycling**

Urban solid waste reduction and reuse involves, among other things, composting of urban organic wastes (especially in cities of developing countries where the organic fraction of municipal solid waste is high) (Furedy & Chowdhury, 1996; Polprasert, 1996; Lardinois & Furedy, 2000). Discussions of urban agriculture frequently point out that city farming often absorbs urban solid waste, thus reducing the volume of waste and the need to collect and transport wastes to distant dumps. In practice, urban farmers in many cities acquire municipal wastes as resources (Lewcock, 1994; Rosenberg & Furedy, 1996; UNDP, 1996).

The combination of urban organic wastes and urban agriculture creates particular issues in the modern urban setting (Gardner, 1998; Rose, 1999; Ojeda-Benitez et al., 2000). On the one hand, the interests of urban waste reduction mesh well with the promotion of urban agriculture, since urban and peri-urban farmers are in need of organic matter as soil conditioner or fertiliser and animal feed, and cities and towns wish to conserve disposal space and reduce the costs of municipal solid waste management (UNCHS, 1989; WHO, 1991). At the same time, some tensions occur between public health officials (with their concerns about diseases affecting both humans and animals and accidents associated with the reuse of municipal solid wastes, (see Box 1.H: Waste recycling potential in India) on the one hand, and the proponents of urban agriculture (who emphasise job creation and increased food production, especially for the urban poor) on the other (Gotaas, 1956; Flintoff, 1976; Furedy & Chowdhury, 1996).

Composting solid waste for use as a soil amendment, fertiliser, or growth medium is important in many countries (Tchobanoglos et al., 1993; Furedy & Chowdhury, 1996; Gardner, 1998; Rose, 1999). Asian countries in particular have a long tradition of
making and using compost (Flintoff, 1976; Polprasert, 1996). In Western Europe, a range of modern technologies is used to produce compost (Suess, 1985).

**Box 1-H Waste recycling potential in India**
Adapted from Harender & Bhardwaj (2001)

India’s current manurial potential of livestock and human excreta is estimated at 14 Mt of nitrogen, phosphorus and potassium nutrients, which is close to the present fertiliser consumption of the country (13 Mt). A few more million tonnes can be made available from crop residue, municipal solid waste, agro-industrial waste, and industrial waste. Careful collection, bio-conversion, conservation and recycling of all these available organic wastes or manures would enable India to meet its nutrient requirement of the crops to a considerable extent and thus its agriculture on a sustainable basis.

India generates around 25 Mt of municipal solid waste every year and about 60% of the waste comprises of biodegradable organic wastes originating from kitchen and markets. In addition, 273 Mt of crop residue and 6 Mt of fruit waste is also generated every year. This waste material can be processed with the help of earthworms in order to produce organic fertiliser at site without any extra cost. Earthworms play a key role in soil biology by serving as versatile natural bioreactor, converting organic wastes into valuable organic manure. The benefits are now being globally realised that earthworms can do wonderful job in the management of different pedo-ecosystems.

They are useful in land reclamation, soil improvement and organic waste management. Earthworms are also efficient environmental monitoring tool because worms can accumulate certain heavy metals, industrial effluents, various biocides, pesticides and their residues. Earthworms improve the soil texture, soil aeration, enrich the soil with nutrients and promote useful soil micro flora required for plant growth. Earthworms eat and mix a large amount of soil and organic matter, then deposit their castings (vermicompost) either on the surface of the soil or in burrow, depending on species. The vermicompost contains high concentration of organic material, silt, clay and is rich in many soil nutrients such as nitrogen, sulphur, potash, phosphor, calcium, magnesium, etc. In soil, much of the phosphorus is bound in organic matter in a form that is not available to plants. Earthworms change the phosphorus into a form that the plant roots can easily absorb. The mixing action of the earthworms can also make slow-release forms of phosphorus fertilisers more readily available.

At the same time, composting has the distinction of being the waste management system with the largest number of failed facilities worldwide. In cities of developing countries, most large mixed-waste compost plants, often designed by foreign consultants and paid for by aid from their home countries, have failed or operate at less than 30% of capacity (Holmes, 1984; Furedy, 1992; Rosenberg & Furedy, 1996; Lardinois & Furedy, 2000). The problems most often cited for the failures of composting include: high operation and management costs, high transportation costs, poor quality product as a result of poor pre-sorting (especially of plastic and glass fragments), poor understanding of the composting process, and competition from chemical fertilisers (which are often subsidised). In many urban places, collection systems are too unreliable for urban authorities to consider running composting facilities efficiently (Tchobanoglous et al., 1993; Lardinois & Furedy, 2000).

Industrialised and transition countries have more mature urban infrastructure, and a more clear separation between urban and rural food production practices. Developing countries tend to have more agriculture and horticulture within urban limits, providing a ready market for compost, depending on its organic and nutrient content (UNCHS, 1989; WHO, 1991; Furedy, 1992). Developing and transition countries tend to have a
higher proportion of vegetable and animal wastes\textsuperscript{24}, sometimes as high as 90\% (Tchobanoglous \textit{et al.}, 1993; Lardinois & Furedy, 2000). People in industrialised and transition countries are also more likely to keep their yard wastes separate, while in developing countries these are likely to be mixed with other household wastes (Lardinois & Furedy, 2000).

Backyard and neighbourhood scale offers an attractive option to the many failed centralised systems in developing countries. Generally backyard composting consists of household-level aerobic decomposition of household organic garden and kitchen wastes, with the resulting compost being used in the yard itself. Such facilities can provide a waste management opportunity to a small group of people at a relatively low cost. Close proximity of yards to each other in many neighbourhoods in both industrialised and developing countries implies a need for management of the compost for vector and odour control, including periodic aeration or turning. In neighbourhoods with gardens or urban agricultural activities ready markets exists and compost can be sold at a price adequate to meet costs (Poerbo, 1991; Rosenberg & Furedy 1996; Lardinois & Furedy, 2000; Ojeda-Benitez \textit{et al.}, 2000).

In recent years, a number of governments in industrialised countries have treated backyard composting as a means of waste reduction, since the materials which are composted remain at home and do not enter the municipal waste stream. Such backyard composting and mulching programmes, which have operated successfully in Northern Europe, North America, Australia, and New Zealand, are much less costly to a community than centralised compostable collection programmes. They have participation rates approaching 30\%, with significant results in terms of wastes diverted from the municipal waste stream (Suess, 1985; Poerbo, 1991; Furedy, 1992; Rosenberg & Furedy, 1996; Lardinois & Furedy, 2000).

However, there are also negative impacts on the environment associated with making and using compost. These impacts depend both on the technical approach used and the waste composition of the input streams. These may include unpleasant odours from gases released from improperly maintained compost piles; leachate production; and the potential to convey heavy metals to the soil (Tchobanoglous \textit{et al.}, 1993; Lardinois & Furedy, 2000). Control of bad odours and rodents can be carefully controlled if composting is performed within household backyards.

\textsuperscript{24} As-delivered (wet basis) municipal solid waste from Accra, Ibadan, Dakar, Abidjan, and Lusaka shows a range of per-capita generation rates of 0.5-0.8 kg/pd (compared to 1-2 kg/pd in the OECD countries); putrescible organic content ranging from 35-80\% (generally toward the higher end of this range); plastic, glass, and metals at less than 10\%; and paper with a percentage in the low teens. Densities in the range of 90-180 kg/m\textsuperscript{3} for un-compacted municipal solid waste are common in OECD case studies, whilst in Africa the range is thought to be between 180-540 kg/m\textsuperscript{3} (Suess, 1985; UNCHS, 1989; WHO, 1991; Tchobanoglous \textit{et al.}, 1993; Lardinois & Furedy, 2000).
Various studies have been conducted to compare ecological sanitation with traditional waterborne sanitation systems (Jonsson, 1997; Jonsson et al., 1998; Loetscher, 1999; Vinneras, 2002; Bijleveld, 2003; Drangert, 2003). Aspects compared range from social, environmental, health, economical and financial and technological. Box 1.1 summarises some of the broad aspects characterising ecological sanitation and traditional waterborne sanitation. Emissions of nutrients, heavy metals, and pathogens into aquatic systems have been compared. The absence of large scale ecological sanitation projects as compared to waterborne sanitation has necessitated the reliance on limited available data and assessment by use of models the possible effects of ecological sanitation (Lundin et al., 1999; Johansson et al., 2000; Karrman, 2000; Van der Vleuten-Balkema, 2003).

Although simulations are not measurements of actual systems, they can provide useful information which cannot be obtained in real life. Models like ORWARE have been developed to simulate the production, treatment and handling of solid and liquid organic wastes (Jonsson et al., 1998; Dalemo, 1999; Karrman, 2000) on various system solutions on the basis of equivalent conditions.

**Paradigm shift in sanitation**

Organic matter and nutrients present in human excreta and the organic part of urban solid waste constitutes an important source of plant nutrients and renewable bio-energy (Niemczynowicz, 1993; 1997a). It could be suggested that a distinct path of evolution is occurring: one that is progressively engaging in the low-technology of naturally occurring processes, such as the ability of wetlands, reed beds, crop products and other biomass products present in terrestrial and aquatic eco-systems, in assimilating urban residues (Beck et al., 1994; Matthews, 1996; Zeeman & Lettinga, 1998). This path has a certain philosophical satisfaction about it - a return to the spirit of the sewage farm, redolent of the ‘good old days’ of a rural society. Yet this is not an especially sound basis on which to prefer one form of technological development over another. However, the barrier against waterborne diseases is still a basic feature of the present urban water system that new technology must not jeopardise (Harremoës, 1997; Drangert, 2003).

Assuming that this path will result in waste load reduction and minimal if not ‘zero’ transfer of the waste problem to land, water and air contamination, then there is sense to propose a “Paradigm shift”. This evolution of water supply and sanitation systems can be represented graphically as in Figure 1.6. Four eras are distinguished based on the major driving forces. Within these time frames certain types of technologies have been developed or dictated by the desired goal or driver. Some important events are also presented in Figure 1.6 as milestones (Niemczynowicz, 1993; 1997a; Gumbo, 2003a).
### Box 1-I Summary features of traditional waterborne sanitation and ecological sanitation

<table>
<thead>
<tr>
<th></th>
<th>Traditional waterborne sanitation</th>
<th>Ecological sanitation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process</strong></td>
<td>• Mixing system</td>
<td>• Source separating system</td>
</tr>
<tr>
<td></td>
<td>• Dilution</td>
<td>• Minimum dilution or dry</td>
</tr>
<tr>
<td></td>
<td>• Linear “end-of-pipe”</td>
<td>• Circular “closed loop”</td>
</tr>
<tr>
<td></td>
<td>• Separation at “end-of-pipe”, containment, bio-digestion and disposal</td>
<td>• Sanitisation, bio-digestion, recycling and reuse</td>
</tr>
<tr>
<td></td>
<td>• Promotes discharge of nutrients into aquatic systems</td>
<td>• Enhances return of nutrients to the soil</td>
</tr>
<tr>
<td></td>
<td>• Point source pollution copious and endemic</td>
<td>• Can result in dispersed pollution if scale and composition of wastes do not conform to the ability of local ecosystems to absorb them</td>
</tr>
<tr>
<td></td>
<td>• Tends to work at one scale at a time</td>
<td>• In principle it should integrate multiple scales, reflecting the influence of larger scales on smaller scales and vice versa</td>
</tr>
<tr>
<td></td>
<td>• Promotes additional water pollution arising from organics,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pharmaceuticals and hormones</td>
<td></td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>• Easy to design and control, standardised templates are readily available and can easily be replicated all over the world</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Design criteria usually based on economics, custom and convenience.</td>
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</tr>
<tr>
<td></td>
<td>• Narrow disciplinary focus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• High to low-tech at “end-of-pipe”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Extends the pathogen cycle away from the user</td>
<td></td>
</tr>
<tr>
<td><strong>Resources</strong></td>
<td>• Energy demanding</td>
<td>• Energy efficient, as it relies mostly on natural processes and renewable sources, solar, wind, biomass and small scale hydro</td>
</tr>
<tr>
<td></td>
<td>• Energy sources usually non-renewable and destructive, relying on fossil fuels or nuclear power</td>
<td>• Minimal or no synthetic additives required</td>
</tr>
<tr>
<td></td>
<td>• Can require chemicals e.g. coagulants and disinfectants</td>
<td>• Simple by-products e.g. methane gas, ammonia and manure</td>
</tr>
<tr>
<td></td>
<td>• Complex by-products e.g. sludge, effluent</td>
<td></td>
</tr>
<tr>
<td><strong>Management</strong></td>
<td>• Centralised and can benefit from economies of scale</td>
<td>• Decentralised</td>
</tr>
<tr>
<td></td>
<td>• Specialised agencies or institutions involved in operation and</td>
<td>• Users need to be mobilised and motivated in the management</td>
</tr>
<tr>
<td></td>
<td>maintenance limited scope for community participation</td>
<td>• Education and awareness of users is crucial and a clear commitment to discussion and debate of possible solutions</td>
</tr>
<tr>
<td></td>
<td>• Limited user education and awareness</td>
<td>• Proven history to provide the much needed plant nutrients</td>
</tr>
<tr>
<td></td>
<td>• Proven history to guarantee public health</td>
<td>• Other spin-offs include food production, poverty reduction</td>
</tr>
</tbody>
</table>
1.5 Systems analysis and material flow and stock analysis

Integrative analysis of city systems helps to see beyond their current environmental and social problems to underlying causes, and it suggests different opportunities for possible interventions. Cities can be viewed as systems involving people’s (social and economic institutions) interactions with one another and with the built environment they have created (Meadows et al., 1972, 1992; Ross et al., 2000). The built environments interact with the natural ecological processes of their sites.

Urban planning and design is usually accompanied by budgets, spreadsheets, bills of quantities, parts lists and so forth. Rarely does the parallel set of accounts that link the designs to the health of ecosystems considered. These accounts cover large square metres of misused land, kilowatt-hours of energy, cubic metres of water, tonnes of eroded soil and many other environmental impacts of the designs. The built-
environment can be developed in the future to cooperate with natural functions and preserve their health (Beck, 1997; Hallsmith, 2003). This entails, for example, recognising the nature of the flood plain system and its drainage requirements and configuring the built environment where possible to complement rather than to resist it (Lyle, 1985; Van der Ryn & Cowan, 1996; Ross et al., 2000). Systems analysis and material flow and stock analysis (MFSA) present attractive tools in desegregating the complex web of cycles, stocks and flows. The two provide a basis of tracking the flow of materials and products through society and the environment, an activity of increasing prominence and consequence throughout the world.

**Systems analysis**

A system is an entity, which maintains its existence through the mutual interaction of its parts (Von Bertalanffy, 1975; Coyle, 1996). A system is a human construct, an analytical artefact. Systems are abstracted for study from much more complex sets of interactions which occur in the ‘real world’. In setting the boundaries of a system, the scale selected (river basin, city or neighbourhood), or which parts of the system to focus on is a question of choice. There is no problem in focusing on a particular aspect of a system, or on a small scale, as long as there is an understanding on how this aspect fits into the rest of its system (or puzzle) or indeed the web of potential systems. Land use and built environment configuration can extensively impair the functioning of the natural ecosystem. What is done at one scale has subtle impacts, both negative and positive, at many other scales (Senge; 1990; HPS, 1992; Senge et al., 1994).

The characteristics of world problems and the functioning of the socio-ecological systems are changing. The cause-effect chains tend to change from local to global levels (e.g. global warming), from specific to diffuse (e.g. air and water pollution), from short delay to long delay (e.g. CFC’s and the ozone layer) and from low complexity to high complexity (e.g. land use changes) (Winograd, 1997). The existence of vertical and horizontal linkages between scales and components and the relationship between variables imply the need to use tools, such as systems analysis, systems dynamics and geographic information systems.

The broad picture in systems analysis implies looking at global and transcending down to local scales; literally when considering natural resource use, but also figuratively in terms of the wider social, economic and political context. Nature’s processes are inherently scale linking, for they intimately depend on the flow of energy and materials across scales (Ayres & Simonis, 1992; Van der Ryn & Cowan, 1996; Ford, 1999). Global cycles link organisms together in a highly effective recycling system crossing about seventeen tenfold jumps in scale, from a ten-billionth of a metre (the scale of photosynthesis) to ten thousand kilometres (the scale of spaceship Earth itself). In other words, a systems analysis approach requires a “bi-focal perspective”: i.e. one eye examines the broad picture, seeing the whole, and the second eye focuses on the detail at a micro scale (Figure 1.7).
The development of sustainability frameworks and indicators should be developed and used at different levels (administrative and ecological), with different scales (local, national, regional and global) and components (economic, social and environmental) (Moldan & Billharz, 1997). The indicator tools should be able to produce a range of information from local to global, from detailed to aggregated and from scientific to policymaking. In the case of land use, for example, it is necessary to have indicators reflecting other variables, in addition to indicators about the pressure, state, impact and response on land (Figure 1.8).
Introduction

Material Flow and Stock Analysis (MFSA) is the investigation of the physical flows of materials, typically on a geographic basis. MFSA can help in understand how changes in land use, industrialisation, consumption and population affect the cycles of elements or chemicals of concern in a watershed. It provides a means of taking a comprehensive rather than an ad hoc view of the drivers and source of substances (Ayres, 1978; Baccini & Brunner, 1991; Wackernagel & Rees, 1996; Ayres & Ayres 1998).

MFSA is an activity of compiling numerical measures of things or actions, in a form that makes comparison and analysis easy, or at least, possible. Although monetary accounts are certainly necessary for modern life, there is no good way to assign monetary values to most of the essential services provided by the environment, ranging from benign climate, breathable air and fresh water to biodiversity, nutrient recycling and waste assimilation (Daly & Cobb, 1989; Ayres & Ayres 1998).

Direct measurement is not enough and never can be enough. The environment is too complex and heterogeneous to understand in terms of direct measurement alone. The essence of real science, therefore, is selection and simplification. Vastly simplified world models are needed, at first. The trick is to build understanding step-by-step by...
starting with simple models that explain the most fundamental phenomenon, adding complexity (or making changes in the assumptions) only, when the existing models are clearly inconsistent with the reality (Anderberg et al., 1993; Daly, 1996; Ayres & Ayres 1998; Brunner et al., 1998). For MFSA, a consistent and meaningful choice of spatial and time boundaries helps to focus the accounting procedure and lend greater value to the problem at hand (Brunner & Baccini, 1992; Van der Ryn & Cowan, 1996).

Broadly there are three different types of data sources which can be used for MFSA purposes as illustrated in Figure 1.9 (Obernosterer et al., 1998):

1. Primary data - generally raw data (e.g. direct experiment results or results from questionnaires, surveys etc.)
2. Secondary data – raw data that has been processed, collated and interpreted (e.g. statistics, publications, proceedings and reports, internet, models)
3. Tertiary data – informal or non-traditional data sources (estimations, interviews, non-published data, local or hands-on knowledge, individually performed estimates, the media etc.)

There is a level of uncertainty associated with all forms of data. To use MFSA as a tool in the decision making process, the uncertainties of the presented results must be known. Since MFSA requires numerous data sources, this means, different levels of data uncertainty must be combined and taken into account. As a consequence, the system is usually not “balanced” i.e. input minus output does not equal stock variation (Baccini & Brunner, 1991; Ayres & Ayres 1998; Obernosterer et al., 1998).

If different values are available for a flow or a stock, the minimum-maximum values are taken into account (data range). This data range could be misleading, if one
supposes that the true value is within this range. It is sometimes the case that this range exists as a result of two different literature values, each with their own level of uncertainty. In addition, sometimes data on material flows and stocks or on a substance concentration of goods is limited or unknown. When no values are available, estimations may need to be made (Baccini & Brunner, 1991; Obernosterer et al., 1998).

**System dynamic models**

The field of system dynamics originated in the 1960’s with the work of Jay Forrester and his colleagues at the Sloan School of Management at the Massachusetts Institute of Technology. Forrester and his colleagues developed the initial ideas by applying concepts from feedback control theory to the study of industrial systems (Ford, 1999). One of the best-known applications of the new ideas during the 1960’s was Forrester’s *Urban Dynamics*, (1969). It explained the pattern of rapid population growth and subsequent decline that had been observed in a number of cities in the USA (Schroeder & Strongman, 1974). *Urban Dynamics* highlighted the field’s expansion outside the industrial area. Its approach came to be known as system dynamics (Meadows et al., 1972).

System dynamics maybe used to simulate material flow through a system (Ford, 1999). Stocks and flows are building blocks of systems dynamics models. The stocks are key variables in the model, they represent were accumulation or storage takes place in the system. Stocks tend to change less rapidly than other variables in the system, so they are responsible for the ‘momentum’ or ‘sluggishness’ in the system (HPS, 1992, 1993; Ford, 1999). Flows are the actions changing the system and they directly influence the stocks. Flow variables are measured in the same units as the stock variable, divided by the appropriate unit of time. The right combination of stocks and flows provides a good foundation for a model.

The third model builder in systems dynamic is the converter, which helps to describe the flows. Frequently converters are used to provide model inputs and those variables that don’t logically meet the description of stocks and flows. The other purpose of converters is to calculate additional measures for the system performance (Ford, 1999). The converters serve a utilitarian role in the software. it holds values for constants, defines external inputs to the model, calculates algebraic relationships, and serves as a repository for graphical functions (HPS, 1996).

Figure 1.10 shows the generic symbols used to represents stocks, flows and converters in computer system dynamics models (HPS, 1993). Rectangles are used to represent accumulations, stocks, reservoirs or inventories. The pipes, with spigot or valve flow regulator and circle attached, represent flows. The connectors of wires indicate relationships. They link stocks back to flows, and in some cases flows to flows. Circles represent converters.
Almost all the concepts basic concepts and techniques needed for constructing and running System Dynamics (compartment-flow) modelling are shared with amongst the most common visual System Dynamics modelling software, such as Stella and ithink (HPS, 1992, 1993), Simile, Model-Maker, Dynamo (Forrester, 1961; Richardson & Pugh, 1981), Power-Sim (Powersim Corp, 1996) and Vensim (Kirkwood, 1995; Ventana, 1995; 1996). Computer simulation models can help in developing instincts for managing ecosystems.

1.6 Scope of research

**Problem statement, the case of the Harare Metropolis, Zimbabwe**

The Harare metropolis in Zimbabwe, extending upstream of Lake Chivero in the Upper Manyame River Basin, consists of the City of Harare and its satellite towns: Chitungwiza, Norton, Epworth and Ruwa (Figure 1.11). The existing urban water and drainage system which is the subject of study in this dissertation is typically a single-use-mixing system: water is used and discharged to “waste”, excreta are flushed to sewers and eventually, after some “treatment”, the effluent is discharged to the main drinking water supply source, Lake Chivero (see Box 1.1: Lake Chivero: A polluted Lake). Polluted urban storm water is evacuated as fast as possible without retention or any opportunity for environmental assimilation, therefore a multitude of other materials form an important source of non-point pollution. This system not only ignores the substantial value in “waste” materials, but it also exports problems to downstream communities and to vulnerable fresh water sources (Bailey et al. 1996; Moyo; 1997a; Gumbo, 2000a).

The main research question in this dissertation is how can the Harare metropolis system, which is complex and has evolved over time be rearranged to achieve sustainability (i.e. water conservation, pollution prevention at source, protection of the vulnerable drinking water sources and recovery of valuable materials like nutrients) (Gumbo, 2000a; 2003a).
In the year 2000, approximately 2.4 million people, 22% of the population of Zimbabwe lived within the Harare metropolis. By 2020 the population of the catchment (2 200 Mm$^2$) is estimated to rise to 3.4 million people which will be 25% of the total population (Zanamwe, 1997). Being on the watershed, the city of Harare and its satellite towns lie within the catchment area of the main sources of water supply.
As a result most of the drainage from the City and the towns flows into its own water supply lakes (Thornton & Nduku, 1990; Moyo, 1997a). Settlement densities are among the highest in the country, with the Harare-Chitungwiza urban areas accounting for about 50% of the national urban population (CSO, 1992). Harare urban has a settlement density of 3 000 people/Mm². Density in the rural parts of the catchment are a lower average of 30 people/Mm² (JICA, 1996; Zanamwe, 1997).

**Box 1-J Lake Chivero: A polluted Lake**
Adapted from Nhapi et al., (2002)

Numerous hydro-biological investigations carried out in Lake Chivero in the 1970’s showed the Lake to be eutrophic, with the eutrophication of the impoundment being caused by the rapid chemical changes from the input of treated sewage effluent to the lake by the City of Harare (Thornton, 1980). Since the 1980’s, no comprehensive research programme has taken place and thus there is a death of information on vital limnological parameters which are useful in the determination of the lake’s present trophic status (Moyo, 1997a). Thornton (1980) made a comparative study of the phosphorous loadings in three reservoirs of varying trophic states. The summer phosphorous loads to Lake Chivero accounted for 80% of the annual phosphorous loading to the lake and much of the phosphorous entering the lake was lost to the sediments. The study by Thornton, (1980) showed the following annual phosphorus loadings to the lake: 74 600 kg/a, or 2.8 g/m² and 0.3 g/m³. Before the diversion of municipal wastewater from the lake catchment to pasture irrigation schemes between 1970 and 1975 the loadings were respectively 288 000 kg/a or 11.0 g/m² and 1.2 g/m³. Magadza (1997) also attributes this increased phosphorous loading to the sewage works in the Lake’s catchment. The high phosphorous content of the effluent is a combination of inadequate treatment, due to overloading, as well as breakdown in the treatment works.

Lake Chivero is already eutrophic (Robarts & Southall, 1977; Thornton, 1980) and a number of fish kills have been reported (Moyo, 1997b). The major cause for the fish deaths in 1996 was de-oxygenation of water compounded by ammonia toxicity (Moyo & Mtetwa, 1999; Magadza, 1997). Most fish are sensitive to DO levels of below 3 mg/l (Welch & Lindell, 1980). Ammonia-N is toxic to fish at concentrations above 0.5 mg/l (Abesinghe et al., 1996).

Both the lake and the inflow rivers are heavily infested with the water hyacinth (*Eichhornia crassipes*) and blue-green algae, principally *Microcystis aeruginosa* and *Anabaena sp.* and this is attributable to the nutrient loadings from sewage treatment works (Jarvis et al., 1982; Mathuthu et al., 1997). Excessive amounts of algae and other organic matter have seriously impacted on raw water abstraction and water treatment (McKendrick, 1982; Moyo & Mtetwa, 1999) and led to clogging of downstream commercial farming irrigation pipes (Bailey et al., 1996). The lake is also losing its value as a recreational area (e.g. yachting, skiing, angling). In addition, the aesthetic qualities of the water has also deteriorated (Mbiba, 1995).

Lake Chivero created in 1952 (full supply capacity of 250 Mm³) is the major raw water source and receives sewage effluent in excess of 120 000 m³/day from an industrialised and densely populated area via Firle and Crowborough sewage treatment works (Gumbo, 2000a; Nhapi et al., 2002). A pollution analysis of rivers was conducted in 1995, 1997 and 2001 in terms of Chemical Oxygen Demand (COD), Total Nitrogen (TN) and Total Phosphorus (TP), under dry and wet season conditions (JICA, 1996; Marshall, 1997; Nhapi et al., 2002; Nhapi, 2004). The research indicates that nutrient inflows into the Lake have increase dramatically since the impoundment formed forty five years ago. Total phosphorus concentrations in the water column of the lake have increased from 0.5 mg/l in 1995 to about 0.8 mg/l as TP in 2001, suggesting a steady build-up of phosphorus in the lake.
The mass fish death witnessed in April 1996 on Lake Chivero is a graphic representation of the consequences of excessive pollution of water sources within the catchment (Moyo, 1997b; Gumbo, 1997a). Other ongoing effects of pollution of Lake Chivero include water treatment difficulties, water hyacinth infestations (Figure 1.12), toxic algae blooms and the clogging of downstream commercial farming irrigation pipes (JICA, 1996; Moyo, 1997b; Marshall, 1997; Magadza, 1997).

Figure 1-12 Water hyacinth infestation on a weir upstream of lake Chivero
Photograph: Gumbo (2000)

Sewage works are the main and most easily identifiable source of pollution contributing about 40% of the nutrient input (Gumbo, 2000a; Nhapi et al., 2002; Hranova et al., 2002). The remainder is from non-point sources emanating from flows within the catchment area which include urban storm runoff and runoff from commercial farming areas. Virtually all domestic and industrial wastewater in the urban centres goes into the sewerage system because of high sewerage service coverage ratio and ideally all wastewater reaches the treatment plants at the end-of-the-pipe and its “treated”. In some locations however rapid development has clearly outstripped urban sewerage infrastructure. In some localities, overflowing sewage from manholes is encountered where domestic sewage is directly discharged into sewer lines. This environmental problem is associated with deficient solid waste management and habitual behaviour of residents, aside from limited absorbing capacity of sewer lines and lack of appropriate maintenance. Due to overload and lack of maintenance of infrastructure specific sections experience sewer blockages on a frequent basis (Taylor & Mudege, 1997).

A study in the 1970’s, on storm water drainage in the catchment showed a clear relationship of increased nutrient loading with urbanisation (Thornton & Ndaku, 1982). From estimations it was found that diffuse source storm water runoff can potentially supply sufficient nutrients to Lake Chivero to maintain a ‘eutrophic state’. Commercial farming is a source of pollution from runoff containing nutrients and various noxious substances from the use of fertiliser, herbicides and pesticides. According to studies into pesticide residues in Lake Chivero (Mhlanga & Madziva, 1990; Zaranyika, 1997)
traces of BHC’s, aldrin, dieldrin, DDE, DDD, and DDT were detected in water, soil, fish and sediment samples.

In Zimbabwe indirect reuse of wastewater to augment potable water supplies is encouraged through a ministerial policy in view of the impending water stress situations in this semi-arid country (Lock, 1994). Even before the advent of planned water reuse, Harare’s citizens had for many years drunk their “own bath water”. However reduced water flows in feeding rivers during droughts have resulted in effluent flows increasing with respect to natural flows (JICA, 1996). If the lake, due to droughts, does not spill then it acts as a 100% sink of all the effluent flowing into it (Fullstone, 1980). This is a form of indirect reuse, which entails the incorporation of reclaimed wastewater into raw water supply source. This concept is based on mixing and assimilation with natural discharge into an impoundment of water, such as a domestic water supply reservoir, where dilution becomes very important (Stewart Scott, 1982; Gumbo; 1995; Asano & Levine, 1996). The wisdom for indirect reuse of wastewater for potable supplies in this basin and in Zimbabwe in general is questionable, “Is it a nuisance or a resource?” The old concept that the solution to pollution is dilution is proving to be unsuitable under these circumstances. The state of Lake Chivero is a manifestation of the ‘dangerous dilution disposal method’ of wastewater (Gumbo, 1995; 1997b).

The Lake Chivero case downstream of the Harare metropolis demonstrates that societies can no longer rely on end-of-pipe sewage treatment works, as kidneys and liver to separate and remove nutrients and other toxic materials in a concentrated form to prevent them from entering the aquatic environment. The existing “conventional” urban water and sanitation system (end-of-pipe) is not efficient and compatible with the needs of an eco-city; the long end-of-pipe recycling loop of wastewater, storm water and improper application or disposal of sludges and solid organic residuals needs some rethinking (Tilth, 1982; Todd & Todd, 1994; Esrey, 2000).

In principle short “circular” or closed systems at neighbourhood scale fit better in the concept of sustainability: these seek to minimise the net use of resources and encourage local recycling, water conservation and source protection inline with the needs of a sustainable urban environment. The main question is however the feasibility such a closed system and particularly of ecological urban agriculture within the Harare metropolis through the use of nutrients derived from human metabolism (excreta and organic residues). What land use changes or infrastructural arrangements have to be developed to promote urban agriculture? What are the social, economic and environmental impacts, costs and benefits of incorporating urban agriculture as part of the urban fabric?

The quantification and establishment of a comprehensive material flux and storage analysis for an urban eco-system in the Lake Chivero basin is the starting point in identifying where short “circular” systems or material recovery techniques could be introduced without transferring the problem from one sphere (hydrosphere, lithosphere, or atmosphere) to the other (Gumbo, 2000a).

Sustainable use of resources has to satisfy several conditions. One can distinguish physical, economic, social, financial, institutional and environmental or ecological sustainability (Savenije, 1998). Physical sustainability means closing the resource cycles and considering the cycles in their integrity (water and nutrient cycles). The
closing of cycles implies that resources are transported back to where they came from. Obviously, in the case of phosphorus (P) this does not imply that P needs to be returned to the mine (lithosphere) it came from, but that food and human wastes need to be returned to the farm as fertiliser.

Closing cycles maybe costly or wasteful in terms of energy (transport mainly). As a result, closing of cycles implies that they should be kept as short as possible. The economic sustainability relates to the efficiency of the system. If all the societal costs and benefits are properly accounted for, and cycles are closed, then economic sustainability implies a reduction of scale by short-cutting the cycles. Examples of short cycles, in the context of this research include; local or on-site recycling, nutrient conservation and recovery; water conservation, making maximum benefit of rainfall where it falls (and not to capture it downstream to pump it up for irrigation or water supply).

Any attempt to close water and nutrient cycles, would mean closing of energy cycles and so would be food supply lines. The distance between “civilised humans” -both urban and rural- and their food source is part of the problem which manifests itself as water pollution problems in the case of Lake Chivero, among others. For instance the energy costs of the food system are enormous. Machinery, fuel, fertilisers, pesticides, water supply, long distance transport (generally requires more energy than is available from the food produced), drives to the supermarket, and home refrigerators. Other resource impacts in the food and agriculture system are related to soil, water and forests (erosion, nutrient loss, water storage for arid land agriculture, irrigation and return flows, deforestation as more and more acreage is needed for food and fodder production or grazing) (see Boxes 1.B and 1.C). These long food-supply lines common in a modern society are also a security risk. If war does not disrupt them, the collapse of economies might. The shortest food supply line is therefore in need of investigation as one of the most interesting alternatives for a sustainable future.

History, however, is not to be ignored. There are sewer networks in Harare metropolis and their existence sets the constraints of the initial conditions for any developments into the future. Similarly, an infrastructure of wastewater collection, conveyance, treatment, reuse and disposal is already in place so that, retrofitting it or “unhooking” certain components from the public urban drainage system network, may not make the best sense for the future. There is still not enough knowledge about what the environmental, economic and social effects of the more general use of source oriented, local and small-scale methods and technologies will be. This is leading to several questions. Should such methods be used only in new developing housing areas or should all systems be gradually replaced? How will the general use of source control options and reuse of nutrients for urban agriculture impact on the entire river basin? A view to the totality of the urban water and drainage system with a proper analysis of flow of water and matter through society is required. Among the tools are input-output analysis, cradle-to-grave analysis, mass balancing, material flow and stock accounting and systems analysis (Gumbo, 1999a; 1999b, 2001).
**Aims and objectives**

This research intends to analyse the ‘paradigm shift’ in the water and sanitation sector in urban areas, by providing a computational and evaluation framework for implementing ecological sanitation concepts based on natural cycles of plant nutrients. The finite resource phosphorus is the main subject of analysis. Recycling of phosphorus (P) in urban or peri-urban ecological agriculture (without synthetic fertilisers) is used to assess the feasibility of concepts such as the Bellagio principles for environmental sanitation (section 1.1). The focus is on the origins, sources and sinks, the different mechanisms which, transform and export phosphorus through an urban-shed of a selected micro-study catchment lying within the Lake Chivero basin in Zimbabwe. These processes are mirrored against the global P-cycle, transformation and transfers. The thesis investigates the flows and stocks of phosphorus in a typical high-density residential suburb in Harare.

The hypotheses is that short-cutting or closing open-ended water and nutrient cycles at the lowest appropriate level would ensure sustainable use of limited resources like phosphorus at the same time protecting the same resources from possible contamination. The reasons for the choice of P as an assessment parameter are outlined in Box 1.K.

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**Box 1-K Choice of P as an assessment parameter**

1. Phosphorus is a major constraint on food and fibre production in many parts of the world especially in developing regions. Therefore, an economic supply of P is a necessity for a secure production in agriculture and forestry (Tiessen, 1995). Since P is an important nutrient in ecosystem productivity in general, its recovery or reuse is attractive and both economically and ecologically justifiable.

2. An inefficient way to satisfy the agricultural P demand is by the exclusive use of inorganic fertilisers, which normally are expensive imports, and which often have relatively low use efficiencies in the field.

3. Management and research should aim at nutrient and organic matter cycling (this includes human and animal waste) in combination with sufficient fertiliser use to avoid ‘nutrient mining’ in agriculture and forestry.

4. Phosphorus originates from a mined rock, therefore its presence in the urban-shed demonstrates the impact of urbanisation and anthropogenic influences on natural cycles of material flow.

5. In passing through the urban system P is mobilised from particulate to soluble forms. Therefore, in the case of P-bearing material fluxes can it be said that the activities of the urban population on the aquatic environment are globally a problem.

6. P is an important limiting nutrient in fresh water quality assessment and its role in eutrophication and its control requires further investigation. Eutrophic inland waters and their watersheds should be managed to limit P inputs, because P is easier to control than N for example, which can be entrained from the atmosphere.

7. Its resistance to be degraded into soluble forms and affinity for binding into particulate matter is representative for other elements (e.g. Si, K, N, Fe).

8. P bearing materials are most easily removed from storm and sewage water in particulate form, therefore making P separation, recovery and reuse less energy intensive.
At the core the real concerns are about food security and environmental integrity. The specific objectives of the investigation are:

- To test the feasibility of ecological sanitation and eco-city concepts in urban centres at household or neighbourhood scale by critically assessing knowledge of the nature, sources, sinks and fluxes of phosphorus at a global scale. Urban agriculture is investigated as the main option for nutrient recycling.

- To establish an inventory of phosphorus bearing materials (fluxes and stocks) within the micro-study catchment where agriculture is already a major activity, by studying; the material use and disposal at the household level; and the urban agriculture dynamics in terms of phosphorus inputs, storage and outputs. Using a system’s thinking approach and MFSA two compartments or subsystems are defined to enable accounting and analysis of P-bearing materials namely the “household” (consumption or use and excretion or waste) and “agriculture” (soil-plant interaction) (Figure 1.13). The identified flows and stocks are used to draw up the P-balance for the micro-study catchment.

- To develop mathematical and conceptual relationships which describe the flows and stocks of phosphorus (origins, sources, pathways and fate) on a monthly time-step in the household and agricultural subsystems of the micro-study catchment.

- To develop a suitable model which can be used to demonstrate the possibility of short-cutting the phosphorus cycle through synchronisation of the activities at household level and those of the urban farm or garden. And to analyse the sensitivity and reliability of the model to input variables.

- To investigate the feasibility of recycling at neighbourhood level in terms of environmental criteria.

Figure 1-13 P-fluxes analysed in the household and agricultural subsystems
Source: Gumbo et al., (2002a)
Limitations of methodology

The various natural cycles are interconnected and depend on one another to a great extent. For example, the burning of fossil fuels not only puts large amounts of carbon into the atmosphere, but also increases the amount of atmospheric nitrogen, phosphorus and sulphur. This interdependence is also obvious when one considers nutrient cycling through organisms. When a herbivore eats a plant or a carnivore an animal, it ingests at one go all the elements, which are found in organisms. Clearly, biogeochemical cycles involve complex interactions between the abiotic environment and living organisms and any one cycle is composed of numerous loops and steps.

In this dissertation in as far as it is an oversimplification to consider the P-flux in isolation, so it will be a limitation to assess the merits of each technological option in isolation. The key to sustainable urban eco-system will be a judgement on the best strand of unit process technologies that transfers wastes from source to sink (in an environmentally efficient manner). The issue, however, is that urban systems should be designed so as not to exacerbate any of the principal, global problems but rather alleviate them. The convenient simplification of analysing material cycles (using material accounting and system’s analysis) in isolation must therefore be acknowledged as merely a device for starting this assessment of the technologies and management of the urban water, sanitation and organic waste system.

The “ecological rucksack”25 of P imports is not considered in approximating the global and regional P fluxes and stocks. Waste emanating from use or consumption is actually a small percentage of material wasted. The world over resource wastage is ten times more than use (Von Weizsackers et al., 1997). The calculations of material flow and stocks are based on the assumption that there is no difference in the ecological rucksack between imports and exports of products.

The P-flux calculations in this dissertation are based on monthly or annual time series. This is of practical significance since most of the urban agricultural activities are seasonal and usually occur between the months of November and March. Data used in the analysis is either aggregated daily data or disaggregated annual data. This approach introduces a number of errors as an average year is normally assumed.

1.7 A guide through the dissertation and its innovations

Chapter one presents an overview of ‘paradigm shift’ with regard to sanitation and management of organic residues from urban centres. The eco-city concept is presented and it is suggested that the problems of water pollution experienced in the Harare metropolis in Zimbabwe can be solved by employing a decentralised system of waste management based on the Bellagio principles. The chapter introduces the methodology used in this dissertation i.e. material flow accounting and systems thinking and its limitations. The choice of P as a parameter of assessment is elaborated, and so is the focus on the urban P-flows (tracking its source to sink).

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25 The ecological rucksack of a product is the portion of the material input used for its production that is not incorporated within the product. This represents inefficiencies in for example in P mining, extraction and conversion to P-based fertilisers.
Ecological sanitation and organic waste recycling are a piece in the global cycling of materials (Figure 1.14) and, as such, it may be useful to postulate that ‘desirable’ technologies for its implementation will be those that introduce minimal distortion of this cycling relative to the global material cycles of the pre-industrial era.

**Chapter two** provides details on bio-geochemistry of P, its history and exploitation by human beings especially in the agricultural sector. The Chapter quantifies the impacts of open-ended P-flows and the need to close its cycle at every possible scale. This chapter provides useful background information on P-cycling at a macro-scale i.e. global and regional. It is especially essential to the reader with little knowledge on soil-plant nutrient relationships and transfer of P from land to riverine ecosystems. Regional P-trade balances in crop, animal and fertiliser commodities is presented for year 2000 based on FAO (2001) data to illustrate the distortions on the natural cycling of P as a result of human activities.

**Chapter three** describes the area of study, within the context of Zimbabwe and the Lake Chivero Basin. The Chapter provides background information on the pollution problems and makes linkages between the various activities in the catchment including urban agriculture and waste management. The micro-study catchment is presented in detail in preparation for Chapter four.

**Chapter four** is the computational heart of this dissertation as it organises data and information collected into a monthly P-flux calculator using STELLA, a systems analysis software developed by High Performance Systems Inc. Mathematical algorithms are developed. The calculator can be used as a planning and decision-making tool for closing the P-cycle within urban ecosystems. It also provides the means to simulate and evaluate different options in linking household waste P-fluxes
to agricultural P-requirements. The calculator is used in **Chapter five** in assessing promising options based on environmental sustainability criteria.

**Chapter six** summarises the methodology and presents recommendations and conclusions.

**Chapter seven** is a closing chapter outlining the feelings of the researcher during the six years of research on this topic and various interactions made with the promoter, supervisor, and resource persons and important of all family members. This Chapter is dedicated to those who might want to follow a similar mode of study and is presented in such a relaxed fashion reflecting that there is fun, frustrations, toil and sweat during this uncertain journey in attaining a PhD.

Figure 1.15 illustrates the linkages between the Chapters, the flow of ideas and thoughts from the initial stages of the research work to its conclusions.
Figure 1-15 Layout of dissertation and linkages within the Chapters