A 3-step strategic approach to sustainable wastewater management

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Abstract

Many cities in developing countries are facing surface water and groundwater pollution problems. This deterioration of water resources needs to be controlled through effective and feasible concepts of urban water management. The Dublin Principles, Agenda21, Vision21, and the Millennium Development Goals provide the basis for the development of innovative, holistic, and sustainable approaches. Whilst highly efficient technologies are available, the infusion of these into a well-thought out and systematic approach is critical for the sustainable management of nutrient flows and other pollutants into and out of cities. Based on cleaner production principles, three intervention steps are proposed in this paper. The first step is to minimise wastewater generation by drastically reducing water consumption and waste generation. The second step is the treatment and optimal reuse of nutrients and water at the smallest possible level, like at the on-plot and community levels. Treatment technologies recommended make the best use of side products via reuse. Once the first two intervention steps have been employed to the maximum, the remaining waste flows could be safely discharged into the environment. The third step involves enhancing the self-purification capacity of receiving water-bodies (lakes, rivers, etc.), through intervention. The success of this so-called 3-step strategic approach requires systematic implementation, providing specific solutions to specific situations. This, in turn, requires appropriate planning, legal and institutional responses. In fact, the 3-step approach could be applied as an overall approach for waste management, although here the focus is on sewage. This paper offers examples under each step, showing that the systematic application of this approach could lead to cost savings and sustainability.

Keywords: cleaner production, nutrients reuse, 3-step strategic approach, sustainable approaches, urban water cycle, wastewater management

Introduction

Many countries are currently facing an environmental dilemma due to rapid population growth and urbanisation, and the related enormous quantities of waste generated in their cities. It is estimated that of the current world population of 6.1 billion, about 47% live in cities, with these cities having an average annual population growth of 2% (UNFPA, 2001). The annual average world population growth is estimated at about 1.2%, resulting in increased energy, food and material demand. Urban migration, due mainly to decreased agricultural production in rural areas and increased job opportunities in towns, has given birth to mega-cities, especially in developing countries. The hopes for job opportunities and a better life in cities have sometimes been dashed by poor performances of most economies, often leading to economic difficulties. The results in some cities have been disastrous as the cities have failed to cater for most residents, the majority of whom make no financial contribution to the development of their communities.

One of the numerous problems being faced by many cities is the management of waste(water) generated, resulting in serious pollution of downstream water-bodies. In some cases the problems have been localised whilst in others pollution has been allowed to cross boundaries, in itself a potential cause of conflicts. Well-known examples include the river Rhine in Europe, and the Nile River in Africa. Nutrients - nitrogen, phosphorus and potassium (NPK) - are known to cause serious eutrophication problems in water-bodies and require proper control. The advent of uncontrolled urban agriculture, passively allowed in most African cities, has compounded the problems as increasing loads of fertiliser are imported into cities. Although urban agriculture seems to offer a logical destination of nutrients in wastewater, not enough emphasis has been placed on this option? There has been little attempt to link wastewater management to urban agriculture despite the logical connection between them. Instead, synthetic (artificial) fertilisers have resulted in an additional stream of nutrient inflow into urban areas. For example, Gijzen and Mulder (2001) did a detailed analysis of the natural and anthropogenic nitrogen cycles and clearly showed an imbalance in nitrogen inflows and outflows from cities. The same arguments can also be advanced for phosphorus. The current mineral reserves for phosphorus will only last for 100 to 150 years at current levels of consumption (Otterpohl et al., 1997). Future strategies for increasing agricultural productivity would have to focus on using available nutrient resources more efficiently, effectively and sustainably than in the past. The abundance of nutrients in domestic wastewater can no longer be ignored.

The historical development of wastewater management has been characterised by efforts to solve mainly one problem at a time; sanitation during the first half of the 20th Century followed by eutrophication of receiving waters and, for the past 10 years or so, recycling of nutrients. After the Dublin Conference on Water and

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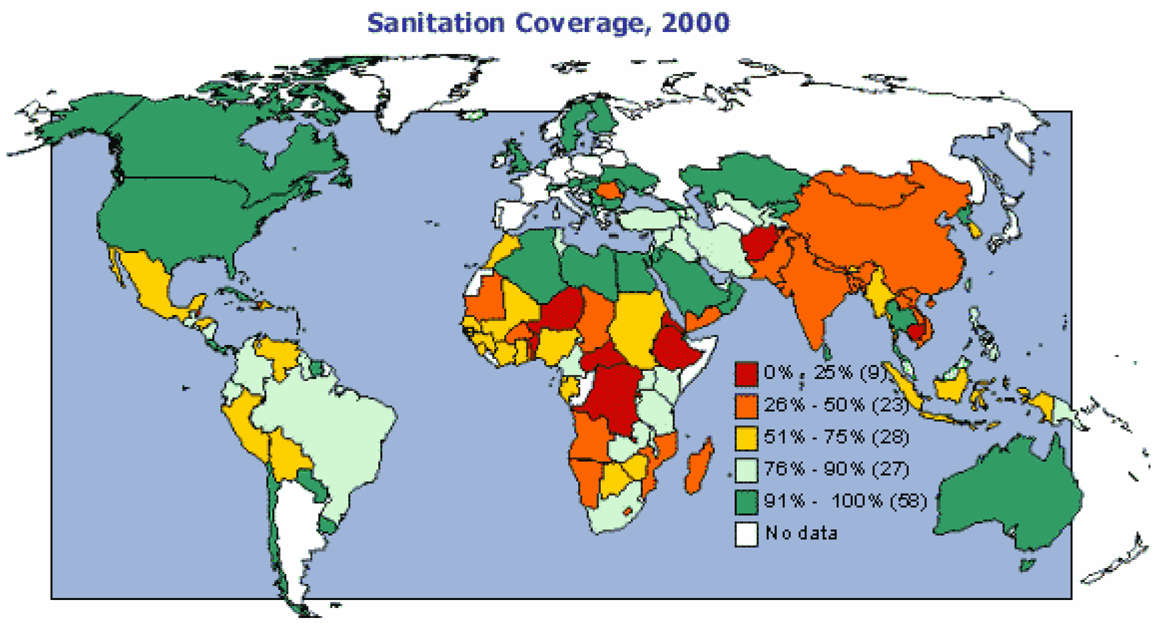

Figure 1
Sanitation coverage for most parts of the world based on year 2000 figures
(Source: http://www.childinfo.org/eddb/sani/printmap.htm, accessed Nov. 2004)

the Environment (ICWE) in Dublin, Ireland, in January 1992, a reversal of the debate occurred where water management was discussed in a more holistic manner than before (ICWE, 1992). Recent water-related mega-conferences emphasized integrated approaches to water management and the need to drastically reduce the number of people without adequate access to water and sanitation services. These conferences include the UN Water Conference (Mar del Plata, 1977), Dublin Conference (1991), UN Conference on Environment and Development (Rio de Janeiro, 1992), Bonn Consultation (2001), Johannesburg Summit (2002), and the three World Water Forums (Marrakech, 1977; The Hague, 2000; and Japan, 2003). Also, the need for ecological responsibility has evoked different responses by governments and municipalities. Stricter regulations have resulted in huge investments in tertiary wastewater treatment (WHO, 2000; WHO/UNICEF, 2004). However, the "end of pipe" technologies often applied in recent investments have very little direct financial return for the municipalities and are mainly blamed for poor sanitation coverage in many developing countries, especially in Africa and Asia (Fig. 1). In developing countries, the situation is more desperate as investments have focused more on clean water provision than on sanitation services (WHO, 2000). This is because the cost of disposing of 1 m^3 of wastewater is higher than the cost of producing 1 m^3 of potable water (Gunnerson and French, 1996).

The origin of wastewater is water consumption. There is, therefore, an urgent need to develop sustainable management strategies that would control both water and nutrient flows in towns and cities with the added advantages of cost reduction, handling efficiency, increased food production, environmental integrity, and social benefits. This suggests a cyclic approach instead of the current linear approaches to nutrient and water management that have led to nutrient accumulation in water-bodies. This could be achieved by an integrated approach to nutrient management. The development of innovative, holistic, and sustainable approaches has been the subject of recent initiatives such as the Dublin Principles, Agenda21, Vision21, and the Millennium Development Goals (Cosgrove and Rijsberman, 2000; King, 2000; WHO/UNICEF, 2001) This paper is based on these initiatives and presents a strategic approach, starting with the generation, treatment and disposal of wastewater. In formulating such a strategy, a number of important characteristics are recognised and discussed in this paper. Briefly these are that:

- Cities are large consumption centres, generating large inflows and outflows of nutrient-bearing materials that need to be kept in balance,
- Pathways of these nutrients need to be tracked in an urban ecosystem so that nutrients are directed to advantageous parts for the benefit of the environment
- The current problems experienced in urban wastewater management are a function of wasteful water-use patterns and practices that need to be corrected through intervention.

In order to solve the above problems, a 3-step strategic approach to wastewater management based on pollution prevention and minimisation, treatment and reuse, and controlled disposal, is proposed. To be effective, this approach needs to be backed by an inclusive system that recognises other stakeholder interests in urban wastewater management.

Waste generation in cities and cleaner production

Urban centres generate a lot of food (nutrients), water supply and raw materials that flow into and out of them and a significant proportion ends up on waste dumps or in water-bodies (Fig. 2). Many cities in developing countries depend on daily markets for most of their domestic food supply because few homes have refrigerators. Thus most of these cities have areas within or just beyond the suburbs devoted to intensive market gardening. Urban gardens and allotments are also a significant part of the food supply and social life of western cities (Douglas, 1983). In most cities, peri-urban agriculture is devoted to intensive vegetable production, supplying fresh vegetables to an expanding urban market. After use, the majority of goods are discarded as waste products. A lot of

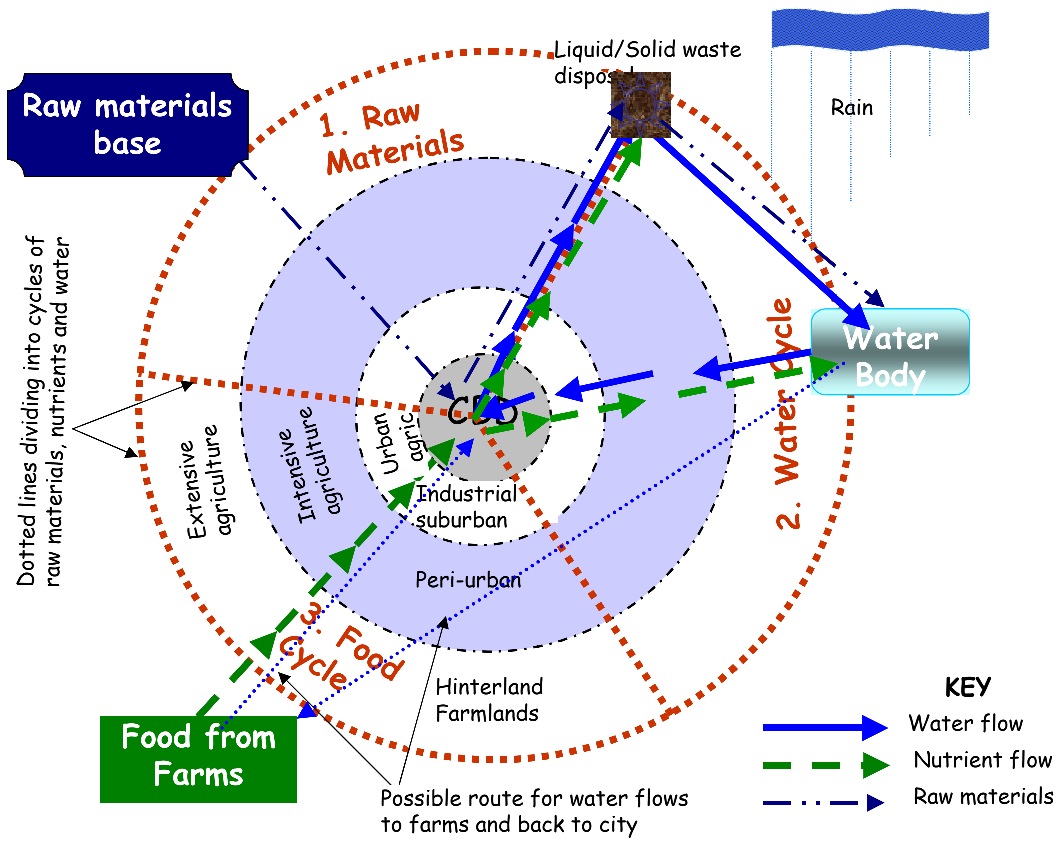

Figure 2

Schematic illustration of the inter-dependencies between water, food and raw materials supply into and out of the city based on landuse classification of central business district (CBD (middle circle)), industrial/suburban, peri-urban and farming hinterland

packaging material is also used in cities after which it is thrown away or recycled after initial use. The degree of waste generation would therefore depend on how much is wasted or recycled. Whilst the management of that part of ”waste” material that goes into sewer systems is quite developed, though in some cases managed irrationally, the management of the solid part has been poor in many cities in developing countries.

Figure 2 shows how food and raw materials flow into and out of the city, ending up in solid waste dumps and water-bodies. Some of the materials brought into cities form part of the immovable part of the city. These are mainly for buildings. However, others decay over time and have to be disposed of after their useful lives. The physical structures, or fabric, of the city, require large quantities of construction materials. The supply of raw materials overlaps in its land-use demands around cities with those for intensive agriculture, and competes for land with other urban uses. The fabric of a city obviously requires an input of materials and the inorganic matter used in the fabric (concrete, steel, etc.) is relatively long-lasting although it will eventually decay and might lead to nutrient enrichment or contamination of some kind. But the organic matter is a much more immediate problem; it is primarily generated by the human inhabitants themselves – the food they eat, the waste matter they produce, various industries that use organic matter, and so on. Organic materials also contain nutrients and these normally quickly flow through the city. Whilst some are retained within the city boundaries, they eventually decay and reach water-bodies via surface or groundwater flows. This is a linear approach to urban waste management, which is often regarded as senseless because of its failure to utilise useful resources in waste and wastewater. Reuse and recycling are therefore necessary to avoid contaminating water-bodies.

The sustainable management of urban water requires the establishment of effective water institutions, the development of low water usage (or even dry) sanitation systems, rain-water harvesting, and the extensive use of resource recovery and reuse techniques for wastewater (Otterpohl et al., 1997; King, 2000; Lens et al., 2001). This entails a holistic approach with waste being seen as a resource, and its management linked to that of water resources and of nutrients. In fact, resource recovery and reuse approaches could, in addition to water savings, result in financial incentives which could be used to cover part of the cost of wastewater treatment (FAO, 1999). In addition, the urban water and waste management situation could be addressed from a “cleaner production” angle (Gijzen, 2001; Nhapi and Hoko, 2004). Cleaner production interventions have been extremely successful in the industrial sector. By evaluating the current urban water management system from a cleaner production point of view, the urgency to re-think current practices/concepts in the light of sustainability becomes evident (Table 1). The cleaner production concept, developed over the past two decades, has brought some innovative environmental thinking into the industrial sector, especially in terms of waste avoidance/reduction and use of substitutes.

Intervention: The 3-step strategic approach

There are three major cycles in an urban set-up, namely the water, food and raw material cycles (Fig. 2). This paper focuses on nutrients, so the issue of raw materials will not be carried further as

TABLE 1 Cleaner production principles and current water management practices	
Principle	**Practice**
Use lowest amount of input material, energy or other resources per unit of product.	We supply between 130 and 350 ℓ of drinking water per capita per day, while less than 2 ℓ are actually used for drinking
Do not use input materials of a higher quality than strictly necessary.	We use water purified to drinking water standards to flush toilets, clean floors, wash cars or to irrigate the garden.
Do not mix different waste flows.	Already in the household various wastewater flows are combined (urine and faecal matter, grey and black water). After disposal into the sewer this combined waste is mixed further with industrial effluents, and often times also with urban runoff. Obviously this practise makes re-use of specific components in the mixed waste flow less attractive and less feasible.
Evaluate other functions and uses of by-products before considering treatment and final disposal.	Domestic sewage is discharged into open water resources either with or without prior treatment. Only few examples of wastewater re-use or (by-) product recovery from wastewater exist.

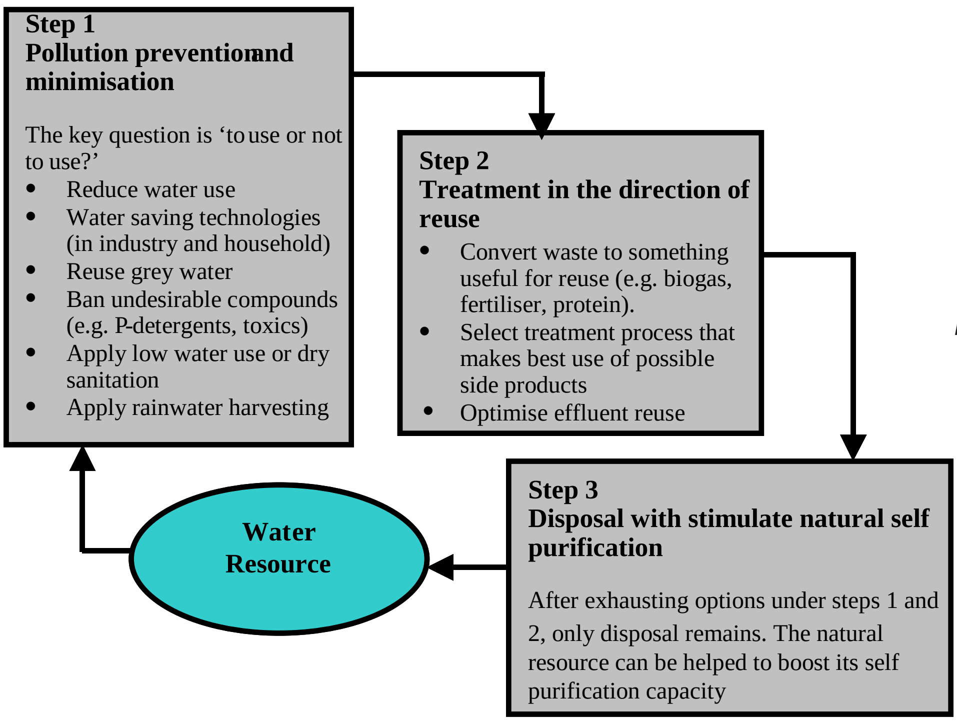

Figure 3 *Schematic representation of the 3-Step Strategic Approach to wastewater management*

these are not a major source of nutrients. The accumulation of food (nutrients) in the water cycle is of major concern as it causes an imbalance and high productivity problems in water-bodies. The improper management of solid waste inevitably results in leaching of nutrients and other pollutants into water-bodies. These problems are further compounded by the advent of intensive urban agriculture (Bowyer-Bower et al., 1994). An ideal situation is one in which an internal urban nutrient cycle is developed, complemented by rational use of water (a crucial component of food security).

To improve the traditional urban water management system, water supply and wastewater management have to be closely interconnected so that water is used with minimal withdrawal from, and reduced discharge to the environment. Options available for this are given by Harremoës (1999) as: No use, reuse, convert, contain, and disperse. These options have been systematically developed and applied in solid water management but could also be translated to the water sector. In fact, they could be reduced into three steps as given by Davidavicius and Ramoškiene (1996) and Nhapi et al. (2003) as follows:

- Prevention or reduction of waste production
- Treatment and recovery of waste components
- Safe disposal of any waste components not recycled or reused.

These options for intervention can be grouped into a systematic 3-step strategic approach (Fig. 3), which is dealt with in detail in this paper. This approach strongly focuses on sewage management, but also considers water supply, nutrient uses and other material flows associated with the urban water cycle.

Step 1: Prevention or reduction of waste production

The levels of water consumption in some parts of the world mean that large quantities of wastewater will be generated, requiring huge investments in collection and treatment infrastructure. A reduction in wastewater generation will be an important contribution to the conservation of both resources and energy. The 3-step approach, therefore, starts by controlling consumption through waste avoidance and reduction measures (cleaner production). For a start, people should ask themselves whether some of the things they use are necessary and consider substitutes if there is a danger to the environment. An example is the continued use of phosphorus-based detergents in some countries. The other question is whether people should really consume at current levels of inefficiency by using things like water, nitrogen and phosphorus only once? For example, the current water consumption levels in some poor African cities are high; the daily production of wastewater was as high as 315 ℓ/cap in low-density suburbs of Harare, Zimbabwe (Nhapi et al., 2003). Such figures have serious implications on the sizing of water and wastewater treatment plants and their efficiencies. Substantial reductions in water consumption could be achieved via demand management and water saving technologies such as low-flush toilets, water efficient shower caps and taps, and efficient dishwashers and laundry machines). These could be supplemented by the collection of rainwater and using it for toilet flushing, washing the car, and gardening while demand management should aim at educating households on efficient water use. Metcalf and Eddy (1991) report that water consumption could be reduced by up to 50% through the application of such intervention measures.

There are also concerns about the supply of good quality water for different uses (Chaplin, 1998). Humans require only 1 to 2 ℓ of potable water per day for drinking, yet about 150 to 300 ℓ are consumed in most cities (Metcalf and Eddy, 1991). Some believe this is abusive use of water and recommend that water of different quality could be supplied for different purposes (Otterpohl et al., 1997). Water from bathing, washing machines, dish washers and kitchens could be collected separately and be reused for purposes that do not require drinking water quality such as gardening or car washing. In some cases, pretreatment could be required. There is also a need to reduce water losses, both at treatment plants and in the distribution lines. In Zimbabwe, for example, water treatment plant losses of 20% and distribution losses of >30% have been reported (JICA, 1996). The detection and repair of leaks, and an improvement in equipment and production processes could greatly reduce water losses and consumption in industries. For example, a brewery in Zimbabwe uses 16 ℓ of potable water per litre of beer produced, whilst one in the Netherlands uses 4 ℓ of water per litre of beer produced (Mlilo, 2002). This inefficiency in water use results in high water bills and wastewater treatment costs.

The management of nutrients in cities could be improved. Although large reductions have been made in end of pipe discharges from point sources, little effort has been invested in controlling phosphorus entering sewage treatment plants since the ban on phosphorus in laundry detergents in the mid-1970s in the USA. This action led to a 40% reduction in effluent phosphorus concentrations from waste water treatment facilities in Vermont (Van Benschoten and Smeltzer, 1981). Similar reductions were achieved nation-wide (Litke, 1999). If the phosphorus that needed to be removed from wastewater were limited, potential savings might accrue in the economics and efficiency of treatment. The efficient use of wastewater nutrients could be directly linked to increased food production in urban agriculture where they could be substituted for chemical fertilisers. Demonstration fields have shown that the productivity

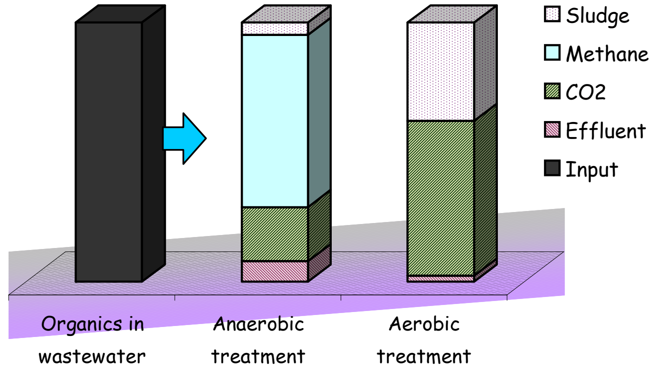

Figure 4
Comparison of aerobic and anaerobic wastewater treatment (Gijzen, 2001)

of crops irrigated with wastewater was comparable to those given artificial fertilisers (Guzha, 2004). Wastewater could be directly reused within the same industry, by other industries (waste trading), within municipalities, or within the wider area for irrigation. Greywater or combined wastewater has been directly reused in agriculture and aquaculture (Metcalf and Eddy, 1991; Lindstrom, 1998). Public health regulations generally require the treatment of wastewater but simpler and cheaper methods of treating it such as natural disinfection using maturation ponds and composting of faeces can be used.

Waste minimisation, therefore, involves not only technology, but also planning, good housekeeping, and the implementation of environmentally sound management practices such as cleaner production. The"polluter pays" concept and discharge limitations are some of the instruments that could be used to control the way in which water is used. Industries could also be compelled by legislation to treat and reuse wastewater within their properties, wherever possible, and thus limit discharges to public sewers and streams.

Step 2: Treatment, recovery and reuse of waste components

The second step focuses on technologies that treat wastewater so that it can be reused. The chosen technologies should be rational, sustainable, and cost-effective. Issues of rationality concern the rational reuse of valuable waste components by, for example, converting COD into energy, incorporating N, P and K into protein, and using effluent as water for agriculture and aquaculture.

Wastewater treatment can be accomplished in aerobic or anaerobic systems but anaerobic systems appear to be more favourable because of energy recovery and cost-effectiveness (Gijzen, 2001). When organic matter is treated anaerobically, about 375 ℓ of methane can be expected from each kilogram of BOD digested. Assuming an almost complete conversion of organic matter into biogas, a daily per capita production of 25 to 45 ℓ of methane can be expected. The mineralisation of organic matter via anaerobic treatment results in less sludge and carbon dioxide (CO_2) production, but more methane compared to aerobic treatment (Fig. 4). Both methane and CO_2 are potent greenhouse gases but methane could be usefully applied for heating in domestic and industrial applications.

Anaerobic treatment systems are also considerably cheaper than aerobic ones with significant cost saving on electricity requirements, nutrient and sludge handling (Fig. 5). The production of biogas can bring in an income for anaerobic systems whilst aerobic systems earn nothing. Anaerobic pre-treatment can reduce influent

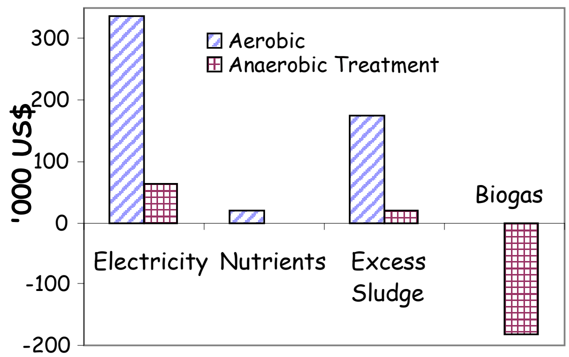

Figure 5
Cost savings resulting from anaerobic wastewater treatment for 2,000,000 hectolitres of beer/yr (Gijzen, 2001)

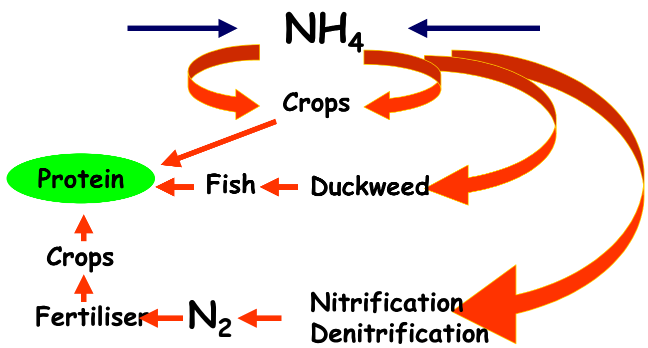

Figure 6
Possibilities for nitrogen reuse

COD by 90 to 95% at about 80% lower power consumption (Gijzen, 2001). Sustainable wastewater treatment should therefore use anaerobic systems as much as possible as a first step in treatment.

Following anaerobic treatment, the recovery and reuse of nutrients, and the destruction of pathogens, are essential elements of a sustainable wastewater management system. Conventional tertiary systems are found wanting in this respect because they normally utilise biological N and P removal, which is very costly and results in no valuable by-products. Energy is wasted for aeration and nitrogen compounds are destroyed instead of being reused. The conventional algae-based stabilisation ponds use natural nitrification/denitrification processes and ammonia volatilisation to destroy nitrogen compounds. Some nitrogen and phosphorus are taken up by algae but released again into the water when the algae die or are eaten by animals. Potent greenhouse gases like NH_3, CO_2 and H_2S are potentially produced and released into the atmosphere. Like conventional tertiary systems, algae-based stabilisation ponds (unless algae are harvested) are not a rational and sustainable way of treating wastewater.

On the other hand, the use of macrophytes for wastewater treatment offers a cost-effective and shorter way of linking wastewater treatment to protein production (Fig. 6). Nutrients are taken up by macrophytes such as duckweed, water hyacinth or reeds which, when harvested, can be used to feed livestock or fish. The remaining nutrients in effluent can be used for irrigation of crops, pastures or plantations after pathogens have been destroyed in maturation ponds. The separation of urine and greywater at source also allows innovations in their treatment, in terms of both process and localisation (Gajurel et al., 2003). Urine is rich in nutrients but contains few pathogens or heavy metals (Jönsson et al., 1997) and contributes less than 1% to the total wastewater volume. Greywater contains the bulk of household phosphorus, but has low pathogen content, and has readily degradable BOD (Lindstrom, 1998). Both urine and greywater could be reused directly or after minimal treatment. Examples of treatment options and the successful uses of urine separation are described by Larsen and Gujer (1996) and Jönsson et al. (1998), and greywater separation by Rasmussen et al. (1996) and Lindstrom (1998).

Options for the reuse of effluents include agriculture and aquaculture, industrial applications, and urban situations such as public parks, recreational centres, golf courses, fire protection, and toilet flushing. In all cases, the quality of wastewater and type of reuse define levels of treatment required. In Zimbabwe, sewage effluent has been used on farms in and around Harare, Chitungwiza and Chegutu for the irrigation of crops such as citrus, animal feed and vegetables, as well as pastures (Nhapi and Gijzen, 2004). Kusina et al. (1999) and Nhapi et al. (2004) reported on the use of duckweed for effluent treatment and subsequent feed to chickens in Zimbabwe. Sewage from some industries and institutions can be reused within the plot boundary as is the case at Leopard Rock Hotel near Mutare in Zimbabwe which employs about 400 people, has 50 beds, and produces about 200 m^3/d of sewage. The influent sewage receives secondary treatment by diffused aeration and is disinfected by UV radiation, after which it passes through a series of constructed wetlands before being used to irrigate a golf course. Fish are allowed to grow in the last pond and all effluent is reused on site. This has enabled the grass on the course to be kept green and healthy all the time without the need to supplement with artificial fertilisers.

Step 3: Disposal of waste with stimulation of natural purification

Once the options available under Steps 1 and 2 have been exhausted it may be necessary to resort to Step 3 if some unmanaged nutrients still remain in the effluent. Step 3 aims to reduce pollutant concentrations and exposure risks by promoting natural purification in receiving water-bodies (rivers, lakes, oceans). Usually the local environment suffers initially after receiving effluent discharge, but the strategy is to boost the self-purification capacity of the receiving water-body so that it can cope with the pollution load. An example is the heavily polluted Bocana de la Virgen Bay, in Cartagena, Colombia (Moor et al., 2002). Six inlet and four outlet doors were constructed to allow water inflows and effluent outflows to be controlled by tidal pressure. This action improved the water quality as dilution occurred and self-purification was enhanced.

Concluding remarks

There is greater scope for the application of the 3-step approach in managing wastewater for both small and large towns. However, the management of wastewater should also take into account the different land uses (residential, commercial, industrial, institutional) in towns and hence apply different solutions for different areas. For all areas, Step 1 should be applied to reduce wastewater volume and the discharge of toxic materials into the sewer system. As a first option, industrial effluents should be handled separately to avoid contamination, as this would affect biological treatment. On-site treatment of sewage would suit industrial and low-density residential stands. Where stands are large enough, the effluent should be treated and reused within the stand boundary. If this is not possible, nutrients should be allowed to filter out to the next stage of decentralised wastewater management. Here, wastewater is treated within neighbourhoods and closer to sources of generation and could also be conveyed back for reuse at a small cost as savings on transmission costs would result. Anaerobic pretreatment with the collection of biogas becomes feasible if the sewage is made more concentrated through the application of cleaner production concepts at each household. The decentralised concept would suit sewage from high- and medium-density residential stands, where no space is available for treating and reusing sewage within the plot boundaries.

In larger towns, the volume of sewage produced is very high so that only centralised treatment is feasible. Even in such areas there is scope for the reduction of wastewater volumes, with savings on treatment costs. At this level, the collection of biogas could become commercially viable. The effluent could still be treated to a standard suitable for use in large commercial irrigation farms. Whatever remains is discharged into the river and efforts should be made to enhance the self-purification capacity of the receiving water-body. Holding ponds or constructed wetlands could be used or interventions could focus on the receiving body itself.

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